Some new ideas for the proton radius puzzle

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The radius of the proton has been measured using several techniques. Methods using electron scattering agree with those obtained using the atomic spectrum of (electronic) hydrogen. Note that the spectroscopy method relies on being able to measure the transition energies accurately enough that the influence of the finite size of the proton can be discerned. Pohl et al have used muonic hydrogen as a third approach to determine the proton's radius. Due to the muon's larger mass, its wave function is more spatially concentrated meaning that it is a better probe of the proton than the electron, and hence can provide more accurate proton radius determinations. Using this method, Pohl et al found that the radius from muonic hydrogen is around 4% smaller than the electronic hydrogen case [1]. Since this represents 7 standard deviations, it is an unresolved puzzle. This paper introduces new ideas which may affect these proton radii measurements.

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R-mode instability of neutron stars using nuclear EoS from DDM3Y

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The oscillations of rotating neutron stars have gained much importance because of the information they send about the properties of the high-density Equation of State (EoS) through electromagnetic and gravitational wave signals. In the present work the r-mode instability has been discussed with reference to the EoS obtained using the density dependent M3Y (DDM3Y) effective nucleon-nucleon (NN) interaction [1]. This EoS provides good descriptions for proton, α and cluster radioactivities, elastic and inelastic scattering, symmetric and isospin asymmetric nuclear matter, neutron star masses and radii, their core-crust transition and crustal fraction of moment of inertia [2, 3].

The r-mode damping mechanism is calculated using the shear viscosity timescale acting along the boundary layer between the rigid crust and fluid core. We have calculated the fiducial gravitational radiation and shear viscosity timescales within the DDM3Y framework for a wide range of neutron star masses. It is observed that the gravitational radiation timescale decreases rapidly with increasing neutron star mass while the viscous damping timescales exhibit an approximate linear increase. Next, we have studied the temperature dependence of the critical angular frequency for different neutron star masses. The implication is that for neutron stars rotating with frequencies greater than their corresponding critical frequencies have unstable r-modes leading to the emission of gravitational waves. Further, our study of the variation of the critical temperature as a function of mass shows that both the critical frequency and temperature decrease with increasing mass. The conclusion is that massive hot neutron stars are more susceptible to r-mode instability through gravitational radiation. Finally we have calculated the spin down rates and angular frequency evolution of the neutron stars through r-mode instability. We have also pointed out the fact that the critical frequency depends on the EoS through the radius and the symmetry energy slope parameter L. If the dissipation of r-modes from shear viscosity acts along the boundary layer of the crust-core interface then the r-mode instability region is enlarged to lower values of L [4].

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Asymptotic analytic expressions for the adiabatic potentials of a particular system of three particles in two dimensions

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In this work, we present an analytical study of the asymptotic behavior of the adiabatic potentials and the subsequent phase shifts, for a particular system of three particles in two dimensions. In this system, the interaction between two of the particles is that of a repulsive step potential and the third particle acts as a spectator. This system is important in its own right, as associated with $\overline{\delta}$ phase shifts, needed in a pioneering calculation of the third quantum mechanical virial (cluster) coefficient, for 3 particles in two dimensions [1]. More important, still, it illuminates the origin of the inverse logarithmic behavior, for large values of the hyperradius, found in some of the adiabatic potentials of the fully interacting 3 particle system [1], and therefore the resulting inverse logarithmic nature of the corresponding phase shifts.

In our analysis of our simplified system, for Bose particles, we first introduce a new set of complex Jacobi coordinates, and then a complete basis of harmonics, involving the angular momentum of the two interacting particles, and of the angular momentum of the third particle about the center of mass of the first two, as associated with good quantum numbers. This then leads to a Differential Equation which - for a fixed chosen value of the hyperradius, ρ, and of the two quantum numbers, above - involves only one variable z. When the potential is zero, the solutions, our $F_\ell^{|\ell_1|,|\ell_2|}(\rho, z)$, reduce to just the Jacobi polynomial $P_\ell^{|\ell_1|,|\ell_2|}(z)$ part of the new hyperspherical basis.

For values of ρ, we were able to obtain solutions of the adiabatic equation, as well as of the corresponding adiabatic potentials - and of associated effective potentials. In addition we were able, *analytically*, exactly, to obtain the leading terms of these effective potentials, confirming - for a certain set of quantum numbers - an inverse logarithmic behavior, first found in the numerical studies. In other cases, we found the leading behaviors to be of inverse powers of ρ.

Drawing on the known solutions of the 2-body problem, we are able to understand the origins of the inverse logarithmic behavior - when it should happen, and when inverse powers are appropriate.

Finally, we gain insight into the numerical results, previously reported, of the behavior of the adiabatic potentials of the fully interacting systems.

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On the bosonic atoms – structure and processes

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We investigate ground state properties of atoms, in which substitute fermions – electrons by bosons, namely π^- - mesons. We perform some calculations in the frame of modified Hartree-Fock (HF) equation.

The modification takes into account symmetry, instead of anti-symmetry of the pair identical bosons wave function. The modified HF approach thus enhances (doubles) the effect of self-action for the boson case. Therefore, we accordingly modify the HF equations by eliminating the self-action terms "by hand". The contribution of meson-meson and meson-nucleon non-Coulomb interaction is inessential at least for atoms with low and intermediate nuclear charge, which is our main subject.

As an example of simple processes with a pion atom, we consider photoionization and pion elastic scattering, comparing it to similar data for ordinary i.e. electron atoms.

To obtain these results, we have solved the following equation

$$-\frac{\Delta}{2}\chi_k(\mathbf{r})-\frac{Z}{r}\chi_k(\mathbf{r})+2(N_\pi^k-1)\int\left|\chi_k(\mathbf{r})\right|^2\frac{d\mathbf{r}'}{|\mathbf{r}-\mathbf{r}'|}=E_k\chi_k(\mathbf{r})$$

Here Z is the nucleus charge, $\chi_k(\mathbf{r})$ is the pion wave function, N_π^k is the number of pions on the level k. in calculations we put all pions on the lowest possible 1*s* level.

According to the data obtained, the total binding energy of a pion atom is much bigger than that for an ordinary atom, and the size of the pion atom is several times bigger than the size of a normal atom. Sizes and energies we express in pionic and normal atomic units, respectively. The ionization potential ($-E_{1s}$,) of a pionic atom in these units is much smaller than that of a neutral atom.

An interesting feature of a pion atom is its ability to easily form negative ions. For pionic *He*, *Ne* and *Ar* we predict the possible formation of single negative pionic ions He_π^-, Ne_π^-, Ar_π^-. For Zn, the formation of Zn_π^- and Zn_π^{-2} becomes possible. *Kr* is able to form up to Kr_π^{-3}, while Xe is able to attach extra four pions that leads to Xe_π^{-4}. In general, the binding energy of pion negative ions A_π^-, pion atoms A_π, and the number of maximal extra bound pions ΔN_π increases with the growth of nuclear charge Z.

While for ordinary atoms, the 1*s* photoionization cross-section monotonically decreases with photon energy growth from the maximum value at threshold, for pion atom that cross-section, on the contrary, reaches its maximum value above ionization threshold, thus forming pronounced maxima, the height of which is decreasing while the width is increasing with Z growth. Formation of negative ions is reflected in corresponding behavior of its elastic scattering s-phase. Negative ion formation and resonances were observed in s-phase only.

Detection and further investigation of pionic atoms is of interest and importance.

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Two dimensional Sturmian basis set to treat three body Coulomb break-up problems

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In a number of atomic or molecular break up processes, the Coulomb three body problem plays a major role. Finding the scattering states with proper boundary conditions is notoriously difficult because of the long range nature of the interactions. *Ab initio* treatments entail a high demand on computational resources [1, 2], both with respect to the memory size of the Hamiltonian matrix representation, and the processor time and memory needed to manipulate and solve the ensuing huge system of matrix equations. The standard treatment, based on total angular momentum conservation laws and on the use of the coupled spherical harmonics basis related to two pair of inter-particle distance coordinates (or a Jacobi pair), converts the three body Schrödinger equation in a coupled set of bi-dimensional radial equations, which have to be solved numerically. An additional, delicate, issue is that the method has to be able to accurately represent the asymptotic conditions at large interparticle distances.

A method based on the use of Generalized Sturmian Functions (GSF) has been developed over the last decade [3]. It effectively deals with the asymptotic conditions of scattering wave functions since each set $S_n(r)$ of GSF (one for each of the two radial coordinates, say r_1 and r_2), corresponds to a discrete and complete set of basis functions with outgoing flux conditions. Using the GSF together with the Galerkin method, solutions with the correct outgoing behavior in the hyperspherical radial coordinate were obtained [1].

From the outset, the idea of the GSF method was to be able to obtain converged cross sections reducing, as much as possible, the minimal size needed for the Hamiltonian matrix representation. While this was achieved efficiently, we have found that the reduction may not be enough for some processes where a high number of partial waves are required. For this reason, we wished to go even further by exploiting our empirical observation that some basis element combinations (i) have very small weight in the final wave function representation and (ii) could not be identified a priori as they change from one problem to another. We have thus designed a reordering methodology which allows us to differentiate the physical combinations of Sturmian functions from the unphysical ones. To do this, we solve a two dimensional Sturmian problem from which we get the same number of two coordinates basis elements $S_n(r_1, r_2)$ than products $S_{n_1}(r_1)S_{n_2}(r_2)$ of one coordinate original GSF. As a consequence, the solution to the three body problem can be represented in terms of the new basis (instead of the standard GSF) with no changes in the Hamiltonian matrix size and without changing the physics included in the basis.

At the conference we will show that the spectrum of the two coordinate eigenvalue problem can be separated in two sets with very different physical properties. One set has spherical outgoing behavior, typical of radial wave functions of the three body break-up problems, while the other set has an irregular (unphysical) behavior. Also, the classification can be done from the eigenvalue set, since each family lies in a different region of the complex plane. Finally, using only the physical basis elements we will evaluate a scattering wave function illustrating how we achieved an important reduction of the computational resources with respect to the original (one-coordinate) GSF method.

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Spherical image potential states for a system of N charged particles

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The states arising from the interaction between a charged particle and a conducting surface are called image potential states [1]. The word "image" makes reference to the image charge method used to obtain the electric field in boundary problems with conductors. Basically, when a charge q is placed in front of an infinite plane conducting surface at a distance z, to get the electric field normal to the surface one may think of an image charge $-q$ located at the opposite position $-z$ (inside the conductor). With this artifact, one is able to find a solution for the Maxwell equations and boundary condition in the $z \geq 0$ region, and uniqueness of the solutions implies that one has solved the problem. Of course, generally, the situation is not as simple since there is no real image charge but a surface charge density induced on the conductor by the original charge [2]. The work needed to move the original real charge q is then used to define the image potential, and the quantum states associated to this interaction are called *image states*.

In real physical situations we usually encounter a geometry more complicated than the infinite plane conductor, so that the previous simple picture needs to be modified. A "friendly" boundary that can be investigated is provided by a spherical surface which could correspond to a metallic ball or a spherical cavity. In this work we study the image potential for a system of N charged particles (a) inside a metallic cavity, or (b) at the surroundings of a metallic ball of radius R. Closed form solutions are obtained for both situations, and the contributions arising from confinement are identified, i.e., the fact that the electric field variations can be only seen in some regions of the space. As an example, in the (b) situation, we found that for the two particles (charges q_1 and q_2, placed at positions $\mathbf{r}_1$ and $\mathbf{r}_2$ respectively), the potential is:

$$V = \frac{q_1 q_2}{|\mathbf{r}_1 - \mathbf{r}_2|} - \frac{q_1 q_2}{|R\hat{\mathbf{r}}_1 - r_1 r_2 \hat{\mathbf{r}}_2|} \tag{1}$$

plus two one-particle potential terms.

Spherical image states for systems of particles confined in metallic cavities or surrounding a conducting ball will be presented at the conference. In particular, the two-body case representing the confinement of atomic hydrogen with a moving nucleus will be illustrated. This kind of atomic confinement systems has been studied before [3], but will be considered here in combination with the metallic model.

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Convoluted quasi Sturmian approach to the three-body Coulomb continuum

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We are interested in representing the continuum wave function for the Coulomb three-body problem. Such scattering states are needed, for example, in the description of the double ionization of the Helium atom by impact of fast projectiles. We have recently [1, 2] developed an *ab initio* approach based on Convoluted Quasi Sturmian (CQS) functions. The present contribution shows that: (i) numerical convergence can be reached; (ii) physical cross sections can be easily extracted from the wave function; and (iii) the results compare favorably with other theoretical methods.

To first order, the double ionization of Helium can be described theoretically by a three-body Schrödinger driven equation. The final scattering state describes three charged particles in Coulomb interaction: a charged nucleus and two (slow) escaping electrons. This is a notoriously difficult problem. Imposing the cumbersome boundary conditions to the wave function constitutes one of the primary mathematical and numerical difficulty. Besides, the long range nature of the Coulomb interaction implies solving Schrödinger's equation on relatively large spatial domains, which eventually translates into using large basis sets and a high computational cost. Ideally, such a domain should be extended up to the boundary of the asymptotic region (Ω_0) where all interparticle distances are large [3].

Only few *ab initio* methods (see, *e.g.*, [4] and the references in the Introduction of [2]) have been and are being developed for dealing with the three-body Coulomb scattering problem. In [2] we proposed an approach to describe such continuum wave functions in the entire space, making use of expansions on a specific basis that contains two ingredients. First, it uses two-particle functions, named CQS in [1]; these behave asymptotically as a six-dimensional outgoing (incoming) spherical wave, so that they already possess intrinsically some three-body features. While promising, truncated expansions on CQS functions failed to converge satisfactorily with increasing basis size because they miss out an important Coulomb logarithmic phase term related to the electron-electron interaction. This brings us to the second ingredient, which consists in introducing – from the outset – an appropriate phase factor into the basis set [2]. The modified CQS functions possess then an asymptotic behavior closer to the formal one in the Ω_0 region, and lead to a considerable convergence improvement in the numerical representation of the double continuum.

We calculated the three-body solution for the electron impact double ionization of Helium with a truncated partial wave expansion on modified CQS. Since the scattering wave function is built in the entire space, we extract the double ionization amplitude from its expansion coefficients. We compared $(e, 3e)$ fivefold differential cross sections, in several kinematical and geometrical configurations, with other theoretical results and with experimental data. The results will be presented at the conference.

The CQS basis combined with the proposed phase factor method provides an effective tool to describe the Coulomb double continuum.

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Electron impact ionization of molecules for different momentum transfers

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The single ionization of molecules by charged particles tests our capacity to describe collision mechanisms but also the molecular initial state. In the case of electron impact, the most severe test is provided by the so called $(e, 2e)$ processes in which triple differential cross sections (TDCSs) are measured or calculated. Under appropriate kinematical and geometrical configurations, the cross section angular structure reflects the nature of the molecular orbital that is ionized.

In this contribution we look at the ionization by electron impact of methane and water. We calculate TDCSs for coplanar asymmetric geometries, fixing the incident energy to 250 eV (as in some experiments [1, 2]), and varying the value of the momentum transfer with the purpose of exploring how the cross section structure changes. In particular, we are interested in the presence (or not) in the binary region of the double peak which is a signature of the p-nature of the initial molecular state.

To obtain TDCSs we used, within the first-Born approximation, a Sturmian approach [3] based on Generalized Sturmian Functions (GSFs); the method has been successfully implemented and applied to study a number of single and double ionization phenomena in atoms and molecules (see Refs. [4, 5, 6, 7] for more details). As molecular initial wave function, we took those reported by Moccia [8], calculated within the one-center expansion. In a one-active electron approach, the scattering wave function is expanded in a set of GSFs that have an appropriate asymptotic Coulomb outgoing-type behavior; this property makes the method rather efficient. Moreover, the scattering amplitude can be extracted directly from the asymptotic behavior of the scattering solution (essentially the expansion coefficients), without the need of calculating a transition matrix element.

We calculated TDCSs for ionization from the $1t_2$ orbital of CH_4 and from the $1b_1$ orbital of H_2O (some of the results were already reported in Ref. [6, 7]). Our results are compared with other theoretical models in absolute scale and relative experimental data (when available). For most cases our calculated cross sections can reproduce the global features observed in the measurements, but differences are also observed for example for the binary-to-recoil ratios. Because of the p-nature of the initial state, a double peak structure appears in the binary region for some values of the momentum transfer. Our investigation aims, in particular, to understand this feature.

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The S_{E1}-factor of radiative α-capture on ^{12}C in effective field theory

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The S_{E1}-factor of of radiative α-capture on ^{12}C at the Gamow-peak energy is estimated in effective field theory up to next-to-leading order [1]. An effective field theory, which provides us a perturbative expansion scheme, for the radiative capture reaction has been constructed in the previous works [2, 3]: the expansion parameter $\sim 1/3$ has been obtained, and some parameters appearing in the effective Lagrangian have been fitted to the α-^{12}C elastic scattering data at low energies. Thus, only three unfixed parameters are remained in the radiative capture amplitude. Those three parameters are fitted to the available S_{E1} data and the S_{E1} factor calculated in the theory is extrapolated to the Gamow-peak energy. In this presentation, I report a preliminary result of the S_{E1} factor at the Gamow-peak energy and discuss the convergence of the perturbative expansion and the uncertainties of the present approach.

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Elastic α-^{12}C scattering at low energies with the bound states of ^{16}O in effective field theory

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The elastic α-^{12}C scattering for $l = 0, 1, 2, 3$ channels at low energies is studied, including the energies of excited bound states of ^{16}O, in effective field theory [1, 2]. A new renormalization method is introduced due to the large suppression factor produced by the Coulomb interaction when the effective range parameters are fitted to the phase sift data. After fitting the parameters, the asymptotic normalization constants of the 0_2^+, 1_1^-, 2_1^+, 3_1^- states of ^{16}O are calculated. The uncertainties when the amplitudes are interpolated to the stellar energy region of the ^{12}C(α,γ)^{16}O reaction are also discussed.

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Properties of supersymmetric transformed alpha-nucleus potentials studied with electric-multipole transitions

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Cluster degrees-of-freedom is one of the most characteristic features and is important for the understanding of an atomic nucleus. Indeed, alpha(^{4}He)-cluster models have often been used to describe light nuclei. Towards the application to multi-cluster systems involving heavy clusters, we study the relative wave functions of the α+^{16}O and α+^{40}Ca systems generated from phase-shift-equivalent potentials [1].

In general, a potential between clusters is deep accommodating several redundant bound states which should be removed in an appropriate way. To avoid such a complicated computation, we generate a shallow-singular potential by using supersymmetric transformations [2] from the original deep potential. Changes in the relative wave functions by the transformations are quantified with electric-multipole transitions which give a different radial sensitivity to the wave function depending on their multipolarity. Despite the fact that the original and transformed potentials give exactly the same phase shift, some observables are unfavorably modified. A possible way to obtain a desired supersymmetric potential is proposed.

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Neutron matter in the unitary limit with implicit renormalization of short range interactions*

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We analyze the unitary Fermi gas in its ground state from an implicit renormalization point of view and compute the effective range dependence of the Bertsch parameter. The tenet of the theory is the scale separation between low and high momentum which we take as the Fermi momentum, and the assumption that energy phenomena below it can be re-parameterized into the low momentum coefficients of the interaction. This choice of separation scale reduces the calculation to the mean field level. After imposing the physical renormalization conditions on the pseudo-potential, given by contact interactions in momentum space, we obtain $\xi = 0.42$ for a vanishing effective range. The result holds for a wide range of systems, including ultra-cold atoms interacting through van der Waals forces and assumes that there are no many-body forces. We analyze departures from the unitary limit due to finite range and scattering length corrections for the case of neutron matter considering a set of contact interactions up to NNLO.

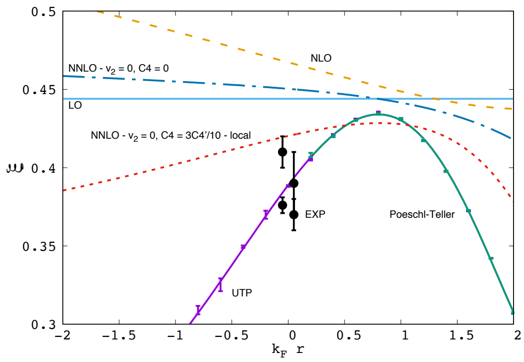

Figure 1: Effective range dependence of the Bertsch parameter with only contact interactions compared to Quantum Monte Carlo simulations and Ultra-Cold Atoms experiments.

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Electromagnetic sum rules in light nuclei *

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We study electromagnetic sum rules in light nuclei using interactions from chiral effective field theory to the purpose of testing the role of certain approximations in the few-body systems, and possibly justify their use in medium-mass nuclei. We focus on the bremsstrahlung sum rule m_0, the polarizability sum rule α_D [1] and the Coulomb sum rule [2]. Within coupled-cluster theory, we perform a series of approximations and benchmark them against the effective interaction hyperspherical harmonics approach (EIHH) in ^{4}He. We extend our previously developed formalism [3] and go beyond singles and doubles excitations (D) by employing linearized triples (T-1), i.e., leading-order three-particle-three-hole ($3p$-$3h$) excitations, in the ground state, in the excited states, and in the similarity transformed operator [1]. We find that the latter are completely negligible and that inclusion of $3p$-$3h$ excitations in the ground state is sufficient to obtain an agreement with the hyperspherical harmonics approach to better than 1%, see Fig. 1. This allows us to implement an efficient approximation and extend calculations to ^{16}O and even heavier systems.

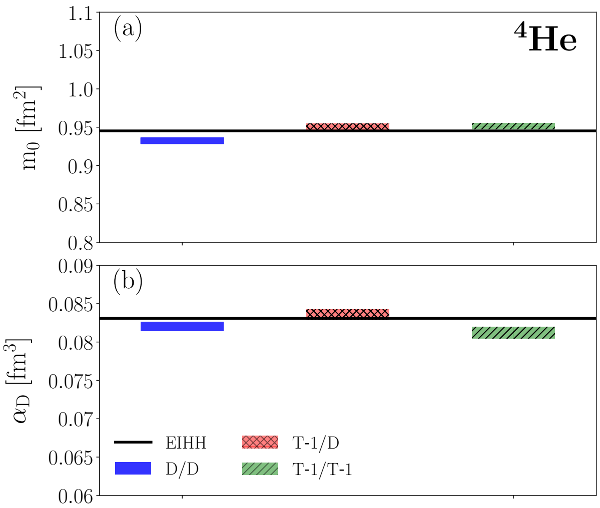

Figure 1: Comparison of m_0 and α_D in the D/D, the T-1/D and the T-1/T-1 approximations against hyperspherical harmonics results (EIHH) in ^{4}He with a chiral two-body force at N^{3}LO. The highest order of coupled-cluster correlations included in the ground- and excited-states is indicated in the left and right of the "/" symbol, respectively.

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Properties of Light Lattice Nuclei from Effective Field Theory

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We utilize nuclear effective field theory (EFT) and *ab initio* nuclear-structure methods to analyze nuclear data from lattice quantum chromodynamics (LQCD). We argue [1] that pionless EFT is the appropriate theory to describe the light nuclei obtained in LQCD simulations carried out at pion masses heavier than the physical pion mass. We solve the EFT using the effective-interaction hyperspherical harmonics method, and the stochastic variational method (SVM). The SVM is also used to solve the EFT with periodic boundary conditions.

Fitting the three leading-order EFT parameters to the deuteron, dineutron and triton LQCD binding energies, we reproduce the corresponding alpha-particle binding and predict the quartet and doublet neutron-deuteron scattering lengths [2].

We also analyze the quark-mass dependence of electromagnetic properties of two and three-nucleon states, and predict the magnetic polarizabilities of helium-3, and the triton [3].

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Exploring high quality chiral forces*

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Over the last two decades great effort has been made towards an effective nuclear force derived from chiral perturbation theory. After working out the chiral expansion up to fourth order, the chiral interactions finally reached the level of precision that was only acquired by phenomenological potentials with large number of parameters. Currently, the state-of-the-art chiral potentials are obtained by computing all pionic contributions up to N4LO and fitting all contact interactions to scattering data. In this work, we first investigate the contributions from pions and contact as the angular momentum is increased and verifiy that the contact contributions become smaller with increasing angular momentum but are still important in F-waves. In fact, in the $^1S_0$ channel the low momentum part of the interaction is mostly given by the contacts. Next we compare multiple subtractions and cutoff renormalization schemes and show that even though cutoff is more effective multiple subtractions are more scale invariant.

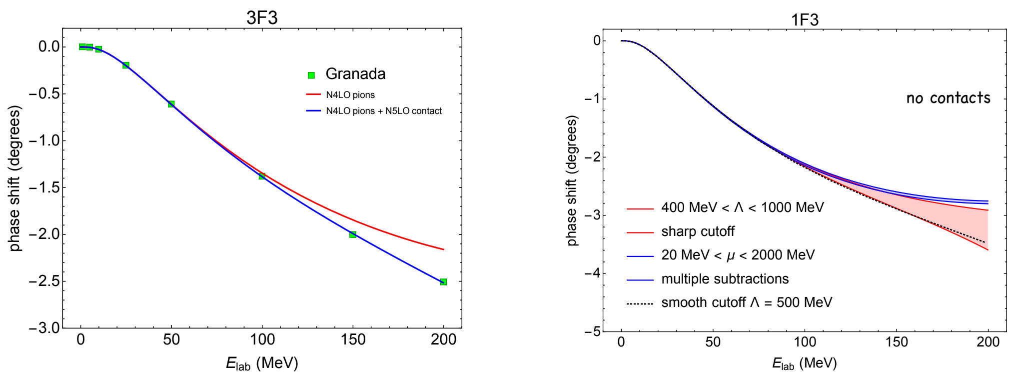

Figure 1: Effect of contact interactions (left) and renormalization scale invariance (right) in higher partial waves. The green squares have been selected from Granada Partial Wave Analysis. The red wide band represents a small cutoff range while the blue narrow band accounts for a wide subtraction point range.

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First measurements of the analyzing powers of the proton-deuteron break-up reaction at large proton scattering angles

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Polarization observables in the proton-deuteron break-up reaction are sensitive probes to investigate the spin structure of the nucleon-nucleon and three-nucleon forces. A measurement of the analyzing powers for the $^2H(\boldsymbol{p},pp)n$ break-up reaction was carried out at KVI exploiting a polarized-proton beam produced in an atomic-beam type polarized ion source [1] at a proton-beam energy of 135 MeV. The scattering angles and energies of the final-state protons were measured using the Big Instrument for Nuclear-polarization Analysis (BINA) [2] with a nearly 4π geometrical acceptance. In this work, we extended the earlier measurements [3] that were done for kinematical configurations at small proton scattering angles by analyzing configurations at which one of the final-state protons scatters towards the backward part of BINA. The results are compared with theoretical calculations based on NN potential alone or combined with the $3N$ potential, with or without the inclusion of the Coulomb effect. Discrepancies between polarization data and theoretical predictions are observed for configurations corresponding to small relative azimuthal angles between the two final-state protons. These configurations show a large sensitivity to $3N$ force effects. In this contribution, some of these configurations along with the analysis method will be discussed.

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Efimov physics beyond three particles

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More that forty years ago, when the Efimov effect was predicted, it was mainly considered as curiosity. However, recent theoretical and experimental progress reveals the richness of Efimov physics and its importance to several area of physics.

Originally, Efimov has dealt with the case of three identical bosons interacting resonantly in three dimensions. A few years later he has also considered the $2+1$ system, composed of two heavy fermions interacting with a lighter atom. In my talk I will review recent theoretical progress seeking for Efimov physics in systems composed of more than three particles.

The first candidate is the case of identical bosons. A relevant system, which is also accessible experimentally, is cluster of few He atoms. I will present a study of such a system within the framework of effective field theory [1], indicating that no additional few-body interactions need to be introduced at leading order. I will also discuss clusters of identical bosons in two dimensions, where the system ceases to have Efimovian nature, while presenting its own peculiar features [2].

The case of few heavy fermions interacting with a lighter atom will also be considered, where the mass ratio of the constituent particles plays a significant role. Following Efimov's study of the $2+1$ system, the $3+1$ system was shown to have its own critical mass ratio to become Efimovian. I will show that the $4+1$ system becomes Efimovian at mass ratio which is smaller than its sub-systems thresholds, giving a pure five-body Efimov effect [3]. The $5+1$ system will also be considered, where the existence of six-body Efimov state is still an open question [4].

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Mesons studies with a contact interaction

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We present a unified formalism for the analysis of mesons provided by a symmetry-preserving Schwinger-Dyson-Bethe-Salpeter-equation (SDBSE) treatment of a vector$\times$vector contact interaction. The contact interaction (CI) model provides a simple-to-implement alternative to perform exploratory studies of QCD within the SDBSE framework. Within the limitations of this model, we calculate observables that can be compared and contrasted with experimental data, lattice QCD and other SDBSE calculations involving sophisticated interaction kernels.

This model was developed to calculate the spectrum, decay constants, elastic and electromagnetic form factors of light mesons and baryons [1, 2, 3, 4, 5]. Later, we modified slightly the model to extend it to the study of the charmonium and bottmonium sectors [6, 7, 8]. Additionaly, we introduced an unification to the model to be able to study both light and heavy regimes [8]. This time, along with novel ideas to implement this CI-model in the light sector [9], we propose the first insights to inspect heavy-light mesons within the CI-SDBSE approach. Our analysis could be helpful in studies of heavy and heavy-light baryons, as well as the hypothesized tetraquarks and pentaquarks states.

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Towards Grounding Nuclear Physics in QCD

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Although we are confident that QCD, the theory of quarks and gluons, dictates the properties and behavior of nucleons, establishing a quantitative connection between QCD and low-energy nuclear observables remains an outstanding theoretical challenge. As it stands, much of nuclear physics requires phenomenological input. Lattice QCD is a nonperturbative first-principles technique that can close this divide. I will discuss some recent efforts towards predictions of nuclear observables, such as the nucleon axial coupling g_A and two-nucleon scattering via lattice QCD.

Zero-Range Effective Field Theory for Resonant Wino Dark Matter*

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Dark matter in the form of weakly interacting massive particles (wimps) with masses at the TeV scale receive nonperturbative "Sommerfeld enhancements" to their pair annihilation rates due to unsuppressed exchanges of weak gauge bosons before the annihilation. These enhancements are conventionally computed numerically through the solution of coupled-channel Schrödinger equations. The most dramatic enhancements occur when there is an S-wave resonance near the wimp-pair threshold. My collaborators and I have developed an effective field theory for wino dark matter near such a resonance. Winos interact nonperturbatively through zero-range contact interactions as well as through the long-range Coulomb interaction. Our analytic results for wino scattering and wino-pair annihilation accurately reproduce the results calculated numerically using the Schrödinger equation. I will show how this effective field theory is systematically improvable, how the Coulomb resummation is carried out, and how to build in the annihilation processes.

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Experimental many-body physics using arrays of individual atoms

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This talk will present our on-going effort to control the dipole-dipole interaction between cold Rydberg atoms in order to implement spin Hamiltonians that may be useful for quantum simulation of condensed matter problems. In our experiment, we trap individual atoms in two-dimensional arrays of optical tweezers [1] separated by few micrometers and excite them to Rydberg states using lasers. The arrays are produced by a spatial light modulator, which shapes the dipole trap beam. We can create almost arbitrary, two-dimensional geometries of the arrays with near unit filling [2].

The talk will present our demonstration of the coherent energy exchange in small chains of Rydberg atoms resulting from their dipole-dipole interaction [3]. This exchange can be controlled by addressable lasers [4]. This interaction realizes the XY spin model. We have also implemented the quantum Ising model [5]. The spin Hamiltonian is mapped onto a system of Rydberg atoms excited by lasers and interacting by the van der Waals Rydberg interaction. We study various configurations such as one-dimensional chains of atoms with periodic boundary conditions, rings, or two-dimensional arrays containing up to about 50 atoms. We measure the dynamics of the excitation for various strengths of the interactions between atoms. We compare the data with numerical simulations of this many-body system and found excellent agreement.

This good control of an ensemble of interacting Rydberg atoms thus demonstrates a new promising platform for quantum simulation using neutral atoms, which is complementary to the other platforms based on ions, magnetic atoms or dipolar molecules.

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Two-nucleon emitters within a pseudostate approach

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Exotic nuclei far from stability give rise to unusual properties and decay modes [1]. In the past few decades, the advances in radioactive beam physics has enabled the study and characterization of nuclear systems close to the neutron and proton driplines. Large efforts have been devoted to understanding the properties of two-neutron halo nuclei [2]. These are Borromean systems, in which all binary subsystems do not form bound states. Theoretical investigations within core+n+n models indicate that the correlations between the valence neutrons play a fundamental role in shaping the properties of two-neutron halo nuclei [3]. The evolution of these correlations beyond the driplines has implications for two-nucleon radioactivity. First proposed for two-proton decays in the sixties [4], this topic gained renewed attention after the first experimental observation of the correlated emission from the ground state of ^{45}Fe [5]. Since then, other examples of two-nucleon emitters have been confirmed, e.g. ^{6}Be [6] or ^{16}Be [7].

The pseudostate (PS) method in hyperspherical coordinates, using the analytical transformed harmonic oscillator (THO) basis, can be used to construct the ground-state wave functions of unbound three-body systems [8]. These resonances are approximated as a stable PS around the known two-nucleon separation energy following a stabilization method [9]. This approach is computationally less demanding than solving the actual three-body scattering problem [10] but still provides a reliable description. For ^{16}Be and ^{6}Be ground states, a dominant dinucleon configuration is found, which favors the picture of a correlated two-nucleon emission from these unbound nuclei. The computation of decay widths and two-nucleon energy correlations, as well as the application to more exotic systems, is ongoing.

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A new measurement of the ^{2}H(p,γ)^{3}He cross section in the BBN energy range at LUNA.

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The abundances of the primordial elements are sensitive to the physics of the early universe and are therefore a tool to test the Standard Cosmological Model.

The Big Bang Nucleosynthesis (BBN) theory is one of the pillars of standard cosmology: for a given baryon density it provides the abundance of the primordial elements.

Interestingly the abundance of deuterium deduced from observation of pristine gas at high redshift is more accurate with respect to the theoretical value [1, 2], mainly because the BBN calculation is affected by the paucity of data for the deuterium burning reaction $^{2}H(p,\gamma)^{3}He$ cross section at the relevant energies [3]. The concern for the $^{2}H(p,\gamma)^{3}He$ cross section error is made worse by the fact that the theoretical and experimental values do not agree at the level of 20% [3, 4, 5].

A new measurement with a 3% accuracy would be very important to push down the BBN uncertainty on deuterium abundance to the same level of observations.

Deep underground in the Gran Sasso laboratory, Italy, the LUNA collaboration is pursuing a dedicated effort to measure the $^{2}H(p,\gamma)^{3}He$ cross section directly at BBN energies (30 -300 keV). The campaign, started in 2016, is divided into two phases based on a BGO and a high-purity germanium (HPGe) detector, respectively.

In the present talk the LUNA measurement will be described and results from both phases will be discussed. The impact of this measurement in cosmology and particle physics is also highlighted: a precision measurement will allow to provide an independent cross-check of the determination of the universal baryon density Ω_b from the cosmic microwave background and to constrain the existence of the so called dark radiation.

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Few-body interactions in a cold Rydberg gas*

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A gas of cold Rydberg atoms generally interacts through 2-body van der Waals interaction. When applying an electric field, it has long been observed that resonant dipole-dipole interactions can arise [1]. More recently we have demonstrated the possibility to find resonant processes involving 3 Rydberg atoms [2]. Although this experiment was performed with cesium atoms, we argued that similar 3-body interaction resonances should be observed in other atoms. It has now been observed by us in rubidium [3] with a small controlled number of atoms i = 2-5 as can be seen in figure 1.

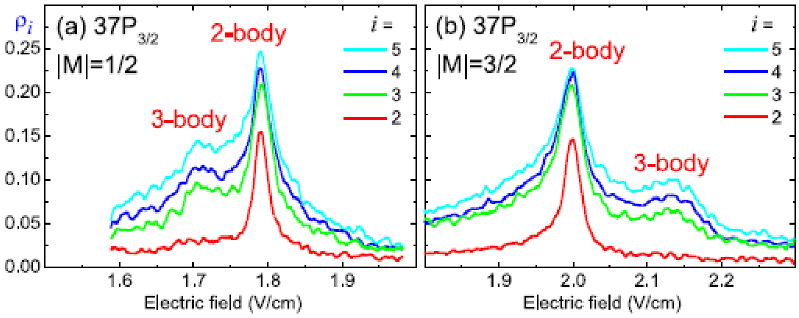

Fig.1. Stark-tuned Förster resonance in Rb atoms observed for various numbers of atoms N=2-5: (a) atoms are in the initial state $37P_{3/2}(|M_J|=1/2)$; (b) atoms are in the initial state $37P_{3/2}(|M_J|=3/2)$. The main peaks are 2-body resonances, the additional peaks are 3-body resonances.

This not only demonstrated the general nature of the process, but also the absence of signature of the three-body Förster resonances for exactly two interacting Rydberg atoms. As the observed three-body resonance appears at a different dc electric field with respect to the two-body resonance, it represents an effective three-body operator, which can be used to directly control the three-body interactions. This can be especially useful in quantum simulations and quantum information processing with neutral atoms in optical lattices.

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Electromagnetic Form Factors: mass dependence and charge symmetry breaking effects

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We explore the mass dependence of electromagnetic form factors of pseudoscalar mesons using the Dyson-Schwinger equation approach in the Rainbow-Ladder approximation. The form factors increase regularly as the meson masses increase. We also explore the charge symmetry breaking effects of the form factors. While our direct calculation is limited in the region $Q^2 < 3\mathrm{GeV}^2$, we do a natural extrapolation of the form factors. We find that in the case of physical quark masses, $m_u/m_d \approx 0.5$, the charge symmetry breaking effects contribute less than 5% to the form factors up to $Q^2 = 10\mathrm{GeV}^2$ (the right panel of Fig. 1).

There are two LQCD calculations of the electromagnetic form factors. Chambers (Ref. [1]) calculates the form factor of a pseudo pion with mass 0.47GeV, and Koponen (Ref. [2]) calculates the form factor of η_s. Their calculations are not consistent when $Q^2 > 3\mathrm{GeV}^2$ (the left panel of Fig. 1). Our results favour Chambers's calculation. The charge symmetry breaking effects calculated by Hutauruk (Ref. [3]) using NJL model are much larger than ours. It might be due to the defect of the NJL model, which is a low energy effective theory.

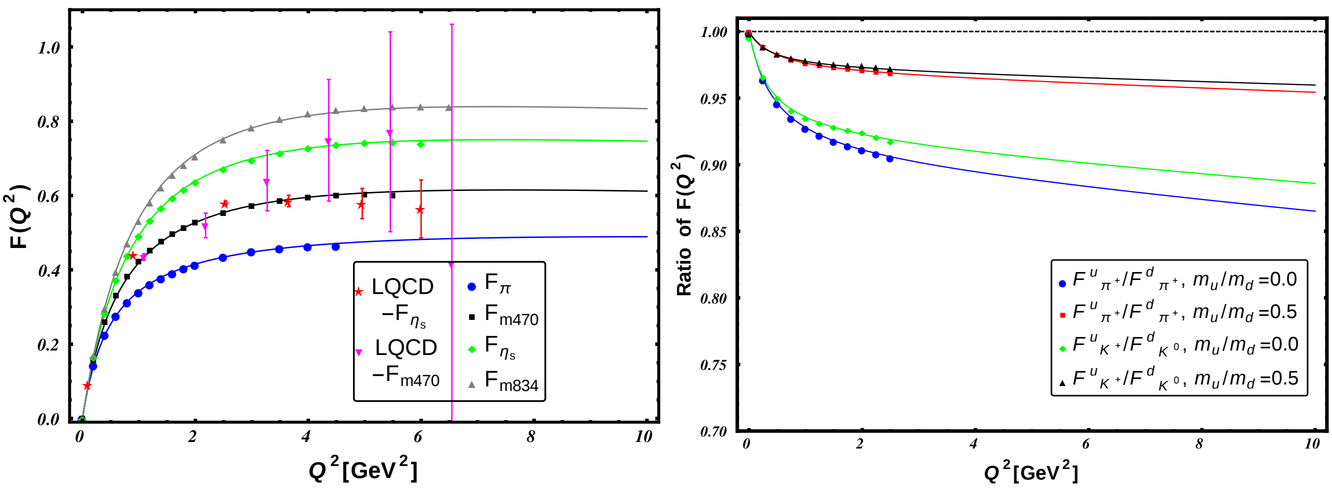

Figure 1: Left panel: electromagnetic form factors of pseudo-scalar mesons with masses 0.138GeV($\pi^{\pm}$), 0.470GeV, 0.694GeV(η_s), 0.834GeV, and the LQCD calculations from Ref. [1] (F_{m470}) and Ref. [2] (F_{η_s}). Right penel: the ratios of form factors of u-constituent and d-constituent, $F^u_{\pi^+}/F^d_{\pi^+}$ and $F^u_{K^+}/F^d_{K^0}$, in the case of $m_u/m_d = 0.0, 0.5$ respectively

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Direct measurement of the $^{13}\mathrm{C}(\alpha, \mathrm{n})^{16}\mathrm{O}$ reaction at LUNA

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Heaviest nuclei (A $>$ 58) are synthesized by sequential neutron capture reactions. There are two main processes, depending on their time scale compared with the beta decay lifetime: these are the so called slow (s) and rapid (r) processes. Both produce about half of the stable isotopes beyond iron in the Universe [1].
Focusing on the *s process*, these take place in low mass ($1-3M_\odot$) Asymptotic Giant Branch (AGB) stars, and their main neutron source is the identified in the $^{13}\mathrm{C}(\alpha, \mathrm{n})^{16}\mathrm{O}$ reaction.
The temperatures involved in these processes are in the range between 90 - 100 MK, which roughly correspond to Gamow energies between 180 and 200 keV. At present, the cross section within the Gamow peak is uncertain by almost one order of magnitude, having a large impact on stellar models.
Currently, direct measurements of the reaction are done at energy above the Gamow window [2, 3]. Extrapolations or indirect measurements have been used to extend the cross section up to lower energies [4], but these need a renormalization or theoretical inputs.
The low background condition in the LNGS deep underground laboratory, combined with the LUNA accelerator [5, 6] offers a unique possibility to perform this measurement with a direct technique at lower energies.
In this talk, I will present the current state of the project, including neutron detectors performance and enriched ^{13}C, solid target characterization and the preliminary results of the first measurement campaign.

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Few-Nucleon System Dynamics Studied via Deuteron-Deuteron Collisions at 160 MeV

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According to our present knowledge the modern nucleon-nucleon forces based on the meson-exchange theory are unable to reproduce the experimental data for the systems with A>2. One needs to include additional piece of dynamics in the calculations, so-called three-nucleon force (3NF) [1,2]. To investigate the nature of 3NF the proton-deuteron breakup reaction characterized by very rich kinematics of the final state was chosen and extensively explored in the medium energy region [1-3]. The interpretation of the experimental data is possible due to rigorous treatment of three nucleon (3N) equations with any potentials. In heavier systems composed of four nucleons (4N) the 3NF effects are expected to be larger in comparison to 3N. This makes the experimental studies more attractive, however the theoretical treatment of 4N scattering is much more complicated and challenging than for 3N systems due to e.g. variety of entrance and exit channels, various total isospin states etc. [4]. The calculations in the 4N field are mainly developed by three groups: Pisa [5], Grenoble-Strasbourg [6] and Lisbon [4]. Only the Lisbon group calculates observables for multichannel reactions, also above the breakup threshold, and with the Coulomb force included. The first estimate calculations for the d − d system at higher energies were performed in the so-called single-scattering approximation (SSA) for the three-cluster breakup and elastic scattering [7]. In the calculations three models of 2N potentials were used: AV18, CD Bonn and CD Bonn+Δ.

In this talk a set of ^{2}H(d, dp)n breakup, d-d elastic scattering and ^{2}H(d, ^{3}He)n transfer differential cross section measured with the BINA@KVI setup at 160 MeV will be presented. The breakup data will be confronted with the recent SSA calculations [7] .

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Few-Nucleon System Dynamics in Deuteron-Deuteron Collisions

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Investigations of few-nucleon systems provide suitable testing ground for different models of the nucleon-nucleon interaction. In three-nucleon systems, at intermediate energy, below the pion production threshold, the effects of three-nucleon forces (3NF) are generally small and hard for experimental study. To take a step forward into larger system, a four-nucleon (4N) were studied, where sensitivity to the 3NF effects becomes higher. Recently, the development of the 4N system calculations became a hot topic in theoretical nuclear physics [1].

Experiment devoted to studies of deuteron breakup reactions were carried out at KVI in Groningen (The Netherlands) with the use of the BINA detector and 160 MeV deuteron beam on deuteron target. The experiment is a continuation of previous very successful few-nucleon reaction studies [2, 3]. The aim of the measurement was to study two reaction channels, three- and four-body breakup. Having determine the differential cross sections for three-body ^{2}H(d,dn)p breakup reaction with the neutron momentum reconstructed one can compare it with already analysed ^{2}H(d,dp)n channel [4] at the same kinematic conditions and directly study the Coulomb effects and possible charge symmetry breaking, like it was suggested in [5]. For the four-body ^{2}H(d,pp)nn channel, the attempt of obtain the inclusive breakup cross section will be made for future comparison with the theoretical calculations. The results, are very important to better understand the nature of nucleon interactions in light nuclei and also to validate the development of the theoretical calculations of the 4N systems dynamics.

In this contribution I will present the preliminary results of the differential cross-section distribution for three- and four-body deuteron breakup reaction with reconstructed neutron as well as some data consistency checks based on the reaction kinematics.

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The GBAR experiment and its positive antihydrogen ion

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Antimatter experiments at CERN have been harvesting high precision spectrometry results, providing stringent CPT tests (see for instance [1][2]). Yet, a direct test of the equivalence principle for antimatter remains to be performed and three experiments are currently racing to measure $\bar{g}$, the gravitational acceleration of antimatter on Earth. Among these experiments, GBAR intends to realise a free fall of antihydrogen atoms at rest. [3] However simple it might look, this scheme relies on a state-of-art laser cooling technique to reach vertical velocities of the order of 1 $m.s^{-1}$, required to get at least 1% precision on $\bar{g}$. In order to achieve this goal, the GBAR experiment will use an ionic species, $\bar{H}^+$, the antimatter equivalent of H^-, that can then be more easily manipulated than neutral atoms and sympathetically cooled in a Coulomb crystal.

This $\bar{H}^+$ ion will be produced from two successive charge-exchange reactions. The first one involves antiprotons colliding with a positronium (Ps) target to form antihydrogen atoms. In the second reaction, these antihydrogen atoms can again capture a positron from a further interaction with positronium and form $\bar{H}^+$. With a foreseen capital of 4.10^6 antiprotons, delivered every two minutes by the CERN new antiproton decelerator ELENA, and a Ps target density of 10^{12} cm^{-3}, that will be achieved thanks to an intense linac-based positron source under commissioning at CERN, cross sections for the two charge-exchange reactions are necessary to estimate and optimise the $\bar{H}^+$ production rate. This motivated new extensive and accurate calculations for the first 3-body reaction [4][5] and stirred up interest in tackling the second 4-body reaction [6].

This talk will present the GBAR experiment and review the work on the relevant cross sections.

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$B_\Lambda({}^5_\Lambda He)$ from short range effective theory

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We present an effective field theory (EFT) at leading order to describe light single-Λ hypernuclei [1]. Owing to the weak Λ binding and to the Λ-n short interaction range, meson exchange forces are approximated by contact interactions within a pion-less EFT where the only degrees of freedom are baryons. At leading order the theory contains both 2-body (singlet and triplet) and three 3-body interactions, a total of 5 terms associated with 5 coupling strengths or low energy constants (LECs). We adjust the 2-body LECs from available data that constrain the Λ-n scattering lengths. Because of the limited 3-body data, both 3-body and 4-body hypernuclear binding energies and excitation energies are used to adjust the 3-body LECs. To calculate the binding energies for the A-body systems with A>2, we have expanded the wave-function using a Gaussian basis. The stochastic variational method was employed to select the non-linear parameters. The resulting EFT is then applied to calculate the Λ binding energy in ${}^5_\Lambda$He, where the adjusted 3-body interactions largely resolve the known overbinding problem of ${}^5_\Lambda$He [2].

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Search for dineutron correlation in borromean halo nuclei

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Light neutron drip-line nuclei are characterized by a dilute neutron density around the nuclear surface and offer a unique testing ground to investigate correlations at different densities. As an example, a strong dineutron correlation was predicted [1] and later found experimentally in ^{11}Li via a measurement of the low-lying dipole strength distribution [2].
In order to directly determine the momentum distribution of the two valence neutrons, which allows access to the dineutron correlation, the first kinematically complete measurement was performed at RIKEN RIBF for the quasi-free *(p,pn)* reaction on Borromean nuclei ^{11}Li, ^{14}Be, and ^{17,19}B. The novelties of the experiment are the capability to select the kinematical region corresponding to high momentum transfer, where the reaction mechanism is simpler, and to pin down the excited states of the core nucleus by γ-ray detection. The experiment was carried out with the SAMURAI spectrometer [3] and the MINOS system which combines a 15-cm liquid hydrogen target with a vertex tracker to increase luminosity without degrading energy resolution [4]. The momentum distribution of the valence neutrons was reconstructed from the measured momentum vectors of all the particles involved in the reaction.
In this talk, we will discuss the dineutron correlation in ^{11}Li from the asymmetry in the opening angle distribution of the emitted neutrons within a newly developed formalism [5]. The invariant-mass spectra of ^{10}Li, ^{13}Be, ^{16}B, where new resonances have been observed, and the core-excitation contribution deduced from γ-ray measurement will also be discussed.

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Electromagnetic transitions of doubly charmed baryons of $J^P = 3/2^+$

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In 2002 the SELEX experiment collaboration reported the evidence of the doubly charmed baryon $\Xi_{cc}^{+}(3519)$ in the process of $\Xi_{cc}^{+} \to \Lambda_c^{+} K^{-} \pi^{+}$ [1]. Recently, the LHCb collaboration discovered a new state $\Xi_{cc}^{++}(3621)$, which is considered to be a new doubly charmed baryon, in the $\Lambda_c^{+} K^{-} \pi^{+} \pi^{+}$ mass spectrum [2]. Many theoretical methods and models, such as the bag model, various quark models, QCD sum rules and lattice QCD, etc, were applied to study these two states and related doubly and triply heavy baryons.

The method of light-cone QCD sum rules has been widely applied to study the decay properties of hadrons [3, 4, 5]. In this work [6], we employ this powerful method to study the electromagnetic transition of the Ξ_{cc}^{*++} into $\Xi_{cc}^{++}\gamma$, whose decay width is estimated to be $13.7\ {}^{+17.7}_{-\ 7.9}$ keV. The results are slightly larger than those obtained using the bag model, but quite comparable with those obtained using some other methods and models. We note that the electromagnetic transition of $\Xi_{cc}^{*++} \to \Xi_{cc}^{++}\gamma$ is probably the main decay mode of the Ξ_{cc}^{*++}, and its decay width is large enough for the Ξ_{cc}^{*++} to be observed in the $\Xi_{cc}^{++}\gamma$ channel. We propose to continually search for it in future LHCb and BelleII experiments. Similarly, we have also investigated electromagnetic transitions of some other doubly charmed and bottom baryons, including $\Xi_{cc}^{*+} \to \Xi_{cc}^{+}\gamma$, $\Omega_{cc}^{*+} \to \Omega_{cc}^{+}\gamma$, $\Xi_{bb}^{*0} \to \Xi_{bb}^{0}\gamma$, $\Xi_{bb}^{*-} \to \Xi_{bb}^{-}\gamma$, and $\Omega_{bb}^{*-} \to \Omega_{bb}^{-}\gamma$. In the end, we may present our preliminary results of the pion decays of doubly charmed and bottom baryons.

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Accessing the generalized parton distributions in the valence region at Jefferson Laboratory

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The generalized parton distributions (GPDs) describe the correlations between the transverse position and the longitudinal momentum of a parton inside the nucleon. They represent the next step toward a complete description of the nucleon in terms of quarks and gluons. They are accessible through deep exclusive processes among which we find the deeply virtual Compton scattering (DVCS) and the deep virtual meson production (DVMP). With its longitudinally polarized electron beam sent on fixed targets inside three experimental Halls, Jefferson Laboratory is a unique facility to probe the quarks and gluons in the valence region of the nucleon. The first experimental evidence of GPD sensitivity at Jefferson lab was providing by measuring a non-zero beam spin asymmetry for photon electroproduction, arising from the interference between Bethe-Heitler and DVCS, in 1999 in the Hall B of Jefferson Laboratory [1]. Then followed a complete experimental program dedicated to DVMP and DVCS in the different experimental Halls. In this talk, we are going to introduce the GPDs and the information they encode about the inner structure of the nucleon. Then we are going to give an overview of the main deep exclusive processes results collected at Jefferson Lab and the information they have provided about the GPDs. Finally we will discuss the answers we can expect from the ongoing/future experimental program with the recently upgraded experimental Halls and the 12 GeV electron beam.

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Light nuclei from lattice QCD: spectrum, structure and reactions

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LQCD studies of light nuclei have entered an era when first results on structure and reaction properties of light nuclei have emerged in recent years, complementing existing results on their simplest properties such as binding energies. Although in these preliminary studies the quark masses are still tuned to larger than the physical values, a few results at the physical point have already been deduced from simple extrapolations in quark masses. The progress made paves the road towards obtaining several important quantities in nuclear physics, such as nuclear forces and nuclear matrix elements relevant for pp fusion, single and double-beta decay processes, nuclear effects in neutrino-nucleus scattering and direct dark-matter experiments, searches for CP violation and gluonic structure of nuclei. Some of the recent developments, the results obtained, and the future outlook of the field will be reviewed in this talk.

Light Hadron Spectroscopy at BESIII *

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The BESIII experiment at the electron positron collider BEPCII is successfully operating since 2008 and has collected large data samples in the tau-mass region, including the world's largest data samples at the J/ψ and $\psi(2S)$ resonances. In particular their decays provide a rich and clean environment to study hadrons consisting of light quarks and to search for exotics.
In this presentation recent BESIII results of the light hadron physics program will be highlighted [1][2][3][4][5].

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Collisions in few-neutron systems*

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Collisions in few-body systems with no bound clusters are described using exact momentum-space integral equations for transition operators [1]. A rigorous treatment of the continuum and associated singularities is highly complicated for more than three particles; a special integration method is used [2]. The developed method is applied to the study of three- and four-neutron systems, in particular, to the investigation of their resonant states [3].

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Four-body effects in nucleus-nucleus scattering

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The main goal of the Continuum Discretized Coupled Channel (CDCC) method is to solve the Schrödinger equation for reactions where the projectile presents a cluster structure, and a low dissociation energy. The CDCC method has been introduced forty years ago [1] to describe deuteron induced reactions. Owing to the low binding energy of the deuteron, it was shown that including continuum channels significantly improves the description of d+nucleus elastic cross sections [1, 2]. The simplest variant of CDCC describes scattering of a two-body nucleus with a structureless target, but extensions to three-body projectiles have been performed recently (see, for example, ref. [3]). The projectile continuum is approximated by a finite number of square-integrable states, up to a given truncation energy.

We present here a new development of the CDCC method, which aims at describing reactions where the projectile and the target have a low separation energy. This leads to four-body (or more) calculations. Since continuum states are included in both colliding nuclei, the number of channels can be extremely large. We solve the coupled-channel system by using the R-matrix method on a Lagrange mesh [4]. Applications to $^{11}\mathrm{Be} + d$ and $^{7}\mathrm{Li} + d$ scattering are presented.

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Baryon resonances with dynamical coupled channels theory*

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Results for baryon spectroscopy by the Jülich-Bonn and other collaborations will be presented [1]. The impact of recent high-precision data from ELSA, JLab, MAMI, and other facilities will be discussed [2, 3, 4]. Questions will be addressed of how to proceed to reach more conclusive answers in baryon spectroscopy and how model selection techniques can increase the reliability in the determination of the spectrum [5]. On the other side, recent developments how phenomenology can be connected to lattice QCD will be highlighted [6].

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Structure and dynamics of He Efimov and Halo states

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We discuss the experimental imaging of the square of the wavefunction of the small Helium cluster He_2, He_3 and the Efimov state of He_3 [1,2,3]. We will show the structure of these states as well as first results of dynamics induced in these systems in pump probe experiments.

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Five-nucleon systems with an hyperspherical harmonic method

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The hyperspherical harmonic (HH) method has been proved to be an efficient tool for studying bound states, via the Rayleigh-Ritz variational principle, and low-energy scattering, via the Kohn variational principle, of three- and four-nucleon systems [1]. Although the method can be applied, in principle, to systems made of an arbitrary number of nucleons (A), the fast increase with A of computational needs, time and memory, makes the application of the HH method to five- and more-nucleon systems particularly challenging. This requires not only a well-balanced parallelization of the computational tasks and an intensive use of supercomputers but also the improvement of the existing algorithms or the development of new ones, valid for any number of nucleons. In this communication, we will present important progresses made in the building of orthonormal bases of fully-antisymmetrized HH [2] and in the computation of matrix elements involving HH and scattering wave functions.

We will apply the present method to the description of the $\alpha + n$ system using a central nucleon-nucleon potential, as a preliminary step before considering more realistic nucleon-nucleon interactions and more complex collisions like the $d + t \to \alpha + n$ reaction transfer.

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The Pion as a tool for discovering new Physics

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The pion was discovered in 1936 after the prediction from H. Yukawa, and it is still at the center of experimental and theoretical activities: it plays a major role in low-energy nuclear physics, and as it will be shown, also in the investigation of fundamental symmetries of the Standard Model (SM). In the SM, leptons have identical electroweak gauge interactions, a hypothesis known as lepton universality. PIENU is a high precision experiment designed to test lepton universality by measuring the ratio of the rate of the pion decay to electron plus neutrino compared to pion decay to muon plus neutrino, including radiative processes. The most accurate SM prediction, based on Chiral Perturbation Theory, has 0.01% uncertainty: this constitutes the most accurate SM calculation involving quarks. The present experimental value is one order of magnitude less precise. Testing lepton universality can constrain many non-Standard Model scenarios and a measured deviation can point towards the presence of new physics with sensitivity up to 1000 TeV. In this contribution, we will present the latest results from the PIENU experiment at TRIUMF [1], which provide the most stringent test of lepton universality [2] as well as limits on the presence of massive neutrino states coupled to electrons [3].

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Hadron spectroscopy and structure in the Dyson-Schwinger approach*

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Over the past years, continuous progress has been made in the application of Dyson-Schwinger, Bethe-Salpeter and Faddeev equations to the spectrum and structure of hadrons. The basic goal is to calculate hadronic observables from the elementary n-point functions in QCD, namely, the nonperturbative quark and gluon propagators and interaction vertices. In turn, this contributes to our understanding of nonperturbative QCD phenomena such as confinement and spontaneous chiral symmetry breaking. Whereas our knowledge of correlation functions has matured substantially in recent years, their systematic implementation in hadron spectroscopy and structure studies is at a comparatively early stage. Still, we have come towards a transition point between phenomenological modeling and systematic truncations of QCD, which enable a common treatment of mesons, baryons and also more exotic hadrons from the same nonperturbative ingredients of QCD [1].

In this talk we review calculations on the spectrum of light and strange baryon resonances and their elastic and transition form factors. We compare results from the covariant three-body Faddeev equation and its quark-diquark simplification employing the same elementary quark-gluon interaction. The spectra of light baryons can be well reproduced and interpreted from their underlying diquark structure [2]. Moreover, the quark-diquark picture allows one to make predictions for excited states in the hyperon sector which can be tested by experiments.

The formalism also paves a path towards addressing multiquark systems. In the light-quark sector the most prominent tetraquark candidates are the light scalar mesons. Here the solution of the four-quark equation shows that the σ meson and its multiplet partners are internally dominated by pseudoscalar meson poles and can thus be understood as meson molecules, however with an admixture of genuine four-quark components [3].

We finally discuss recent progress on calculating scattering amplitudes, such as nucleon Compton scattering where nucleon resonances play an important role, and implementing resonance mechanisms in Bethe-Salpeter equations towards a more complete description of bound states and resonances in QCD.

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Strong interactions for precision nuclear physics

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Nuclear physics is a cornerstone in our scientific endeavour to understand the universe. Indeed, the study of atomic nuclei helps us reveal e.g. the fundamental symmetries of nature and can guide us through the reaction networks of the stellar explosions where elements are formed. To enable precision-studies it is essential to construct an accurate description of the fundamental nuclear interaction with quantified theoretical uncertainties. Indeed, uncertainty estimates on theoretical predictions are pivotal to determine to what extent a disagreement between experiment and theory hints at new physics. Error bars on theoretical calculations can also lead us to the most relevant experiments for generating new knowledge about the strong interaction.

In this talk I will address the prospect of using chiral effective field theory (χEFT) for accurate *ab initio* predictions of low-energy observables in few-nucleon systems as well as heavier nuclei. To this end, I will also discuss recent developments in the application of mathematical optimization methods and statistics, leveraged by high-performance computing, for exploring the multi-dimensional parameter spaces of χEFT.

Lattice simulations with chiral effective field theory for light and medium-mass nuclei

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In this talk I present recent results from lattice simulations with chiral effective field theory at next-to-next-to-next-to-leading order. I discuss ground state of calculations of light and medium-mass nuclei as well as new algorithms for the excited state spectrum and other properties.

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Ab initio folding potentials for proton-nucleus scattering based on NCSM nonlocal one-body densities*

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Constructing effective interactions ('optical potential') between a proton or neutron and a nucleus for computing elastic scattering has a long tradition. A renewed interest in considering this challenging task stems from the possibility to combine today's *ab initio* structure work with elastic scattering from light nuclei using the framework of the spector expansion [1] and compute the first order term in the expansion consistently. The calculation of the effective interaction in first order relies on two basic input quantities, which are the fully-off-shell nucleon-nucleon (NN) t-matrix and the translationally invariant nonlocal one-body density matrix of the target. The latter has recently been constructed within the framework of the NCSM [2] for the nuclei ^{4}He, ^{12}C, and ^{16}O.

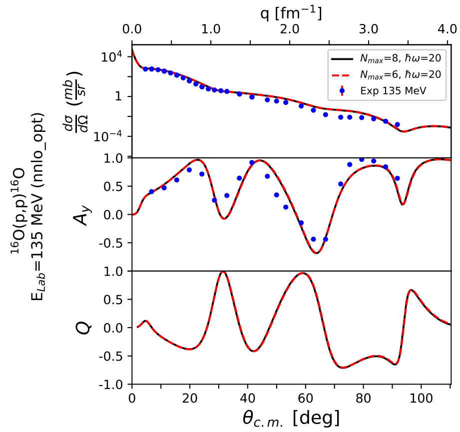

Figure 1: The angular distribution of the differential cross-section ($\frac{d\sigma}{d\Omega}$), analyzing power (A_y) and spin rotation function (Q) are shown for elastic proton scattering from ^{16}O at 135 MeV laboratory energy.

The standard approach to elastic scattering of a strongly interacting projectile from a target of A particles is the separation of the Lippmann-Schwinger equation for the transition amplitude into two parts, namely

$$T = U + UG_0(E)PT \quad (1)$$
$$U = V + VG_0(E)QU, \quad (2)$$

where P and Q are projection operators such that $P+Q=1$, and P conventionally taking to project on the elastic channel such that $[G_0, P] = 0$. The free propagator for the projectile+target system is given by $G_0(E) = (E + i\varepsilon - h_0 - H_A)^{-1}$. The effective interaction (optical potential) is defined by (2) and is expanded according the number of active target nucleons interacting directly with the projectile [3]. In first order only fully-off-shell NN t-matrices together with nonlocal one-body density matrices enter, which are both calculated using the N2LO$_{\text{opt}}$ chiral NN interaction [4]. Elastic scattering observables for proton scattering off ^{16}O at 135 MeV proton laboratory kinetic energy are shown as function of *c.m.*-angle and momentum transfer and compared to experiment. Details of the calculations follow the scheme of Ref. [5]. We will present results for proton and neutron scattering from ^{4}He and ^{16}O for projectile energies between ~ 100 to 200 MeV and explore which specific ingredients of the calculation may be significant for a successful description of experimental data.

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Experiments with multi-component ultracold fermions *

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Ultracold quantum gases are an attractive platform for the investigation of few- and many-body quantum physics. In this context, I will report on recent experiments performed at University of Florence with quantum gases of ultracold ^{173}Yb fermions. These two-electron atoms exhibit a rich internal structure, with distinct degrees of freedom – nuclear spin and electronic orbital state – that can be both manipulated in a quantum coherent way and metrological accuracy, and used as resources to engineer novel types of interactions in synthetic quantum systems. I will describe the experimental developments in the study of multi-component systems with SU(N) interaction symmetry and the new perspectives offered by the control of atom-atom interactions for the study of strongly-interacting and topological quantum states.

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Description of the Z_c exotic states in a quark model coupled-channels calculation.

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Since early 2000s, signals of non-conventional meson structures, such as the $X(3872)$, the $D^*_{s0}(2317)$ and the $D_{s1}(2460)$ resonances, have appeared in accelerators and B-factories. Those resonances have quantum numbers compatible with naive $q\bar{q}$ structures, but their masses and decay properties show a more complex dynamics involving higher Fock components.

It was not until 2011, with the discovery of the $Z_b(10610)$ and $Z_b(10650)$ in the bottom sector [1, 2], and in 2013, with the discovery of the $Z_c(3900)$ and $Z_c(4020)$ in the charm sector [3, 4], when we had evidence of structures with exotic nature, meaning states with forbidden quantum numbers for a quark-antiquark pair. Those resonances, close to the $B\bar{B}^*$-$B^*\bar{B}^*$ and $D\bar{D}^*$-$D^*\bar{D}^*$ thresholds, respectively, are charged resonances, which reveals a non-conventional inner structure.

The nature of the $Z_c(3900)^\pm/Z_c(3885)$ and $Z_c(4020)^\pm$ is puzzling due to their charge, an exotic characteristic that forces its minimal quark content to be $c\bar{c}u\bar{d}$ ($c\bar{c}d\bar{u}$). Thus, in order to understand their inner structure it is necessary to explore four-quark systems. Additionally, their strong coupling to two-meson channels such as $\pi J/\psi$ and the closeness of their mass to $D^*\bar{D}^{(*)}$-channels stimulates different theoretical interpretations, from molecules to tetraquarks or simple kinematic effects(see [5] for a review) In this work we perform, in the framework of the constituent quark model, a coupled-channels calculation of the isospin-1 $J^{PC} = 1^{+-}$ sector including $D^*\bar{D}^{(*)} + h.c.$, $\pi J/\psi$ and $\rho\eta_c(1S)$ channels. The meson-meson interaction is described in terms of quark-quark interaction using the Resonating Group Method (RGM). For the quark-quark interaction a nonrelativistic quark model is employoed [6], which satisfactorily describes a wide range of properties of (non)conventional hadrons containing heavy quarks, thus we present a parameter-free calculation.

The results support that both $Z_c(3900)^\pm$ and $Z_c(4020)^\pm$ arise as virtual states below the $D\bar{D}^*$ and $D^*\bar{D}^*$ thresholds, respectively, which causes an enhancement over such thresholds, describing the available data. This conclusion coincides with that of the other calculations made with effective Lagrangians [7]

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Dipolar quantum liquids: using two-body interactions to make a many-body bound state

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Dilute, degenerate samples of lanthanide atoms have emerged as a promising new research frontier. Their strong magnetic moment indeed allows to study the many-body consequences of long-range anisotropic dipole-dipole interactions. Experiments benefit from the control tools of ultracold atomic physics allowing to characterize few-body effects and to isolate the key many-body mechanisms. In recent years, manifestations of dipolar interactions have been observed in Bose-Einstein condensates, Mott insulators and Fermi seas.

In these systems one can reach the regime where dipolar interactions dominate over usual short-range interactions of van der Waals origin. I this talk I will present our experimental results on magnetic quantum fluids made out of a Bose-Einstein condensate of dysprosium atoms. Striking effects of magnetic interactions can be observed. We have in particular discovered a phase-transition between a gas and a liquid, characterized by the formation of a many-body bound state. The liquid owes its stability to quantum fluctuations of the fluid's collective modes, and the same mechanism is relevant for other seemingly unrelated systems where similar liquid phases can be reached, defining a new class of ultra-dilute quantum liquids.

The dipole-dipole interaction also allows to explore the consequences of long-range, anisotropic interactions on self-organization. We namely observed the onset of a modulational instability in constrained geometries resulting in spontaneous structure formation, and investigated the possibility of simultaneously sustaining self-organization and long-range superfluidity.

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Full list:

Group webpage

Few-nucleon reactions in underground laboratory

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Accurate knowledge of thermonuclear reaction rates is important in understanding the generation of energy, the luminosity of neutrinos, and the synthesis of elements in stars. The LUNA Collaboration ([1] and [2]) has shown that, by going underground and by using the typical techniques of low background physics, it is possible to measure nuclear cross sections down to the energy of the nucleosynthesis inside stars.

This talk will give the general features of resonant and not resonant few nucleon reactions with stable beam and an overview of the experimental techniques adopted in underground nuclear astrophysics. It will be presented a summary of the main recent results and achievements.

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Depolarization ratio of gamma rays as a tool to untangle the shape of alpha-clustered nuclei*

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Beams of polarized photons of appropriate energy can be used as a tool to investigate the electromagnetic properties and the details of molecular shapes of alpha-clustered nuclei, such as ^{12}C and ^{16}O seen as geometric arrangements of 3 and 4 alpha particles. The accurate determination of the so-called depolarization ratio, through the measurements of perpendicular and parallel emitted intensities in nuclear resonance fluorescence experiments can lead to a precise understanding of the symmetries of a nuclear molecule and its normal modes of vibration. We will present a table with all possible theoretical scenarios based on discrete symmetries, that can be ruled out or confirmed experimentally and we will formulate predictions that should be tested in future experiments whenever polarized gamma-ray will become available at ELI-NP.

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Effective description of $^{5-10}$He and the search for a narrow 4n resonance*

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Open quantum systems that are at or beyond the limit of particle-emission stability exhibit generic features stemming from their coupling to an environment of positive energy states and decay channels. In this talk, I will present two nuclear physics cases: the exotic helium isotopes $^{5-10}$He[1] and the four-neutron system 4n[2]. In the first part, I will introduce a practical approach inspired by halo effective field theory for the description of $^{5-10}$He within tens of keV uncertainties and discuss the parity inversion in ^{9}He, as well as the possible two-neutron decay of ^{10}He. The second part will focus on the last *ab initio* results obtained with chiral forces and continuum couplings.

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On the inversion of the Nakanishi Integral Representation for relativistic bound state problems in Minkowski space *

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The bound state Bethe-Salpeter amplitude described by a Nakanishi two-dimensional integral representation has a smooth weight function g, which carries the detailed dynamical information on the relativistic bound state allowing the calculation of observables like form factors [1] and momentum distributions. The inversion problem to obtain g either from the valence light-front wave function or Euclidean Bethe-Salpeter amplitude is challenging and attempts to solve it numerically has been pursued with some limitations [2]. However, the one dimensional integral representation of the valence light-front wave function with the same weight function g can be mathematically inverted. By using the generalized Stieltjes transform, g can be written in terms of the light-front wave function in the complex plane of its arguments. Also a new integral equation for g is derived for a bound state case [3], and the method is valid for any kernel given by an irreducible Feynman amplitude. We briefly discuss a possible application in hadronic physics, where from the light-front wave function one obtains the Nakanishi weight function and the associated Bethe-Salpeter amplitude.

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Few Nucleon Experiments in the Hadronic Weak Interaction

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The Hadronic Weak Interaction (HWI) has been of great interest over past years, since the first models in the early 80's [1]. Within the HWI, strong and electromagnetic effects dominate, but since the weak interaction violates parity, experiments involving few nucleons can measure observable asymmetries that violate parity to probe the HWI which connects to the poorly understood, low energy non-perturbative limit of QCD. The mixing of strong to weak amplitudes produces small, 10^{-7}, parity-violating (PV) amplitudes. Experiments with both heavy nuclei and few body nuclei have been performed and have different advantages and disadvantages. While heavy nuclei experiments offer amplified PV enhancements from small nuclear energy spacings, their theoretical interpretations are not as clean as few nucleon experiments. Few nucleon experiments have large level spacings and small PV asymmetries, which make these experiments difficult. New few body experiments hope to clear up the landscape of the HWI.

The two main approaches to studying the HWI include a meson exchange model devised by Desplanques, Donoghue, and Holstein (DDH) [1] and effective field theory (EFT) [2, 3, 4, 5]. The DDH model is theoretically developed enough for experiments to be expressed in the framework, but it is highly model dependent which carries more theoretical error. Over past years, as experiments become more precise, their sensitivity becomes comparable to the theoretical error in the DDH model. Thus, in a sense the DDH framework has almost reached its limits [6]. EFT is completely model independent, and the input parameters must be measured by experiments. Additionally, recent theoretical developments in $1/N_c$ QCD expansions [7, 8, 9] provide relationships that have implications for the number of experiments and which experiments are necessary to describe the theory. Few nucleon experiments such as NPDGamma ($n + p \to d + \gamma$), n-^{3}He ($n +^3$ He $\to t + p$), Neutron Spin Rotation ($p, d, ^4$He), Photodisintegration ($\gamma + d \to n + \gamma$), and others have either completed or are on the horizon.

This talk will discuss the experimental status of few nucleon experiments in the HWI, highlighting some of the most recent neutron physics experiments that have recently completed.

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Background free measurement of the γ-decay of the 17.64MeV (1^+) state in ^{8}Be.

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A current challenge for ab initio calculations is systems that contain large continuum contributions such as ^{8}Be. We report on new measurements of radiative decay widths in this nucleus that test recent Green's s function Monte Carlo calculations [1]. Traditionally, γ-ray detectors have been utilized to measure the high energy photons[2], however, due to the intrinsic nature of these detectors it is not possible to resolve weakly populated broad states using this method. Here we present an alternative measurement using large area Silicon detectors, thus providing a background free measurement with good resolution[3] .

The experiment was conducted at the 5MV Van de Graaff accelerator at Aarhus University. The 17.64MeV state was populated using the 7Li(p,γ) reaction.

The results of the R-matrix analysis show that transitions to the ground state in ^{8}Be contributes significantly to the full energy range and dominates the spectrum below 2MeV. This implies that simply integrating the excitation energy spectrum would overestimate the decay strength to the first excited state. In order to achieve a good fit to data, it is necessary to include a 2^+ background pole. This indicates that the spectrum has non-resonant continuum contributions. Additionally, we find tentative evidence for a broad 0^+ state at 12 MeV. The extracted widths for the 2^+ doublet is in agreement with previous measurements, while the results for the ground and first excited state differ. The agreement with GFMC calculations depends on the adopted isospin mixing, but shows significant differences.

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Boron isotopes at the dripline: the ^{19}B case

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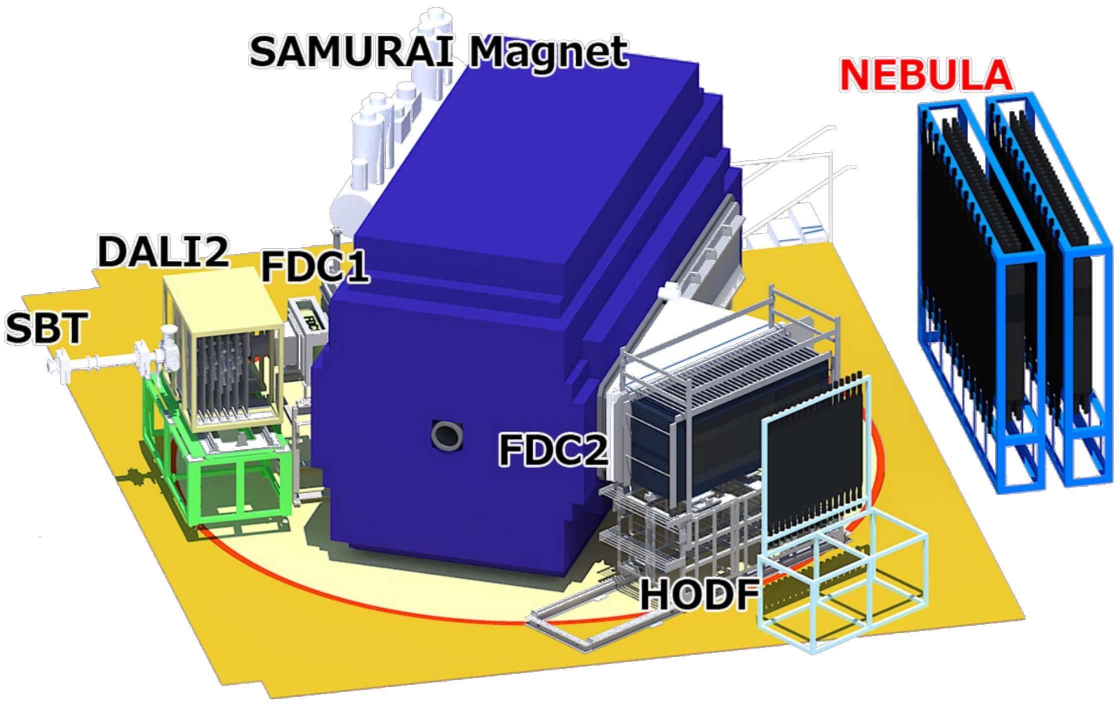
As part of the first phase program of experiments utilizing the SAMURAI spectrometer [1] and NEBULA [2] neutron array, we have undertaken invariant mass spectroscopy of neutron-rich boron isotopes at and beyond the neutron dripline using several complementary probes. After a brief introduction to the experimental setup and analysis techniques, we will focus on the structure of ^{19}B, the heaviest bound isotope. This very weakly bound nucleus exhibits several unique properties: a two/four neutron halo/skin, the lowest $4n$ separation energy measured [3], and the potentiality to develop Efimov states due to the huge scattering length of the ^{17}B+n subsytem [4]. We will present the first experimental observation of ^{19}B excited states, and compare them to theoretical calculations.



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Dibaryon candidates in decuplet baryons from lattice QCD

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In recent years, there is a renewed interest in the dibaryons due to exclusive measurements in hadron reactions as well as the direct measurement in relativistic heavy-ion collisions. In this talk, we present the result of the first principle calculation using lattice QCD. Particularly we focus on the study for dibaryon candidates involving with the decuplet baryon: (i) the Delta-Delta system with the heavy pion mass, and (ii) the Omega-Omega system with the physical pion mass [1]. Our result of the Delta-Delta interaction is that in the $^7S_3$ channel, only an strongly attractive interaction (no repulsive core) appears, which leads to a bound state of two-Delta's, the so-called "ABC effect", observed as a resonance of two-nucleons in experiment by CELSIUS/WASA Collaboration. The result of the Omega-Omega interaction in the $^1S_0$ cthannel at physical point shows a shallow bound state, which is similar to deuteron.

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Pentaquark system at LHCb[*]

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The LHCb experiment is designed to perform the precision studies of the properties of heavy flavored hadrons produced in pp collisions at the LHC. The unprecedented data samples collected in the LHC RUNI allow the first observation of the charmonium pentaquark states $P_c(3800)$ and $P_c(4450)$, and the determinations of their properties. The latest results on the studies of the pentaquark system at LHCb will be reviewed.

[*] On behalf of the LHCb Collaboration

EFT descriptions of few-nucleon systems

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The understanding of nuclear systems as composed of interacting nucleons has been significantly sharpened by the effective field theory (EFT) framework. The latter provides a link between the nuclear interaction and the underlying quantum chromodynamics, as the relevant degrees of freedom result, at least ideally, from a decimation process starting from fundamental quarks and gluons.

Owing to chiral symmetry and the Goldstone bosons' characters of the interchanged pions among nucleons, the properties of heavier nuclei can in principle be traced back to a restricted set of low-energy constants (LECs) to be determined in lighter systems in the framework of a systematic low-energy expansion [1, 2].

As the order of the expansion is increased, the determination of LECs from experimental data becomes more and more involved. It appears particularly challenging to address the three-nucleon sector at the same level of the two-nucleon sector, where the low-energy expansion has been pushed to the fifth order.

In a restricted domain of applicability, at smaller energy scales, the interactions among nucleons simplify considerably and become of contact type, resulting in what is called pionless EFT. The low-energy expansion is organized differently, relying on the emergence of universal properties, characteristic of systems with large two-body scattering lengths [3, 4].

We will examine the two above schemes and discuss their relation, with the aim of devising viable power counting schemes for applications in nuclear physics [5].

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Time Reversal Violation in two and three Nucleon Systems

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The Time Reversal Violation (TRV) is present in the Standard Model (SM) through the complex phase in the Cabibbo-Kobayashi-Maskawa (CKM) matrix and the so-called θ-term in the quantum chromodynamics (QCD) sector. The TRV interaction at quark level induces a TRV interaction between nucleons, which could be revealed by performing studies of selected nuclear observables, for example by looking at the presence of a permanent nuclear electric dipole moments (EDM). The CKM phase gives very small contributions to observables that do not involve flavour change between the initial and final states, and therefore its effects should be negligible in nuclei. On the other hand, the TRV effects due to the θ-term could be more sizable. In this work, we discuss the first complete derivation of the TRV nucleon-nucleon and three-nucleons potential induced by the θ-term up to the next-to-next-leading-order within the framework of chiral effective field theory (χEFT). With the present potential we compute the EDM of ^{2}H, ^{3}He and ^{3}H as function of the θ parameter. Our results, combined with experimental data, can be used to test the θ scenario of the SM.

Nucleon resonances and their quark structure*

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Meson-photoproduction measurements and their reaction-amplitude analyses can establish more sensitively, and in some cases in an almost model-independent way, the nucleon excitation and non-resonant reaction amplitudes and has recently led to the discovery of new baryon states. However, to investigate the strong interaction from partially explored – where meson-cloud degrees of freedom contribute substantially to the baryon structure – to still unexplored distance scales – where quark degrees of freedom dominate and the transition from dressed to current quarks occurs – we depend on experiments that allow us to measure observables that are probing this evolving strong QCD regime over its full range [1]. Once the dressed quark contributions to the baryon structure are identified, one can aim to pin down the meson-baryon contributions, which is essential to finally connect perturbative QCD over strong QCD to the strong nuclear forces.

Transition form factors are uniquely suited to trace this evolution by measuring exclusive single-meson and double-pion electroproduction cross sections off free protons [2]. Recent efforts try to access their isospin dependence by analyzing the cross sections off the quasi-free neutron and proton in Deuterium [3]. The exclusive transition form factor measurements are currently extended to higher momentum transfers with CLAS12 and the energy-upgraded CEBAF beam to study the strong interaction where the dressed quark degrees of freedom dominate, which in turn are responsible for the ground and excited nucleon state formations. Recent and preliminary results will highlight the status of the analyses and of their theoretical descriptions, and an experimental and theoretical outlook will outline what shall and may be achieved in the new era of the 12-GeV upgraded transition form factor program.

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Nuclear pasta phases within the quark-meson coupling model

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In this work the low density regions of nuclear and neutron star matter are studied. The search for the existence of pasta phases in this region is performed within the context of the quark-meson coupling (QMC) model, which incorporates quark degrees of freedom. Fixed proton fractions are considered, as well as nuclear matter in beta equilibrium at zero temperature. We discuss the recent attempts to better understand the surface energy in the coexistence phases regime and we present results that show the existence of the pasta phases subject to some choices of the surface energy coefficient. We also analyze the influence of the nuclear pasta on some neutron star properties. The equation of state containing the pasta phase will be part of a complete grid for future use in supernova simulations.

The work presented here was published on the Physical Review C journal [1] where you can find more details of our calculations and results.

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Adiabatic hyperspherical picture of 3n and 4n states*

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Recent interest in exploring the possible existence of bound states or resonances in few-neutron systems will be considered using the framework of the adiabatic hyperspherical method. [1,2] In that method, the adiabatic eigenvalues at fixed hyperradius R yield effective potentials U(R) and from their appearance it is often immediately obvious whether there is any possibility for the existence of a bound or quasi-bound energy eigenstate. Based on our preliminary explorations, both the 3n and 4n systems are quite far from having sufficiently strong attraction to produce a bound or resonant state at low energy.

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Assessing Theory Errors Using Residual Cutoff Dependence*

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I present a method to quantitatively assess the consistency of the momentum-expansion scheme in Effective Field Theories (EFTs) which are non-perturbative at leading order. There is a renewed emphasis to reliably quantify residual theoretical uncertainties [1, 2] since the ability to falsify predictions is central to the Scientific Method. Ideally, "double-blind" calculations would assess them based on input and method, and not by comparison to data – especially where data is absent or its consistency must be checked. EFTs promise a well-defined scheme to provide such reproducible, objective, quantitative error estimates. This is relatively straightforward when all interactions are perturbative, but it is a particularly nagging problem for few-nucleon systems. There, a lack of universally accepted analytic solutions obfuscates the relation between convergence pattern and numerical results and led to proposals which predict different numbers of parameters at a given level of accuracy; see the even-handed account of ref. [3].

The dependence of observables $\mathcal{O}(k;\Lambda)$ at low momentum k on the cutoff Λ of numerical calculations checks the internal consistency of a non-perturbative expansion on a semi-quantitative level [4]. This turns into an advantage the feature that most nonperturbative systems do not allow for closed-form calculations. The power-counting in the small, dimension-less quantity $Q \propto k$ of an EFT predicts (up to logarithmic corrections)

$$1 - \frac{\mathcal{O}(k;\Lambda_1)}{\mathcal{O}(k;\Lambda_2)} \propto \left(\frac{k}{\bar{\Lambda}_{\mathrm{EFT}}}\right)^{n+1} \tag{1}$$

at order Q^n, where $\bar{\Lambda}_{\mathrm{EFT}}$ is the typical high-energy scale at which the EFT description breaks down. The slope of a double-logarithmic plot of a suitable quantity against k reveals thus the order of accuracy n and an estimate of $\bar{\Lambda}_{\mathrm{EFT}}$. In contradistinction to a method proposed by Lepage [5], this approach does not compare to data to assess uncertainties. Passing this test is a necessary consistency criterion for a suggested power counting whose exact nature is disputed.

This method checks whether an observable is properly renormalised at any given order, and estimates both the breakdown scale and the momentum-dependent order-by-order convergence pattern. Conversely, it may help identify those LECs necessary for renormalised observables at a given order. I discuss underlying assumptions; the relation to the Wilsonian Renormalisation Group Equation; useful choices for observables and cutoffs; the momentum window with best signals; dependence on the values and forms of cutoffs and on the EFT parameters; the impact of fitting Low Energy Coefficients to data in different or the same channel; and caveats as well as limitations. Since the test is designed to minimise the use of data, it allows one to quantitatively falsify if the EFT has been renormalised consistently, before addressing data. Its application in particular to the attractive triplet-partial waves of NN scattering in χEFT may elucidate persistent power-counting issues. I will also address results for the various power-counting proposals of χEFT.

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Polarisabilities from Compton Scattering on ^{3}He – and Beyond*

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Low-energy Compton scattering $\gamma X \to \gamma X$ probes a target's internal degrees of freedom in the electric and magnetic fields of a real, external photon. As these fields induce radiation multipoles by displacing the target constituents, the angular and energy dependence of the emitted radiation provides detailed tests of the symmetries and strengths which govern the interactions of the constituents with each other and with photons; see e.g. a recent review [**?**]. Since it is related to the (real and virtual) excitation spectrum of the target, this probe of the two-photon response of a nucleon also complements the information available in the one-photon response (e.g. in form factors). Differences between proton and neutron values stem from isospin-breaking interactions, exploring the interplay between chiral symmetry as well as the pattern of its breaking, and short-distance Physics. This contribution addresses opportunities to serve as intermediary between first-principle calculations in lattice QCD and efforts at MAX-lab, HIγS and MAMI.

In the single-nucleon sector, information beyond the one-nucleon response is often compressed into the static scalar dipole polarisabilities. These are experimentally not directly accessible but encode information on the pion cloud, the $\Delta(1232)$ excitation, and short-distance nucleon-photon interactions. Their values provide stringent tests for our theoretical description of hadron structure and are thus fundamental quantities in their own right. Moreover, they are crucial to the neutron-proton mass difference, the proton charge radius puzzle, and the Lamb shift of muonic hydrogen.

To extract polarisabilities from data, one has to reliably extrapolate to the zero-energy limit in which they are defined. In addition, the interaction of the photon with the charged pion-exchange of nuclear systems provides a conceptually clean probe of few-nucleon binding. Since the most reliable neutron values come thus far from deuteron data, nuclear binding and meson-exchange effects must be subtracted with reliable theoretical uncertainties. Chiral Effective Field Theory is an ideal analysis tool since it provides such theoretical uncertainties by a model-independent estimate of higher-order corrections and encodes the correct low-energy dynamics of QCD, including, for few-nucleon systems, consistent nuclear currents, rescattering effects and wave functions.

I report new results for unpolarised and polarised observables in elastic Compton scattering from ^{3}He in Chiral Effective Field Theory with an explicit $\Delta(1232)$ degree of freedom (χEFT) for energies between 50 and 120 MeV [1]. The $\gamma\,^3$He amplitude is complete at N^{3}LO, $\mathcal{O}(e^2\delta^3)$, and in general converges well order by order. It includes the dominant pion-loop and two-body currents, as well as the Delta excitation in the single-nucleon amplitude. Since the cross section is two to three times that for deuterium and the spin of polarised ^{3}He is predominantly carried by its constituent neutron, elastic Compton scattering promises information on both the scalar and spin polarisabilities of the neutron. We study in detail the sensitivities of 4 observables to the neutron polarisabilities: the cross section, the beam asymmetry, and two double asymmetries resulting from circularly polarised photons and a longitudinally or transversely polarised target. Including the Delta enhances those asymmetries from which neutron spin polarisabilities could be extracted. We also correct previous, erroneous results at N^{2}LO, i.e. without an explicit Delta, and compare to the same observables on proton, neutron and deuterium targets. An interactive *Mathematica* notebook of our results is available from `hgrie@gwu.edu`.

I also elaborate on promising extensions to heavier nuclei which take full advantage of the numerical power of modern few-nucleon methods.

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Theoretical studies of few-body phenomena in light exotic nuclei

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Few-body phenomena concerning structure and decays of exotic nuclear systems located in proximity of driplines are studied in the framework of the three-cluster core+N+N model. Several interesting recent results are reviewed in this report.

(i) Recently importance of "transitional dynamics" in the studies of three-body decay mechanisms was understood [2]. This is form of decay mechanism available on the borderlines between well-defined "true $2p$", "democratic $2p$" and "sequential $2p$" decay mechanisms. There is experimental evidence that the decays of the recently discovered $2p$ emitters ^{30}Ar and ^{67}Kr belong to transitional dynamics [1, 2, 3, 4]. This decay regime has features typical for phase transitions enabling in-depth studies for parametric dependencies of three-body and two-body decays. In particular, a new method for determination of decay width of two-body systems is proposed in the case of "transitional dynamics" population in three-body decay.

(ii) Emission of two neutrons or two protons in reactions and decays is often discussed in terms of "dineutron" or "diproton" emission. Such discussions of "dineucleon" emission also often lack clarity. In the paper [5] we proposed a way to formalize the discussion exploring the manifestation and nature of a dineutron in two-neutron emission using a dynamical dineutron model. It is demonstrated that properly formally defined dineutron emission may reveal properties which are drastically different from those traditionally expected, and properties which are actually observed in three-body decays.

(iii) An important way of few-body continuum studies is population in direct reactions. It is demonstrated how the high-statistics few-body correlation data can be used to extract detailed information (in certain cases — most complete quantum-mechanical information) on the reaction mechanism of such a reaction. The approach is based on the fact that highly spin-aligned states are typically populated in the direct reactions. We use the example of ^{6}Be continuum states populated in the charge-exchange ^{1}H(^{6}Li,^{6}Be)n reaction providing very high-statistics data [6].

(iv) The only way to extract experimental information about non-resonant three-body radiative capture reactions is to study the reciprocal photodissociation and Coulomb excitation reactions. We discuss the obstacles and advances in "converting" the Coulex cross sections to non-resonant astrophysical rates for three-body capture processes by example of ^{15}O+p+p $\rightarrow ^{17}$Ne+γ reaction [7].

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Cluster configuration effects in elastic scattering of light proton and neutron-rich nuclei

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Some light proton and neutron rich exotic nuclei are characterized by cluster configuration where one or more valence particles orbits a core nucleus and the borromean structure in ^{6}He and halo structure in ^{8}B are typical examples. Correlations of the valence particles and the strong coupling with the continuum can significantly distort the shell structure as well as the collective properties of these weakly bound exotic nuclei. Effects due to these properties and configurations are also expected in the dynamics of the reactions induced by these nuclei. The angular distributions for the elastic scattering process using these nuclei as projectiles may contain effects due to the configuration and couplings with the continuum. For exotic nuclei, those processes introduce characteristic dynamic polarizations (attractive or repulsive) in the optical potential which are not present in the case of stable projectiles.

In this contribution I will discuss about these effects in the angular distributions data for the elastic scattering of boron isotopes; ^{8}B, ^{10}B, ^{11}B and ^{12}B, as well as for ^{10}C on several targets. The proton-halo configuration for ^{8}B has already been established by the strong dynamic effects observed in elastic, breakup and fusion measurements [1,2]. However, the influence of the breakup in the elastic and fusion is not well established yet. The ^{10}C nucleus has a four-body cluster configuration p+p+α+α and it is the only nucleus supposed to have a Brunnian (super-borromean) structure where four rings interconnected are associated to the four body interactions [3]. These facts motivated us to perform new measurements of the elastic scattering for ^{8}B and ^{10}C on ^{208}Pb at energy close to the barrier at Cyclotron Institute of the Texas A&M University (TAMU), USA. In this contribution I will present the preliminary results for these measurements with radioactive ^{8}B and ^{10}C, as well as for experiments with the ^{10}C radioactive beam on ^{58}Ni performed with Twinsol [4] at University of Notre Dame, USA, radioactive ^{12}B beam on ^{58}Ni performed with RIBRAS [5] at Universidade de São Paulo, Brazil and ^{10,11}B beams on ^{58}Ni at Tandar, Argentina.

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Nucleon structure from LQCD

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We present lattice QCD results for the structure of the nucleon using twisted mass clover improved fermions tuned to reproduce the physical value of the pion mass. Quantities such as charges, form factors and moments of GPDs will be included in the presentation. Spin decomposition will be discussed including sea quarks and gluons contribution. Graphics cards have been employed to sufficiently suppress statistical and stochastic noise. Excited state effects have thoroughly been studied to isolate the ground state. Results have been published in Refs [1, 2, 3, 4, 5, 6]. Representative quantities are shown in Fig. 1.

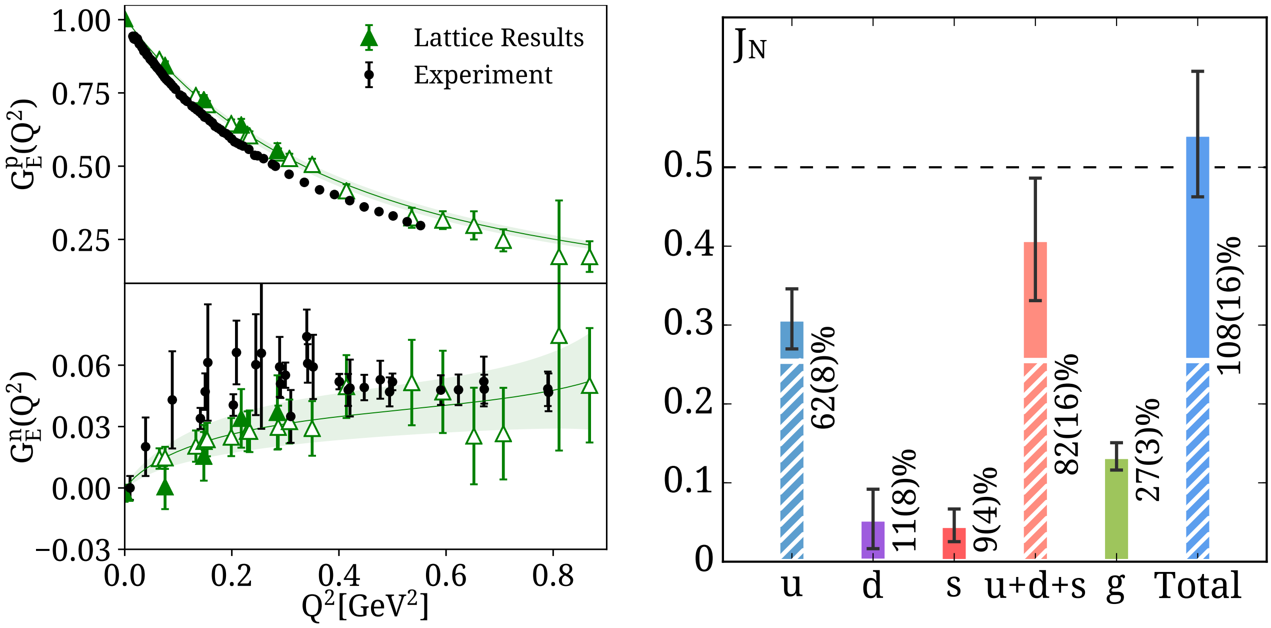

Figure 1: Proton and neutron electric form factors (left) and nucleon spin decomposition (right).

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Baryon-baryon interaction in chiral effective field theory

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Over the last few years the Jülich-Bonn-Munich Group has performed extensive studies of the baryon-baryon interaction involving strange baryons (Λ, Σ, Ξ) within chiral effective field theory (EFT) [1, 2]. A selection of the achieved results will be presented. First, a calculation of the in-medium properties of a hyperon-nucleon interaction derived within chiral EFT and fitted to ΛN and ΣN scattering data is reviewed. Implications on the properties of neutron stars and, specifically, on the so-called hyperon-puzzle are addressed [3]. Furthermore, the relevance of three-body forces for hypernuclei is discussed and potentials for the leading order three-baryon interactions are presented, which involve contact terms and irreducible one- and two-meson exchange diagrams [4]. Finally, results for baryon-baryon scattering in the strangeness $S = -2$ sector, obtained at next-to-leading order in the chiral expansion [2], are presented.

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How To Use Renormalization Group Analysis in Lattice Nuclear Effective Field Theory *

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In this presentation, we propose a new approach to Nuclear Effective Field Theory (NEFT) on a lattice on the basis of Renormalization Group (RG) analysis.

In order to perform lattice numerical simulations for NEFT, the nucleon field must be integrated and the effects are represented as a determinant. A NEFT Lagrangian contains four-nucleon contact interactions (to represent NN interactions at low energies) such as $(N^\dagger N)^2$. In order to integrate the nucleon field out, we rewrite these interactions as bilinear terms by introducing auxiliary fields. The procedure is known as Hubbard-Stratonovich transformation. The problem is that certain coupling constants of the four-nucleon contact interactions are negative and thus the corresponding coupling to the auxiliary fields become complex. It leads to a complex determinant, which cannot be considered as a part of the probability distribution function in the Monte Carlo algorithm. It is known as the (numerical) sign problem.

A viable method is the reweighting method: to introduce a positive definite reference determinant, which is supposed to be "similar to" the original one. The reference determinant is to be considered as a part of the probability distribution function and the ratio of the original determinant to the reference one is included in the operators to be calculated. Schematically the expectation value of an operator $\mathcal{O}$, $\langle\mathcal{O}\rangle$, is calculated as

$$\langle\mathcal{O}\rangle = \frac{\int d\Phi \left\{\mathcal{O}\frac{\det M(\Phi)}{\det M_R(\Phi)}\right\} \det M_R(\Phi) e^{-S(\Phi)}}{\int d\Phi \left\{\frac{\det M(\Phi)}{\det M_R(\Phi)}\right\} \det M_R(\Phi) e^{-S(\Phi)}},$$

where Φ collectively represents auxiliary fields, and $\det M(\Phi)$ and $\det M_R(\Phi)$ are the original and the reference determinants, respectively. There is, however, a wide variety of the choices of the reference determinant.

We propose to choose an optimal reference determinant on the basis of RG analysis. RG analysis tells us that physical two-nucleon system is close to the RG nontrivial fixed point. A very important feature of the nontrivial fixed point is there is a relevant operator, which dominates physics at low energies. In our approach, the reference determinant is constructed only with the relevant operator, and the original (physical) determinant contains operators in the irrelevant direction from the reference one.

We show how this approach works for a simple example: isospin-symmetric S-wave NNLO NEFT without pions. We consider the standard deviation of the absolute value of the reweighting factor $|\det M(\Phi)/\det M_R(\Phi)|$ as a measure of similarity of the probability distribution functions. We have shown that going from the reference point to the relevant direction leads to much more rapid growth of the standard deviation than going to the irrelevant direction. This implies that our choice of the reference determinant is optimal.

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State-to-state chemistry for three-body recombination in an ultracold rubidium gas

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Experimental investigation of chemical reactions with full quantum state resolution for all reactants and products has been a long-term challenge. We have recently developed an experimental method for detecting molecules in a quantum state resolved way with unprecedented resolution, which we can use to study chemical reactions [1]. As a benchmark reaction, we investigate three-body recombination of ultracold Rb atoms, where two atoms combine to form a Rb_2 molecule while the third atom carries away part of the released binding energy. Initially the atoms are prepared in a well-defined internal quantum state. After the reaction we state-selectively ionize the produced molecules with a resolution of about 5 MHz such that most molecular quantum states can be spectroscopically distinguished. Our results allow for formulating propensity rules for the distribution of products. Furthermore we have developed a theoretical model that predicts many of our experimental observations. The scheme can readily be adapted to other species and opens a door to detailed investigations of inelastic or reactive processes.

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The deuteron-radius puzzle is alive: a new analysis based on chiral EFT theory

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The charge radius of the deuteron (d), the simplest nucleus consisting of one proton and one neutron, was recently determined to three times the precision compared with previous measurements using several Lamb shift transitions in muonic deuterium (μd) [1]. However, the μd value is 5.6 σ smaller than the world averaged CODATA-2014 [2] values, and 3.5 σ smaller than the results from ordinary deuterium spectroscopy [3]. Furthermore, the measured radius squared difference $r_d^2 - r_p^2$ obtained from isotope shift experiments on ordinary hydrogen and deuterium [4] can be combined with the absolute determination of the proton radius from muonic hydrogen experiments [5, 6] (dubbed as "μp + iso") to obtain a charge radius which is much closer to the μd result, but still differs from it by 2.6 σ (see Ref. [1] for details). Altogether, these significant discrepancies have been coined "the deuteron radius puzzle" and the 2.6 σ discrepancy has been suggested to be due to uncertainties in the nuclear structure corrections.

To shed light on the deuteron radius puzzle in our recent paper [7] we analyzed the theoretical uncertainties of the nuclear structure corrections to the Lamb shift in muonic deuterium. We found that the discrepancy between the calculated two-photon exchange correction and the corresponding experimentally inferred value by Pohl et al. [1] remained and that the present result is consistent with our previous estimate, although the discrepancy is reduced from 2.6 σ to about 2 σ. The error analysis included statistic as well as systematic uncertainties stemming from the use of nucleon-nucleon interactions derived from chiral effective field theory at various orders. We therefore conclude that nuclear theory uncertainty is more likely not the source of the discrepancy.

This talk will emphasize the details related to the statistical and systematic uncertainty analysis carried out in our recent work on the deuteron [7] which addressed the propagation of uncertainties from the low-energy-constants embedded in chiral effective field as well as probing systematic uncertainties from the chiral potentials and the associated electromagnetic operators.

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Dipole-dipole dispersion interactions between neutrons

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Beyond charge and permanent magnetic moments, polarizabilities provide the response of the internal structure of composite objects, like atoms, nuclei, and hadrons, to an applied electromagnetic field. For two neutrons, dipole polarizabilities also lead to a long-range Casimir-Polder dispersive interaction. In this work we present results of the dipole-dipole long-range interactions between two neutrons, a neutron and a conducting wall, and a neutron between two walls. As input, we use dynamical electric and magnetic dipole polarizabilities fitted to chiral EFT results up to the pion production threshold and at the onset of the Delta resonance.

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structure of tetraneutron system

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The key question is whether or not $4n$ system exist as a bound or resonant state. In order to answer this question, there are many experimental and theoretical effort. A recent experiment on the ^{4}He(^{8}He,^{8} Be)$4n$ reaction generated a excess of $4n$ events with low energy in the final state [1]. The reported data is that the energy $E_R = 0.83 \pm 0.65 \pm 1.25$ MeV with width (upper limit) $\Gamma = 2.6$ MeV. Motivated by the data, we studied this system using Gaussian Expansion Method and Faddeev-Yakubovsky method. We use NN AV8 potential and a phenomenological three-body force. We found that to generate narrow $4n$ resonant state, it is necessary to have a remarkably strong attraction of $3N$ force. The detail is written in Ref.[2]. The detail will be discussed in the conference.

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Three-body approach to deuteron-alpha scattering and bound state using realistic forces in a separable or non-separable representation*

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Deuteron-induced reactions constitute an important tool for extracting nuclear structure information such as spectroscopic factors and asymptotic normalization coefficients. In order to treat the dynamics in all reaction channels on the same footing, it is advantageous to view (d,p) reactions as a three-body problem $(n+p+A)$ within a Faddeev framework. The input to such Faddeev calculations are the effective two-body interactions between the np, $n+A$, and $p+A$ pairs. The Coulomb repulsion in the $p+A$ subsystem poses severe difficulties when studying these reactions on heavy nuclei with momentum space Faddeev equations. One way to address those challenges is to formulate the problem without screening and employing separable interactions in the two-body subsystems [1]. However, implementation of this approach is hindered by the fact that realistic pair interactions are generally not separable. It is thus a goal of this work to show that a Faddeev approach in momentum space using separable expansions of realistic interactions in the two-body subsystems gives equivalent results to a Faddeev approach using those interactions directly. Using the example of $d+\alpha$ scattering and the ^{6}Li three-body bound state, we will demonstrate that the separable expansion (1) converges quite rapidly, and (2) yields the same two- and three-body observables.

First, we employ the Ernst-Shakin-Thaler [2] (EST) formulation to construct multi-rank representations of the realistic interactions for in the two-body subsystems. The CD-Bonn potential is adopted for the np pair while a Woods-Saxon form is used for the $n(p)$-α subsystem. Then the resulting separable representations are used to solve momentum space Faddeev equations for either the bound state or the scattering problem.

By comparing binding energies and momentum distributions obtained with separable potentials of various ranks, we demonstrate that only a few terms are needed for convergence of the bound state calculations. Furthermore, the converged results are in excellent agreement with those obtained by directly solving the Faddeev equations with non-separable forces [3].

For $d+\alpha$ scattering, the Faddeev-AGS equations are solved in momentum space using the same two-body interactions as well as their separable expansions. Preliminary calculations of elastic scattering observables indicate a rapid convergence of the separable expansion. We will present results for $d+\alpha$ angular distributions and discuss their convergence with respect to the number of terms in the separable expansion. The accuracy of the separable representation with respect to the original realistic interactions shall also be analyzed. Future prospects for solving the momentum space Faddeev-AGS with full inclusion of the Coulomb potential will discussed.

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In-medium properties of SU(3) baryons*

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In this talk, we discuss how the nucleon and hyperons undergo the changes in nuclear environment within the in-medium modified SU(3) Skyrme model. We consider the nuclear effects on the dynamical parameters of the model. In particular the parameters related to the pion are modified, the experimental and empirical information being taken into account. As a result, the chiral soliton is affected by these medium effects. We find that the mass changes of the nucleon and hyperons are rather nontrivial funtions of the nuclear-matter density. We also see that the effects of the flavor SU(3) symmetry breaking tend to decrease as the density increases, which is a specific feature of the present model.

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Low-Energy QCD Research at TUNL*

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The goal of the low-energy QCD (LEQCD) program at TUNL is to perform measurements that advance the descriptions of few-nucleon reaction dynamics and the long-range structure of nucleons in terms of QCD. The central themes are to reduce uncertainties in low-energy nucleon-structure parameters in effective field theory calculations, to evaluate ab-initio few-nucleon calculations, and to probe for experimental evidence of three-nucleon interactions in the nuclear continuum. The main components of the program are measurements of: (1) the electromagnetic response of the nucleons below the pion-production threshold and (2) few-nucleon reactions. The first and main part of the program is carried out using the nearly mono-energetic and highly polarized gamma-ray beam at the High Intensity Gamma-ray Source (HIγS). The second part involves few-nucleon reaction measurements at HIγS and experiments that use the nearly mono-energetic and pulsed neutron beams in the tandem lab. This talk will describe and present highlights from both program components.

The main thrust of the nucleon-structure component of the LEQCD program is to perform high-accuracy measurements of the Compton-scattering cross sections on few-nucleon targets, i.e., nuclei with A $<$ 5. The driving motivation for these measurements is to reduce the experimental uncertainty in the determination of the dipole electric (α^n_{E1}) and magnetic (β^n_{M1}) polarizabilities of the neutron. We are measuring angular differential cross sections for Compton scattering from ^{4}He, ^{2}H and ^{3}He at incident gamma-ray beam energies between 60 and 110 MeV. The results of our measurements on ^{4}He at 61 MeV are reported by Sikora *et al.* [1]. These data are used to determine values for the isoscalar dipole electric and magnetic polarizabilities of the nucleon. Also, recently the HIγS Compton-Scattering Collaboration (see ref. [1]) measured cross sections for Compton-scattering from ^{2}H at 65 MeV. To provide beam-asymmetry data for extraction of the dipole electric and magnetic polarizabilties of the proton, we measured Compton-scattering on ^{1}H at 85 MeV using a linearly polarized gamma-ray beam. The Compton-scattering cross-section measurements are performed using circularly polarized gamma-ray beams. Highlights of results from recent measurements and descriptions of plans for the next three years will be presented.

The few-nucleon measurements performed at HIγS and in the tandem lab provide complementary information in evaluating ab-initio theory calculations. The current focus is on the three-nucleon system, which has highly developed theory and has sufficient complexity to exhibit influences of three-nucleon forces. We have performed the first exclusive differential cross-section measurements for photodisintegration of ^{3}He at low energy. The measurements were performed at an incident beam energy of 15 MeV. A modification in the value of the ^{1}S$_0$ neutron-proton scattering length determined in this reaction from the value established by two-nucleon scattering data would indicate the effect of long-range three-nucleon interactions that are not included in current nuclear potential models. The experimental technique and preliminary results from these measurements will be presented. Also, the strength of the neutron-neutron (nn) ^{1}S$_0$ interaction is evaluated using nn quasi-free scattering in neutron-deuteron breakup. These measurements are carried out at two incident neutron beam energies, 10 and 16 MeV, in the tandem lab. The experiment methods and preliminary results will be presented.

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p-shell Structure Through the Looking-Glass of *Ab Initio* Transfer Reactions

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Advances in the fundamental description of the interaction among nucleons, in many-body techniques and in scientific computing, have opened new avenues for the modeling of low-energy light-ion structure and reactions on an equal footing. This provides a new tool for accurate evaluations of crucial reaction data for nuclear astrophysics, fusion-energy research, and other applications. I will present an efficient many-body approach to nuclear bound and scattering states alike, known as the *ab initio* no-core shell model with continuum [1]. This method can accurately describe reaction systems of more than four nucleons starting from two- and three-nucleon interactions [2]. In this work, we aim at modeling the $\mathrm{t}(d,n)^4\mathrm{He}$ reaction from an *ab initio* point of view. Thanks to a near-threshold resonance closely related to major shell splitting, the reaction cross-section is enhanced, making the deuterium (D) and tritium (T) an ideal fuel for thermonuclear fusion. Even more efficient energy generation may be obtained if the spin of the reactants align. We predict for the first time the enhancement factor of the polarized DT fusion rate and the anisotropy of the polarized cross section.

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Incomplete breakup reaction of a two-cluster projectile on a two-fragment target: A genuine four-body problem

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The ongoing research on the reaction of radioactive nuclei has supplied us with invaluable information about the structure of nuclei near the drip line. Further, they produced important capture reactions and other direct reactions needed to fill the gaps in the chain of reactions in the r and s processes in astrophysics. The neutron capture reactions referred it above involves capture by stable nuclei. neutron capture reactions on radioactive nuclei, especially near the drip nuclei are not available. A possible way to obtain these cross sections is through indirect hybrid reactions. One such method is the Surrogate Method . So far this method was mostly used to obtain neutron capture cross section of fast neutrons by actinide nuclei for use in research in fast breeder reactors. The theory employed for this is the Inclusive Nonelastic Breakup (INEB) Reaction theory. In this talk we report on a recent work that extends the application of the INEB to the case of capture by a radioactive target or projectile. In our approach we consider first the three-body case of a non-cluster radioactive projectile interacting with a two-cluster target, such as the deuteron. In this case the reaction is a neutron pickup. Through the measurement of the inclusive proton spectrum one is able to extract the neutron capture cross section. This cross section is not the free capture cross section as several factors come into play owing to the fact that the neutron is bound in the deuteron. The second case we consider is the four-body one involving two-cluster projectile and two-projectile target. One such reaction involves the one proton halo nucleus ^{8}B, ^{8}B + d $\rightarrow$ p + ^{9}B or p + (^{7}Be + d). So the inclusive proton spectrum will exhibit two groups a low proton energy one associated with the incomplete fusion ^{7}Be + d and a higher proton energy group connected with the capture reaction. Our work reported here should be useful to assess the applicability of the INEB theory to isotopes such as ^{135}Xe whose lifetime is 9.8 hours, which is a notorious nuclear reactor poison as its thermal neutron capture cross section is huge, 2.5×10^6 barns. Several other nuclei exhibit very large thermal neutron capture cross sections [2]. Our aim is to use this nucleus as a benchmark to test to proton spectrum in a reaction of the type d + ^{135}Xe $\rightarrow$ p + ^{136}Xe. Further our discussion here should constitute an important extension of the four-body formulation involving a three fragment projectile on a "structureless" target developed recently in [1] to two-fragment on two-fragment nuclear reactions.

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Hadron interactions from lattice QCD - application to hadron resonances

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I will present recent progresses of LQCD on hadronic interactions which play a crucial role to understand hadron resonances and the properties of atomic nuclei. So far, two theoretically equivalent methods, the Lüscher's method and the HAL QCD method, to extract the hadronic interactions were proposed. First, I will discuss hadron interactions using so-called the "plateau method" in which the energy eigenvalues calculated from the temporal correlation of two hadrons are used to extract the scattering phase shifts by the Lüscher's method. I will demonstrate that energy eigenvalues in the plateau method have a serious contamination of the mixing with different states, so that the results obtained are inconsistent with the effective range expansion. I then demonstrate how the HAL QCD method solves this issue. I then proceed to discussions of coupled-channel hadron interactions on the lattice with the HAL QCD method, which are important to study the nature of hadron resonances.

Study of dibaryon resonances via coherent double neutral-meson photoproduction from the deuteron

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The search for non-strange dibaryon states has a long history [1]. A dibaryon state is of particular interest, which can be a molecule consisting of two baryons or a spatially compact hexaquark object. The $d^*(2380)$ resonance observed in the pn-collision reactions by the CELSIUS/WASA and WASA-at-COSY collaborations [2, 3] may be attributed to a mixing state of the isoscalar $\Delta\Delta$ quasi-bound state, $\mathcal{D}_{03}$, predicted by Dyson and Xuong [4] and spatially compact six-quark state [5].

The $\gamma d \to \pi^0\pi^0 d$ reaction, which selects only isoscalar intermediate state, has been experimentally investigated to study the properties of $d^*(2380)$ at the Research Center for Electron Photon Science (ELPH), Tohoku University, Japan [6]. The γd center-of-mass energy, $W_{\gamma d}$, is covered from 2.38 to 2.80 GeV. A slight enhancement is observed in the excitation function near $W_{\gamma d} = 2.38$ GeV [7], where $d^*(2380)$ is expected to appear. Although the measured excitation function is consistent with the existing theoretical calculation for this reaction [8], the angular distribution measured is quite different from the calculation for the pions and deuteron [9]. The angular distribution is rather flat for the deuteron, suggesting that a sequential process, quasi-free $\pi^0\pi^0$ production on the nucleon followed by recombination of the two nucleons into the deuteron, does not reproduce the experimental data. Thus, a peak observed at approximately 2.15 GeV in the $\pi^0 d$ invariant-mass distributions would be attributed to a dibaryon state, possibly being a $N\Delta$ quasi-bound state, $\mathcal{D}_{12}$.

We have also measured the differential and total cross sections for the $\gamma d \to \pi^0\eta d$ reaction. The deuteron emission angle also shows a rather flat distribution, and an enhancement is observed near the threshold in the ηd invariant mass distribution. We will discuss candidates for non-strange dibaryons observed in coherent double neutral-meson photoproduction from the deuteron.

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Ab initio calculation of nuclear-structure effects in muonic atoms

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The proton charge radius, determined in high-precision spectroscopy of muonic hydrogen [1, 2], revealed a 6σ deviation from that obtained in hydrogen spectroscopy and electron-proton scattering. The radius puzzle has stimulated a series of spectroscopy experiments in other light muonic atoms, aiming to accurately determine the charge radii of light nuclei. The subsequent measurement of muonic deuterium [3] recently determined the deuteron charge radius that is 3.5σ different from deuterium spectroscopy, and strengthened the puzzle. As the limiting factor, nuclear-structure effects remain the largest uncertainty in the experimental extraction of nuclear charge radii.

Nuclear-structure effects are driven by two-photon exchange contributions to muonic-atom spectra, whose evaluation relies significantly on nuclear theory. With ab-initio calculations, we have studied nuclear-structure effects in several light muonic atoms, including μD, μ^3H, μ^3He$^+$, and μ^4He$^+$ [4, 5, 6, 7]. We utilize the effective interaction hyperspherical harmonic method [8] and a generalized Lanczos [9] method to compute nuclear electromagnetic sum rules associated with two-photon exchange. The calculation is done with the implementation of state-of-the-art two-nucleon and three-nucleon interactions, derived either phenomenologically or from chiral effective field theory. The accuracy in predicting nuclear-structure effects greatly depends on the uncertainty in nuclear forces due to their non-perturbative nature. We analyze statistical and systematic uncertainties from nuclear theory, by potential-model comparison, and by using power-counting and order-by-order parameter-optimization techniques, that have been developed in chiral effective field theory.

We present our results of nuclear-structure effects with unprecedented high precision, that fulfills the requirement in muonic atom spectroscopy measurements. Our results can be instrumental to the experimental determination of nuclear charge radii.

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Experimental study of few nucleon correlations using deuteron beam at Nuclotron*

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The main goal of the deuteron spin structure (DSS) collaboration is to investigate the structure of few nucleon correlations through the measurements of the polarization observables in the deuteron induced reactions at intermediate energies. Few nucleon correlations are studied using polarized and unpolarized deuteron beams and Polyethylene and Carbon targets at Nuclotron, JINR. The *dp* breakup reaction is investigated at the deuteron energies from 300 - 500 MeV in the region where non-nucleonic degrees of freedom and relativistic effects can play a significant role. Analyzing powers of the dp breakup reaction using polarized beam were investigated at Internal Target Station (ITS) of Nuclotron at deuteron energies of 270 and 400 MeV using $\Delta E - E$ technique. Recently, *dp* elastic scattering is investigated using polarized deuteron beam at ITS under various kinematic configurations in the angular range (70° - 120°) in c.m. at deuteron energies of 400, 700, 800, 1000, 1100, 1300, 1500 and 1800 MeV. Preliminary results of the differential cross sections and analyzing powers are obtained and compared with the calculations based on relativistic multiscattering model.

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Turning-off two-body and generating three-body interactions between ultracold neutral bosonic atoms *

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We discuss our recent work showing how the effect of pair-wise (two-body) interactions between ultracold neutral bosonic atoms can be suppressed, to generate a low-energy Hamiltonian in which attractive three-body interactions are dominant [1]. Our results rely on either adjusting the strength of a trapping potential or exploiting a Feshbach resonance such that there is a cancellation between the influence of the scattering length and effective range contributions to two-body interactions, while leaving an effective three-body interaction that is of sufficient magnitude to be experimentally observed. For van-der-Waals potentials, which for example describe scattering of alkaline-earth atoms, we find that turning off pair-wise interactions requires atoms with a small negative scattering length (e.g., the Sr88 isotope is a possible candidate). For atoms with collisional magnetic Feshbach resonances this restriction does not apply, and we show examples involving several known narrow resonances between alkali-metal as well as chromium atoms. Using these results, we simulate the coherent collapse-and-revival dynamics of ultracold bosons with dominant three-body interactions in optical lattices, discuss experimental observables, and consider the role of anisotropic confinement.

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Pion-cloud contribution to the $N \to \Delta$ transition form factors*

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We examine the contribution of the pion cloud to the $N \to \Delta$ transition form factors within a relativistic hybrid constituent-quark model. In this model baryons consist not only of the $3q$ valence component, but contain, in addition, a $3q + \pi$ non-valence component. We start with constituent quarks which are subject to a scalar, isoscalar confining force. This leads to an $SU(6)$ spin-flavor symmetric spectrum with degenerate nucleon and Delta masses. Mass-splitting is than caused by pions which are assumed to couple directly to the quarks. The point-form of relativistic quantum mechanics is employed to achieve a relativistically invariant description of this system [1, 2, 3]. The $N \to \Delta$ transition current is then determined from the one-photon exchange contribution to the Delta electroproduction amplitude. A common choice for the covariant decomposition of this transition current is [4]:

$$\begin{aligned} J^{\mu}_{N\to\Delta}(p',\sigma';p,\sigma) \quad = \quad & i\sqrt{\frac{2}{3}}\frac{3e\left(m_\Delta + m_N\right)}{2m_N\left[\left(m_\Delta + m_N\right)^2 + Q^2\right]}\bar{u}_\beta\left(p',\sigma'\right) \\ & \times\Big\{ g_M\left(Q^2\right)\epsilon^{\beta\mu\rho\sigma}p'_\rho q_\sigma \\ & \quad + g_E\left(Q^2\right)\left(q^\beta p'^\mu - q\cdot p' g^{\beta\mu}\right)i\gamma_5 \\ & \quad + g_C\left(Q^2\right)\left(q^\beta q^\mu - q^2 g^{\beta\mu}\right)i\gamma_5\Big\} u\left(p,\sigma\right)\,, \end{aligned} \tag{1}$$

where the form factors g_M, g_E, and g_C are related to the more conventional magnetic dipole form factor G^*_M, the electric quadrupole form factor G^*_E, and the Coulomb quadrupole form factor G^*_C. We will give predictions for these form factors, showing that pion-cloud effects are of particular significance, if one wants to understand the measured G^*_E/G^*_M and G^*_C/G^*_M rations.

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Formation of few electron complexes (pairs, triples, quadruples).

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Few(2-4) active electrons experience equilibrium configurations in an ion field. The multidimensional potential surface shows ridges near these configurations. Diffraction of an electron wave from such ridges are shown to induce a fictitious force leading to a temporary electron-electron attraction independent of temperature. That force ressembles formally to a Lorentz force. In contrast to Cooper pairs our complexes need only one nucleus rather than a vibrating lattice. We take correlation exactly into account, and employ nonadiatically modified plane waves. Along these lines we derive equations for wavenumbers which replace the wave equation. They can be solved exactly. Pairs and quadruples are bosons whereas the triples are fermions. Results compare favorably with experimental ionization data.

Cluster structure of the ground and excited states of ^{9}Be and ^{10}B nuclei*

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Reactions of quasielastic (p, px), (e, ex) knockout and reactions of (γ, x) photodisintegration show that particles x – deuterons, tritons, α-particles and nucleons escape with a comparable probability from light nuclei. The significant values of spectroscopic S-factors in these channels are evidence of this. This situation is well interpreted by the wave functions of multiparticle shell model [1] which allows considering from the unified position both cluster and nucleonic degrees of freedom. The situation in ^{9}Be and ^{10}B nuclei is of peculiar interest. In these nuclei from analysis of symmetry of orbital part of wave functions of states lying at high energies it was suggested for instance in ^{9}Be nucleus to search three-cluster αtd-states in reactions with ^{6,7}Li ions on the same target nuclei [2]. It is known that ^{6}Li and ^{7}Li nuclei have a pronounced two-cluster αd- and αt-structure respectively. That is why it was supposed that the three-cluster states will be excited more intensively in reactions like ^{6}Li(^{7}Li, α)^{9}Be (triton cluster transfer) and ^{7}Li(^{6}Li, α)^{9}Be (deuteron cluster transfer). It was believed that the three-cluster states should lead to states of ^{9}Be with Young [432] scheme. However the flexibility of multiparticle shell model is that the Young [441] scheme admits an escape of deuterons and tritons since according to Littlewood theorem the fragmentations [441] $\leftrightarrow$ [43] + [2] and [441] $\leftrightarrow$ [42] + [3] are possible. Our calculations showed that in excitation spectra of ^{9}Be nucleus there are three-cluster αtd-states lying in range of both 17-19 MeV and 10-11 MeV. These states have large S-factors in triton, deuteron (and α-particle) channels simultaneously, moreover the last ones appear exactly due to [441] states.

Similar conclusions were also obtained for ^{10}B nucleus where three-particle $\alpha\tau t$-levels are connected not only to states with Young [433] scheme, but with [442].

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Relativistic Faddeev Calculation for Nd Scattering with Kharkov Potential

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Relativity in the three-nucleon (3N) system has been studying [1] under the Bakamjian-Thomas frame, which belongs to the relativistic quantum mechanics and is dictated by the Poincaré algebra. Since a relativistic two-nucleon (2N) potential is not easily provided, we need some schemes which would allow us to transform a nonrelativistic potential into the corresponding relativistic one. Such schemes are required to fulfill the condition that the generated relativistic potential yields the same observables in the 2N system as the original nonrelativistic potential. We have two schemes which satisfy that condition. One was proposed by Coester *et al.* [2] and we call it the CPS scheme. It requires a solution of a nonlinear integral equation, which can be achieved numerically by an iteration method [3]. The other scheme is a momentum scaling method (MSM) [4], realized by an elaborate change of momentum variables. We are actually interested in a comparison between the original nonrelativistic and the modified relativistic potential predictions in the 3N system. In the case of the triton binding energy we have already been demonstrating this comparison [5] that the difference is smaller when the CPS scheme is employed.

On the other hand, the Kharkov model [6] provides directly the relativistic 2N potential, therefore, it needs CPS nor MSM. We would like to present not only the relativistic results of the triton binding energies for the Kharkov potential* [7] but also the Nd elastic scattering observables. Using the CDBonn potential we have investigated the Nd elastic scattering [8, 9]. Although relativistic calculations [8, 9] show only small effects for elastic scattering cross sections and practically no effect for spin observables below 150MeV, however, the effect works in the nucleon-induced deuteron breakup [10]. Beyond 150MeV the difference between relativistic and nonrelativistic property will be concretely shown by comparison between this Kharkov potential and the CDBonn potential.

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*Only the 5channel result of the Kharkov potential was already shown in [7].

Tensor correlations in α clustering studied with antisymmetrized quasi cluster model

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It has been widely known that the tensor interaction is indispensable in binding mechanism of the ^3E pn state, i.e., the deuteron. The tensor correlation, which is the coupling of the ^3D state with the dominant ^3S state caused by second order contribution of the tensor interaction to the energy, gives essential contribution to the deuteron binding. The tensor correlation in many-nucleon systems is one of the long-standing problem in nuclear physics. Thanks to recent development of *ab initio* approaches, remarkable progress has been made in study of the tensor correlation. In physics of nuclear clustering, the tensor correlation is considered to play important roles in cluster structures. Various approaches have been developing to explicitly treat the tensor correlation in cluster states [1–6]. Very recently, a new framework using imaginary centroid Gaussians has been proposed to efficiently deal with the tensor correlation in ^{4}He firstly by Itagaki *et al.* [5], and later by Myo *et al.* [6] The framework is a version of antisymmetrized quasi cluster model (AQCM), which has been developed by one of the authors (N. I.) and extended for the tensor correlation, and therefore it can be called "AQCM-T". It is also regarded a specific version of the antisymmetrized molecular dynamics (AMD) and called high-momentum AMD by Myo *et al.* [6].

In this paper, we extend the AQCM-T framework and investigate the tensor correlation in ^{4}He, which is the most important and fundamental cluster unit. We analyze internal wave functions of the correlated NN pair in ^{4}He and show that the tensor correlation is contributed by ^3D and ^3S correlations in a range relatively shorter than the typical range of an uncorrelated $(0s)^2$ NN pair. We also apply the method to ^{8}Be and study the tensor correlation in 2α cluster structure. It is found that, suppression of the tensor correlation gives significant contribution to the short-range repulsion between two α clusters, whereas kinetic energy increase contributes to the relatively long-range repulsion. Both the repulsive effects in α-α potential energy can be understood by the Pauli blocking, but come from different origins. The kinetic energy increase originates in the Pauli blocking between $0s$-orbit nucleons in an α cluster and those in the other α cluster. However, for the tensor suppression in the 2α system, the Pauli blocking between $0p$-orbit nucleons inside an α cluster and $0s$-orbit nucleons in the other α cluster is essential. The tensor correlation is characterized by the ^3D component in the correlated $T = 0$ NN pair, which involves $(0s)^{-2}(0p)^2$ excitations in the correlated α cluster. As mentioned above, the range of the ^3D component in the $T = 0$ NN pair is shorter than the range of the uncorrelated NN pair. Therefore, the $0p$-orbit nucleons are moving in an internal region of the α cluster. As a result, the tensor suppression occurs only when two α clusters are placed enough close to each other.

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Unveiling new features in nuclear properties with rare isotopes*

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Our Universe has a variety of visible matter made up with various types of nuclei that embodies nature's beauty of assembling few body systems into complex many-body objects. While much has been understood about the long-lived or stable few nucleon systems, the light neutron-proton asymmetric, short-lived nuclei, i.e. the rare isotopes, bring a wealth of new information. The presentation will outline how radioactive (RI) beams are allowing us to uncover their unknown properties and leading to revelation of unconventional forms of nuclei such as, nuclear halo and skin structures and fundamental changes of nuclear shells that break the bounds of our traditional knowledge. The discussion will show examples of how both low-energy RI beams from Isotope Separator Online (ISOL) facilities and relativistic energy in-flight RI beams offer complementary avenues that have different sensitivities to different characteristics of the exotic nuclei.

The new features in the rare isotopes challenge our understanding of the nuclear force bringing new insight. It has been a century-long challenge to understand the nuclear force between protons and neutrons forming many-body nuclei, from the fundamental basis of quantum chromodynamics (QCD). The formulation of the chiral effective field theory has paved the closest link with QCD making it possible to predict some observable properties of many-body nuclei. The presentation will show selected examples of recent achievements of how theoretical predictions relate to observations of some properties of the rare isotopes thereby unfolding information on the nuclear force.

An outlook will be presented on some future prospects at new generation radioactive ion beam facilities that will extend our reach further for accessing the heavy neutron-rich and proton-rich nuclei.

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Accurate solutions of the three-body Coulomb problem, and applications to molecular QED

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While for many years, the calculation of molecular energy levels has been performed only in the framework of the adiabatic approximation, variational methods which do not rely on this approximation have been intensively developed in the last two decades. In the simplest molecule, the three-body H_2^+ ion and its isotopes, impressive accuracies have been reached for low-lying ro-vibrational levels [1], and even high-lying states close to the first dissociation limit can be obtained with high precision [2]. Recently, the energies of all the bound states and resonances of H_2^+ supported by the ground $1s\sigma$ electronic curve have been published with an accuracy of 10^{-7} cm^{-1} [3]. Significant progress has also been achieved in the more complex case of the two-electron molecule H_2 [4].

These variational solutions of the Schrödinger equation allow for precise theoretical predictions of ro-vibrational transition frequencies by including quantum electrodynamics corrections. The current status of theory in the hydrogen molecular ions will be presented [5]. Comparison with experimental results provides a new method to measure the proton-electron mass ratio [6, 7] as well as the Rydberg constant and proton charge radius [8].

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Two-neutron correlations in ^{6}He studied with spin-flip charge-exchange transitions

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Neutron-halo structure is observed as one of the unique phenomena of neutron-rich unstable nuclei near the neutron dripline. In such low density nuclear matter, strong two-neutron correlations, the so-called dineutron correlations, are predicted [1, 2] and have attracted much interest to observe the evidence of the correlations. However, its direct measurement is difficult partly because the two neutrons do not form a bound state.

Exploring such observables that reflect the dineutron correlations is one of our interests. Here we study spin-flip charge-exchange transitions from ^{6}He to ^{6}Li and discuss the possibility to be observables that can be useful to study the dineutron correlations. We consider two types of spin-flip-change-exchange type operators, Gamow-Teller (GT) and isovector spin-monopole (IVSM), which give different sensitivity to the spatial overlap between the initial ground and the spin-flipped final states. If the ground state of ^{6}He has spatially localized two-neutron pair, these transition strengths to ^{4}He(α)+deuteron(d) states could be enhanced.

The ^{6}He and ^{6}Li states are described with α plus two-nucleon three-body model [3]. For the ground states, the three-body dynamics with Pauli constraint is fully taken into account with use of correlated Gaussian expansion with global vectors [4] (See also recent review [5]). The continuum states are also represented by a superposition of many correlated Gaussian states.

Strong IVSM transition strengths are obtained in the low-lying energy region below $\alpha + d$ threshold, whereas almost no GT strengths is found in this region due to small overlap between the ^{6}He and $\alpha + d$ wave functions. We discuss the sensitivity of the GT and IVSM transition strengths to the binding energy of ^{6}He.

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Trions in three-, two- and one-dimensional materials

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Negative (T^-) and positive (T^+) trions are formed in semiconductors when a single exciton is correlated with an additional electron in a conduction band or hole in a valence band, respectively, and produces the complexes with two identical particles: *eeh* and *ehh*. We present the results of the theoretical studies of the negatively and positively charged trions in bulk (3D materials), transition metal dichalcogenides (TMDC) monolayers (2D materials) and quantum wires (1D materials) within the framework of the effective-mass potential model. In particular, we present the influence of the confinement due to reduced dimensionality and the ratio of the effective masses of the electron and hole on the binding energy of the trions.

The binding energy of trions in various bulk semiconductors are calculated by employing Faddeev equations with the Coulomb potential in 3D configuration space. The results for the calculations of the binding energy for T^- are in reasonable agreement with experimental measurements, while the T^+ is unbound for all considered mass ratio. Thus, we show that for the same bulk semiconductors the negatively charged trions are weakly bound, while the positively charged trions are completely unbound [1]. The mechanism of the formation of the binding energy of trions is analyzed by comparing contributions of a mass-polarization term related to kinetic energy operators and a term related to the Coulomb repulsion of identical particles. Within our approach of the treatment of trions in 3D materials, the origin of a discrepancy for the binding energies of T^- and T^+ trions is analyzed.

The binding energy of trions in monolayer semiconductors are calculated by solving the 3-body problem using the method of hyperspherical harmonics in 2D configuration space by employing the Keldysh potential [2]. The Keldysh potential presents a 2D reduction of the Coulomb interaction and has the three-dimensional Coulomb tail, while for small electron-hole distances it turns into a logarithmic Coulomb potential. This potential describes the screening caused predominantly by the valence electrons that leads to a weaker Coulomb interaction between charged particles in 2D space. It is shown that T^- and T^+ trions in 2D materials are bound and the binding energy of T^+ is always greater than that of the negative trion. Our calculations for MoS_2, $MoSe_2$, $MoTe_2$, WS_2, and WSe_2 demonstrate that screening effects play an important role in the formation of bound states of trions in 2D semiconductors [3]. It should be mentioned that, firstly, the strength of electron screening in 2D TMDC semiconductors presented by the Keldysh potential and, secondly, the confinement of the *eeh* and *ehh* system due to the reduced dimensionality, lead to the existence of the bound state for T^- and T^+ trions [4].

A theory of the trion and biexciton in a quantum wire in the framework of the effective-mass model using the Born-Oppenheimer approximation is discussed. We consider the formation of trions and biexcitons under the action of both the lateral confinement and the localization potential. The binding energies are obtained using effective one-dimensional cusp-type Coulomb potentials. This potential is a result of the reduction of the Coulomb interaction in a 1D dimension. The parameters of the effective one-dimensional cusp-type Coulomb potentials between the charged particles are determined self-consistently by employing the same eigenfunctions of the confined electron and hole states. Our calculations for the core/shell cylindrically-shaped nanowires show that the trion binding energy in a quantum wire is size dependent. It is demonstrated that there is a possible formation of trions from biexcitons via the associative ionization of a biexciton to a trion and an electron.

We analyze how the confinement due to reduced dimensionality and the ratio of effective masses of the electron and hole affect trions binding energy. For completeness in our analysis, we review and discuss the calculation of the binding energy of trions obtained within a variety of approaches: the time-dependent density-matrix functional theory, the variational method, the fractional dimensional space approach, the stochastic variational method with explicitly correlated Gaussian basis, and quantum Monte Carlo methods.

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Excited Ω_cs as heavy pentaquarks*

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Very recently, the LHCb Collaboration announced the excited five heavy baryons, Ω_cs [1], of which $\Omega_c(3050)$ and $\Omega_c(3119)$ have rather narrow decay widths. Using a pion mean-field approach, also known as the chiral quark-soliton modek, we assert that these two narrow Ω_c belong to the baryon anti-decapentaplet ($\overline{\mathbf{15}}$) which consist of four light valence quarks and one charmed quark, whereas three of these Ω_cs can be classified as the members of the excited baryon sextet [2]. Interestingly, the pentaquark Ω_cs in the $\overline{\mathbf{15}}$ representation belong to the isotriplets, while the other Ω_cs are the usual isosinglets. We also show that the results of the decay widths of both the pentaquark Ω_cs and the other excited $\Omega_c s$ are in good agreement with the LHCb data [3]. In the present talk, we discuss the physical implications of these results and give future outlook.

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Electromagnetic properties of singly heavy baryons *

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In this talk, we present recent results of the electromagnetic form factors of singly heavy baryons in a mean-field approach. When a heavy-quark mass is infinitely heavy, a heavy baryon can be viewed as a bound state of $N_c - 1$ valence quarks bound by the pion mean field with the heavy quark regarded as a mere static color source. In this mean-field picture, the dynamics inside a heavy baryon is governed by the $N_c - 1$ light quarks. We first show that the electric form factors of the positively charged heavy baryons fall off much slower than that of the proton, as the momentum transfer increases. It indicates that the heavy baryon is an electically compact object. We also presents the results of the magnetic form factors in comparison with those from other works, in particular with those of lattice QCD.

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Ab initio calculations for p-shell nuclei with Daejeon16

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The ab initio theory requires a high-quality realistic inter-nucleon interaction providing an accurate description of NN scattering data and predictions for binding energies, spectra and other observables in light nuclei and selected heavier nuclear systems around closed shells. Three-nucleon forces require a significant increase of computational resources, for instance, by a factor of 30 in the case of p-shell nuclei. Therefore, it is important to develop realistic nucleon-nucleon interactions with a good convergence which requires less computational resources.

In Ref. [1], we developed a realistic nucleon-nucleon interaction, dubbed Daejeon 16, start- ing from a chiral N3LO interaction which is SRG (similarity renormalization group) evolved. Then, we apply the PET (phase-equivalent transformation) to the SRG-evolved interaction. It turned out that Daejeon 16 provides a good description of various observables in light nuclei without NNN forces, for example see Fig. 1, and also shows rapid convergence in ab initio calculations.
Daejeon is the name of a city in Korea, where RAON (Rare isotope Accelerator complex for ON-line experiments) will be located in. In this talk we will present our new results for p-shell nuclei using the ab initio no core shell

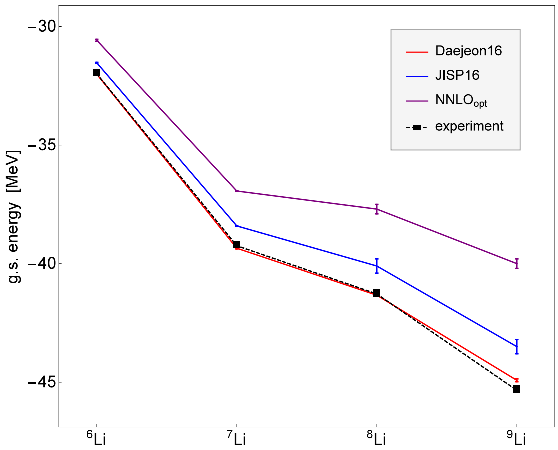

Figure 1: The ground state energies of Li isotopes with Daejeon16 and other NN interactions. The ab initio calculations were done with $N_{\max} = 18$ for ^{6}Li and with $N_{\max} = 10$ for other isotopes.

model (NCSM) with the Daejeon 16 interaction [2]. One of the interesting results is that the ab initio NCSM with Daejeon 16 clearly demonstrates the phenomenon of parity inversion in ^{11}Be, i.e., the ground state in ^{11}Be has the spin-parity $1/2^+$ in experiments contrary to the expectation from conventional shell model calculations.

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Asymmetric regularization
and
the universal character of the helium-4 spectrum*

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FB22 relevance: We apply a novel type of regulator function to the helium-4 nuclear four-body system. The regulator discriminates between partial waves of different angular momentum and spin/parity. It is devised in order to facilitate the numerical renormalization-group analysis in few-body systems and improves on the conventional regulator types which are spatially rotationally invariant. We demonstrate the usefulness of this regulator by proving through numerical calculation the consistency of the pionless effective field theory for the ground **and** excited state of the helium-4 nucleus. While this application improves our understanding of light nuclei in terms of a theory with a systematic connection to quantum chromodynamics, the regulator technique benefits few-body calculations, in general, because it avoids, amongst other hindrances, the explicit calculation of extremely short-range interactions ($\Lambda \gg Q$[breakdown]).

Details: We find the threshold structure of the two- and three-nucleon systems, with the deuteron and ^{3}H/^{3}He as the only bound nuclei, sufficient to predict a pair of four-nucleon states: a deeply bound state which is identified with the ^{4}He ground state, and a shallow, unstable state at an energy $B^*_\alpha = [0.38 \pm 0.25]$ MeV above the triton-proton threshold which is consistent with data on the first excited state of the ^{4}He. The analysis employs the framework of Pionless EFT at leading order with a generalized regulator prescription which probes renormalization-group invariance of the two states with respect to higher-order perturbations including asymmetrical disturbances of the short-distance structure of the interaction. In addition to this invariance of the bound-state spectrum and the diagonal ^{3}H-p $^1S_0$ phase shifts in the ^{4}He channel with respect to the short-distance structure of the nuclear interaction, our multi-channel calculations with a resonating-group method demonstrate the increasing sensitivity of nuclei to the neutron-proton P-wave interaction. We show that two-nucleon phase shifts, the triton channel, and three-nucleon negative-parity channels are less sensitive with respect to enhanced two-nucleon P-wave attraction than the four-nucleon ^{3}H-p $^1S_0$ phase shifts.

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Study of Three-Nucleon Dynamics in the dp breakup collisions using the WASA detector

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An experiment to investigate the ^{1}H$(d, pp)n$ breakup reaction using a deuteron beam of 300, 340, 380 and 400 MeV and the WASA detector has been performed at the Cooler Synchrotron COSY-Jülich. As a first step the data collected at the beam energy of 340 MeV are analysed, with a focus on the proton-proton coincidences registered in the Forward Detector. The results of this analysis will be presented. The studied energy region, below but close to a pion production threshold, may provide information on various aspects of nuclear interactions, in particular on relativistic effects and their interplay with the three nucleon force (3NF). The differential cross section is determined for 189 configurations on a dense angular grid defined by the emission angles of the two outgoing protons: two polar angles θ_1 and θ_2 (in the range between 5° and 15° with the step size of 2°) and the relative azimuthal angle φ_{12} (in the range from 20° to 180°, with the step size of 20°). Elastically scattered deuterons are used for precise determination of the luminosity. The main steps of the analysis, including energy calibration, particle identification (PID) and efficiency studies, and their impact on the final accuracy of the result, are discussed. The data have been compared to calculations performed by leading theory groups with the state-of-the-art 2N potentials, combined with 3NF, Coulomb interaction or carried out in a relativistic regime.

Few neutron resonances from chiral effective field theory

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A recent experimental claim of a low-lying four-neutron resonance has sparked renewed interest in the topic and several follow-up experiments are planned in the near future (or already completed). On the other hand, a large number of theoretical studies have investigated possible tetraneutron resonances with varying outcome. Therefore, the time is right for ab initio theoretical techniques to address the question of few-neutron resonances. In this talk, I present our recent quantum Monte Carlo calculations of few-neutron systems confined in external potentials based on local chiral interactions at next-to-next-to-leading order in chiral effective field theory. The energy and radial densities for these systems are calculated in different external Woods-Saxon potentials. We assume that their extrapolation to zero external-potential depth provides a quantitative estimate of three- and four-neutron resonances. The validity of this assumption is discussed in the context of an exact diagonalization in the two-body case. We find that the extrapolated trineutron resonance as well as the energy for shallow well depths is lower than the tetraneutron resonance energy. This suggests that a three-neutron resonance might exist below a four-neutron resonance in nature and is potentially measurable. To confirm that the relative ordering of three- and four-neutron states is not an artifact of the external confinement, we have tested that the odd-even staggering in the helium isotopic chain is reproduced within this approach. Finally, I discuss some ongoing work to confirm these calculations using other approaches.

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Nuclear physics around the unitarity limit*

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In the unitarity (or unitary) limit, where the two-nucleon S-wave channels have infinite scattering lengths and zero-energy bound states, only one dimensionful parameter is left and set by the triton binding energy. While the proximity of the real world to this idealized scenario has been discussed qualitatively for a long time, it has traditionally not played any special role in constructing nuclear forces.

Here it is argued that at least light nuclei may reside in a sweet spot: bound weakly enough to be insensitive to the details of the interaction, but dense enough to be insensitive to the exact values of the large two-body scattering lengths as well. In this scenario, a systematic expansion of nuclear observables around the unitarity limit converges. In particular, this scheme expands the nuclear force so that the gross features of states in the nuclear chart are determined by a very simple leading-order interaction, whereas—much like the fine structure of atomic spectra—observables are moved to their physical values by small *perturbative* corrections. Explicit evidence in favor of this conjecture is shown for the binding energies of three and four nucleons.

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Van der Waals three-body systems, potentialities for Efimov state observations

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Van der Waals molecules at ultralow energies are of a great interest in both experiment and theory. The ability to control the scattering length in ultracold gases make these systems ideal candidates for experimental study of Efimov physics [1]. After the first successful observation of Efimov states in an ultracold Cesium gas [2], a lot of the experimental evidence for the Efimov states in three-atomic systems consisting of He, Li, K, Rb, Cs atoms and its combinations were reported (see review [3]).

The properties of ultracold triatomic systems are determined by the van der Waals interaction. Analyzing interaction potentials between different species we discuss the possible existence of Efimov states in three-body systems. Some our results obtained using Faddeev calculations [4] and a short review of other calculations will be presented.

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Experimental studies of unbound neutron-rich nuclei

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Structure of atomic nuclei near the limit of stability, called drip line, has attracted much attention because several exotic strucutre such as neutron halo and neutron-neutron correlation have been found and discussed in this region. Neutron-unbound oxygen isotopes located beyond the neutron drip line are good samples of few-body systems, consisting of the sub-shell closed nucleus ^{24}O [1] and a few neutrons. Theoretically, three-body model [2] predicts the neutron-neutron correlation, called dineutron correlation, in the ground state of the unbound nucleus ^{26}O. It is thus interesting to speculate that ^{28}O might have two dineutrons or ^{24}O plus tetra neutron structure. Currently, only few experimental data is availabe for ^{25}O and ^{26}O, and the more-neutron rich isotopes ^{27}O and ^{28}O have never been observed because of experimental difficulty. The experimental study for the unbound oxygen isotopes towards ^{28}O is thus strongly desired.

The unbound oxygen isotopes are also interesting in terms of oxygen anomaly. It is experimentally known that the neutron drip line for oxygen ($Z = 8$) is located at ^{24}O ($N = 16$), while that for fluourine ($Z = 9$) extends to ^{31}F ($N = 22$), having more 6 neutrons. This sudden change of the neutron drip line is called oxygen anomaly, because the neutron drip line gradually extends with increase of atomic number Z. Theoretical study [3] suggests that three-nucleon forces play an important role in the binding of the oxygen isotopes. The experimental study of the isotopes is thus expected to give knowledge on the three nucleon forces. Change of the nuclear shell structure seen in the region around $Z = 10$-12 and $N = 20$, called island of inversion, is also important to understand the oxygen anomaly. Recent in-beam γ-ray spectroscopy [4] suggests that the island of inversion extends to ^{29}F ($Z = 9$, $N = 20$). The spectroscopy of the possible doubly magic nucleus ^{28}O ($Z = 8$, $N = 20$) is thus strongly desired to see the shell evolution along $N = 20$.

In this context, series of experiment for the unbound oxygen isotopes $^{25-28}$O has been performed at RI Beam Factory (RIBF). As a first step, invariant-mass spectroscopy of ^{25}O and ^{26}O were carried out by the SAMURAI DayOne collaboration. The unbound oxygen isotopes were produced by one-proton removal reactions from secondary beams of ^{26}F and ^{27}F on a carbon target at 201 MeV/nucleon. The decay products, ^{24}O and neutron(s), were detected in coincidence by the SAMURAI spectrometer [5], which consists of heavy ion detectors and a large neutron detector array NEBULA. It is found that the ground state of ^{26}O is barely unbound with respect to the two neutron emission by 18 keV [6]. In addition, the first 2^+ resonance has been also observed for the first time.

Second experiment for ^{28}O and ^{27}O has been carried out by the SAMURAI21 collaboration. These unbound nuclei are produced by one- and two- proton removal reaction from secondary beams of ^{29}F and ^{29}Ne at 235 and 228 MeV/nucleon, respectively. Since the study requires 3 and 4 neutron coincidence measurement, a 15 cm-thick liquid hydrogen target with proton tracking detector (MINOS) and the large neutron detector array NeuLAND were additionally installed in the SAMURAI setup to improve the luminosity and neutron detection efficiency. Results of the experiments will be presented in the talk.

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Ultracold three - body rare gas atomic clusters

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Small clusters of rare gas atoms are of a great interest in the recent years. They belong to a large class of molecules interacting via potentials of van-der-Waals type and have unique quantum properties. One of these properties is the Efimov effect [1]. This effect reflects the difference in the properties of the two-body and the three - body systems. When there are at least two subsystems of zero binding energy, the three - body system has an infinite number of weakly bound states - this is the essence of the Efimov effect. Calculations of ultracold three - body clusters require methods suitable for solving three - body bound state and scattering problems in configuration space [2]. One of the effective methods for studying three - particle systems is based on using the differential Faddeev equations in the total angular momentum representation [3].

This work is aimed at a theoretical investigation of the rare gas atomic clusters. We used a accurate methods [4], without physical approximations, suitable for solving three-dimensional Faddeev differential equations in the total angular momentum representation [3]. We developed a numerical algorithm for solving differential Faddeev equations. This algorithm has been realized in the programming language C++. The developed numerically effective computational scheme, especially in combination with an option of using multiple processors, makes it possible to calculate wide range of three - body problems. For the calculations of the spectrum of neon trimer we use finite-difference approximation and cubic polynomial splines for solving the differential Faddeev equations with the zero asymptotic boundary conditions. We have applied developed numerical algorithm for solving the above mentioned equations for the ^{20}Ne three - atomic system. The calculated results of bound states energy of the neon trimer are in a good agreement with the results obtained using different methods by other authors [5]. Investigation of the ground state energy convergence with respect to the number of grid points demonstrates that N_ρ = 250 is sufficient to get up to four accurate figures for the energy of the ground state (see Fig. 1).

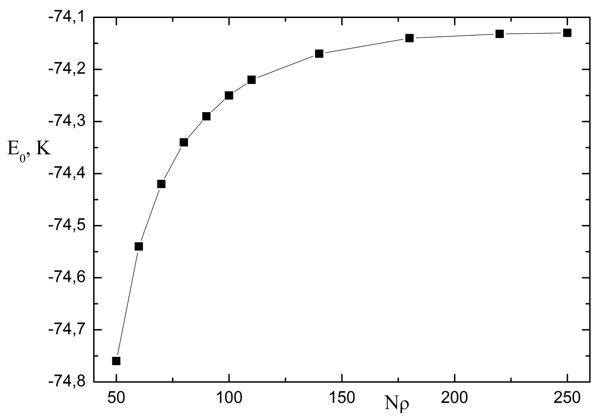

Fig. 1. Convergence of the neon trimer ground state energy on a grid points N_ρ for fixed values of $N_\theta = 100$ and $N_\chi = 10$.

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4-nucleon system dynamics in proton helium-3 scattering

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While the best available nucleon-nucleon potentials reached their mature state, being able to describe systems composed of two nucleons close to perfectly [1, 2], addition of the third nucleon spoils the situation considerably. Accounting for a new dynamical component, appearing in such systems, referred to as a three-nucleon force (3NF), greatly decreases the differences between the experiment and theoretical calculations, still leaving a lot of space for improvement. The same holds true even after recent, technically very demanding, inclusion of Coulomb force and relativistic effects [3, 4]. One still observes discrepancies in differential cross section and observables involving nucleon's polarization, which change smoothly with relevant dynamical variables. It is a general expectation that these deficiencies will increase after transition to the systems involving four nucleons. Though even more difficult, such systems offer quite new possibilities for 3NF studies (as e.g. accessibility of new izospin channels) and appearing here 4-nucleon force. Different theoretical approaches, like e.g. single-scattering approximation [5], call for measurements precise enough to validate or fine tune the models.

Answering to these expectations, we propose entering this area by performing kinematically complete measurement of proton polarized helium-3 elastic scattering and breakup. The proposed method, involving tracking of reaction products for subsequent reconstruction of the reaction vertex, should be regarded as a novel experimental approach in this low energy nuclear physics experiment. The details of a proposed experimental setup and results of the first tests of its components will be given.

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Studies of hyperon production in HADES*

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Study of the interaction and production mechanisms inside the hypermatter is one of the hot topics in the nuclear physics nowadays. The mass spectra of strange baryons are only poorly measured, although the theoretical models of hyperon structure have been already described in the mid 80s [1]. An interesting field of investigations is a production mechanism of a cascade Ξ — hadron containing two strange quarks. The production rates of Ξ^- measured in p-A [2] and A+A [3] experiments by HADES strongly overshoot model predictions [4]. In order to better understand production mechanism of the cascade close to the threshold reference measurements in proton-proton collisions are badly needed.

The HADES detector (High Acceptance DiElectron Spectrometer) [5] is a magnetic spectrometer, which allows one to measure charged hadrons (like protons, pions, kaons) and leptons (electrons, positrons) in a wide angular range. It is possible to measure proton, pion and heavy-ion collisions on various nuclear targets in the beam energy range of 1 GeV–4.5 GeV. Currently the HADES setup is being updated by adding new detectors: Electromagnetic Calorimeter (ECAL) for gamma detection and Forward Detector (FD) to cover the very forward scattering angles region. Access to the events detected at small polar angles is crucial for measurement of the cascade reaction $pp \to \Xi^- p K^+ K^+$, in which protons are emitted only in forward direction.

In the talk the upgraded HADES experimental setup and results on hyperon studied at HADES will be presented. As an outlook, plans and extensive simulations for measurements of the cascade at 4.5 GeV will be presented [6]. The simulation of cascade reaction will be discussed together with the most significant background channels. The first results of the simulation will be shown, including expected count rates and signal-to-background ratios.

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Few-Body Reactions and Processes in Neutron Star Envelopes*

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In this work, we studied the processes and reactions in the crystalline crusts of neutron star envelopes occurring under the powerful gravitational compression. The density oscillations in deep layers of the crystalline structure and the dynamics of stimulated reactions and transformations of matter were analyzed (see, for example [1-3]).

The body-centered cubic lattice with cells comprising of a few nuclei surrounded by electron Fermi liquid was considered. For each type of nuclei, there are certain critical layers in the envelopes where the chains of new reactions and processes appear. Moreover, these reactions are significantly different for even-even and odd-even or odd-odd nuclei. In particular, for the paternal even-even nuclei like ${}^{56}_{26}Fe$, the two-steps chain of successive reactions with capture electrons and emission of neutrinos leads to irreversible transformation of the nuclei: ${}^{56}_{26}Fe \to {}^{56}_{25}Mn \to {}^{56}_{24}Cr$. However, the reactions with the odd-even nuclei demonstrate some different features in the critical layer of the crystalline envelope: in the phase of cell compression, the ${}^{57}_{26}Fe$ nucleus captures a Fermi-electron and emits a neutrino: ${}^{57}_{26}Fe + e^- \to {}^{57}_{25}Mn + \nu_e$. In this case, we have the one-step reaction. Then in the expansion phase of the cell, the new nucleus ${}^{57}_{25}Mn$ can emit an electron and an anti-neutrino, transforming itself back into the iron nucleus: ${}^{57}_{25}Mn \to {}^{57}_{26}Fe + e^- + \bar{\nu}_e$. This process can repeat many times.

The phenomena are associated with the density oscillations in the critical layers of the crystalline envelope. Each type of the nuclei with the odd number of protons or neutrons takes part in direct and reverse reactions in a specific critical layer and emits neutrinos and anti-neutrinos. Such emissions contribute to the neutron star cooling. The nonlinear phenomena and the neutron resonances of a few-body type in the neutron star envelopes are also considered. There is proposed a model of the crystalline structure destruction and decomposition of nuclei into different clusters. This model has been used to study the nuclear reactions in the lower layers of the neutron star inner crust at its boundary with the mantle. Formation of overdense liquid consisting of a mixture of nuclear clusters, nucleons and an electron-muons component in this region has been considered.

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Meson-baryon Scattering in Extended-on-mass-shell Scheme at $O(p^3)$

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Abstract

The scattering processes of particles have always been one of the focus of attention. Since the fundamental theory for strong interaction, quantum chromodynamics (QCD), was proposed, people are always very curious and enthusiastic to figure out how particles interact, or in another word, scatter with each other in all energy sector. However, as is known to us all, one critical feature of QCD is its asymptotic freedom, that is, the coupling constant increases extremely fast in the wake of the decreasing of transfer momentum. This means that in the low energy sector, one cannot apply a perturbation theory to treat the scattering processes. To deal with these problem, effective field theory (EFT) is introduced as a substitute of QCD in low energy sector. Taking hadrons, i.e. pions, kaons, eta-mesons, and baryons as the degrees of freedom rather than quarks and gluons, the EFT is formulated in terms of the most general Lagrangian consistent with chiral symmetry as well as the other continuous and discrete symmetries. The corresponding field theoretical formalism is called chiral perturbation theory (ChPT).

Organized according to certain power counting rules and absorbing the divergence and other contribution into low energy constants (LECs), the ChPT allows a systematic method to improve the description about the target process. This makes the ChPT extremely advantageous. The application of ChPT on meson scattering processes turned out to be a huge success. However, since the masses of baryons at chiral limit do not vanish, the powering counting rules for baryons make the Baryon chiral perturbation theory (BChPT) a tough problem. People first proposed a non-relativistic scheme assuming infinite baryon masses, which is now called heavy baryon(HB) ChPT. Soon afterwards, a relativistic scheme called infrared (IR) method was proposed. But the analytic properties are somehow broken. The third one is the so-called Extend-on-mass-shell(EOMS) scheme. In the last few years, the EOMS scheme has been applied to solve many problems such as baryon magnet [1], baryon sigma terms [2] and so on. Compared to the former two schemes, EOMS scheme seems to converge faster and has fewer LECs at certain order.

In the meson baryon scattering, the EOMS scheme seems to be rather popular. In SU(2) cases, pi-N scattering was calculated up to $O(p^4)$ by Deliang Yao et.al [3]. In this work, we try to extend the calculation to SU(3) up to $O(p^3)$. Combining the recent scattering data of Kaons and nucleons, we try to fit the LECs in the theory. We investigated the convergence and try to include the contribution from $\Delta(1232)$ and resonances like $\Lambda(1405)$.

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Reaction mechanisms in deuteron-proton elastic scattering at intermediate energies.

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We study deuteron- proton elastic scattering in the deuteron energy range between 500 MeV and 1.5 GeV. Nowadays, a significant amount of the experimental data at these energies has been accumulated both with unpolarized and polarized beams. However, a description of the data faces problems because of well developed Faddeev calculation technique cannot be applied at these energies.

In this report we consider deuteron- proton elastic scattering in the relativistic multiple scattering expansion framework [1],[2], and [3]. We start from the AGS-equations and iterate them up to a second-order of the nucleon-nucleon interaction. The four reaction mechanisms are included into consideration: one-nucleon exchange, single scattering, double scattering, and the term corresponding to the delta excitation in the intermediate state.

This model was applied for a description of the experimental data both on the differential cross section and polarization observables in a whole angular range. It is shown that inclusion of the double scattering and delta excitation terms into consideration significantly improves the agreement between the experimental data and theoretical predictions at the scattering angles larger than 60^0.

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Strangeness instability in asymmetric nuclear matter

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The proposal that multistrange clusters could be a metastable or even an absolutely stable state at finite chemical potential and zero temperature has stimulated substantial activity. By considering a fluctuation of the strangeness concentration of strongly interacting matter, we study a finite density phase transition characterized by pure hadronic matter with both mechanical instability (fluctuations on the baryon density) that by chemical-diffusive instability (fluctuations on the strangeness concentration). The main goal is to investigate how the constraints on the global conservation of the baryon number, electric charge fraction in the presence of Delta-isobar degrees of freedom, hyperons, and strange mesons, influence the behavior of the equation of state in a regime of finite values of baryon density. It turns out that in this situation hadronic phases with different values of strangeness content may coexist, with several implications in hypernuclear physics.

Recent developments in solving a few-particle scattering problem by the solution of Faddeev-Yakubovsky equations

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Rigorous solution of the few-particle scattering problem turns to be an extraordinary task both from the formal (theoretical) as well as from the computational points of view. In early 60's Faddeev formulated the t-matrix approach [1], providing a mathematically rigorous description of the three-particle scattering problems governed by short-ranged interactions. Just a few years later Faddeev's revolutionary work has been generalized to any number of particles by Yakubovsky [2]. Regardless these revolutionary mathematical developments progress in solution of Faddeev-Yakubovsky equations (FYe) is slow and for long years was limited to A=3 and 4 cases [3, 4].

In this presentation a short overview of the FYe formalism will be provided, summarizing major assets and shortcomings of this approach. Progress in solving few-particle problem based on solution of the FYe will be discussed. The first numerical solution of the 5-body FYe will be presented [5]. These equations will be solved to describe neutron elastic scattering on ^{4}He as well as trying to identify the resonant states of ^{5}H nucleus. Realistic nuclear Hamiltonians will be employed in describing these five-nucleon systems.

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Analysis of 72-82Se within the framework of the IBM and the Few-body aspects*

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An analysis of 72-82Se within the framework of the interacting boson model (IBM) [1] and the Few-body aspects [2] are presented. Selenium with mass number (A) ranging from 72 to 82 are typical vibrational nuclei [3] that can be explained by the U(5) limit [4] of the IBM. However, they are not fully symmetrical nuclei, and are represented by adding a perturbed term to account for the symmetry breaking. These nuclei tend to exhibit properties of a harmonic oscillator and an asymmetric deformed rotor. The low-energy level and B(E2) ratios are calculated using the IBM via direct diagonalization of the perturbed Hamiltonian and the E(5) symmetry breaking. Comparisons between the theoretical and experimental results of the even-even Selenium isotopes with A ranging from 72 to 82 are presented.

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Photodisintegration of Beryllium-9 in Cluster Effective Field Theory

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In extreme stellar conditions of temperature and density such as in supernovae, the α-α-n process, could be the main source of carbon generation. However it is very difficult to study such a reaction, since it is a three-body process involving a two-body resonance. Therefore in experiments the inverse reaction, namely the ^{9}Be photodisintegration is studied using photons generated by various methods, ranging from bremsstrahlung to inverse-Compton scattering of free-electron-laser.
From the theoretical point of view there have been calculations of such a reaction within cluster models, using purely phenomenological potentials. The objective of this research is instead the study of ^{9}Be photodisintegration using EFT potentials, interactions with a more solid theoretical background.
We have derived the $\alpha\alpha$ and αn interactions in an effective field theory for halo-like systems [1, 2]. For the calculation of the ^{9}Be ground state we use a non symmetrized hyperspherical harmonics (NSHH) approach [3] in momentum space, since the halo-EFT potentials are defined in momentum space. It is planned to compute the E1 photodisintegration of ^{9}Be using the Lorentz integral transform method [4] which reduces the continuum-state calculation to a more manageable bound-state like calculation.

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Hyperspherical Harmonics Method with Particle Excitation Degrees of Freedom

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We introduce a few extensions to the Hyperspherical Harmonics (HH) approach in order to include the intrinsic excitations of the particle degrees of freedom. To this end we adapt the HH expansion method, usually built up starting from the mass-weighted set of Jacobi coordinates, to the more general case where an arbitrary weighted set of coordinates is adopted.
The main application is the possibility to use interaction models that include particle excitations, as is the case for most hypernuclear interactions. In fact, for example, almost all the available ΛN interaction models are based on the explicit $\Lambda - \Sigma$ coupling. Moreover in the $S = -2$ sector additional channels open up, including ΛΛ, ΛΣ, ΣΣ and NΞ degrees of freedom.
In line with our recent introduction of the HH method in the hypernuclear $S = -1$ sector [1] and in view of a future application in the $S = -2$ sector, we describe in a general form the extensions and the transformations needed in order to treat multiple particle excitations.
As an application, separation energies of 3- and 4-body Λ-hypernuclei with a realistic $\Lambda - \Sigma$ coupling hyperon-nucleon interaction are calculated and benchmarked with results from the literature [2]. An other application is the calculation of the triton binding energy and wave function, by considering the explicit Δ(1232) isobar degrees of freedom and including all the NN, NΔ and ΔΔ 2-body channels. In this last case we adopt the Argonne v28 potential [3].

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Transition exponent and condensate fluctuation of mesoscopic Bose-Einstein condensate in anharmonic trap

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We define the transition exponent for mesoscopic Bose-Einstein condensate and present our numerical results for finite sized system. We observe that a single critical exponent can be obtained for large particle limit and the universal behaviour in the thermodynamic quantities are noted near the transition temperature when the particles are confined in a harmonic trap. However, for the anharmonic trap we notice the absence of the universality behaviour in the thermodynamic quantity so we fail to define a unique critical exponent. We also report several condensate fluctuation measures in the anharmonic trap. We conclude that anharmonicity not only favours the BEC, as critical temperature increases, but also it enhances the probability of phase transition in strong anharmonic trap. The sharp change in various fluctuations near the critical temperature supports our conclusion.

Building Single Molecules - collisions and reactions of two atoms

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I will present our work to create single molecules. We started by tweezing and merging single cesium and sodium atoms into a single dipole trap. We studied their collisions and reactions at the ultracold regime. We built a molecule out of two atoms by photoassociation [1]. And currently, we have tamed the individual atoms with full quantum control [2, 3] and are learning to create many single molecules coherently for quantum simulation, quantum information processing, and ultracold chemistry with precise initial reactant preparation.

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Few-Body Methods and Results for Hadrons In-Medium*

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The variation behavior of hadron properties in strong interaction matter (SIM) plays an essential role in investigating the evolution of early universe SIM (QCD phase transitions). Since the formation and evolution of hadrons and the phase transitions are definitely non-perturbative phenomena, one must take the non-perturbative QCD which involves not only the dynamical chiral symmetry breaking (DCSB) and its restoration but also the confinement–deconfinement aspects simultaneously as the tool to carry out the study. It has been known that the Dyson-Schwinger (DS) equations of QCD [1] are "almost uniquely, the one approximation scheme" with the two characteristics [2], we then investigate the variation behaviors of some hadrons' properties in the matter via the DS equation approach of QCD.

With the scheme combining the DS equation with the four-dimensional covariant Bethe-Salpeter (BS) equation [3], we have obtained the variation behaviors of the mass and the decay constant of pion with respect to the interaction strength [4]. It provides an intuitive view for that the DCSB is generated by the strong interaction. With the scheme being extended to finite temperature (T), we show that the screening masses of the chiral partner mesons $\pi-\sigma$, $\rho-a_1$ get degenerate at high T. It indicates that the chiral symmetry will get restored at high T [5]. By extending the BS equation to Faddeev equation, we calculate the T-dependence of the screening masses (m_{sc}) and the "di-quark" components of nucleon and Δ-isobars and show that the m_{sc}s of both the nucleon and the Δ-isobars increase with the increasing of T. Considering the relation between the m_{sc} and the screening radius (r_{sc}), we know that the deconfinement phase transition happens at high T (as r_{sc} is smaller than the matter distribution radius).

By combining the DS equation with the Roy equation of π–π scattering, we obtain that the masses and widths of the σ and ρ mesons at $T = 0$ are $m_{\sigma,0} = 427\,\text{MeV}$, $\Gamma_{\sigma,0} = 624\,\text{MeV}$, $m_{\rho,0} = 770\,\text{MeV}$ and $\Gamma_{\rho,0} = 134\,\text{MeV}$, agree with experimental data very well. As the T increases, the masses of the mesons decrease at low T and turn to increase after reaching their respective minimum. At $T \approx 183\,\text{MeV}$, $M_\sigma = M_\rho = 2M_\pi = 4M_q$, It manifests that the mesons get melted to quarks, i.e., deconfinement phase transition takes place at $T \approx 183\,\text{MeV}$. Meanwhile, as T increases, the width of σ meson decreases but that of ρ meson get enlarged. Furthermore we obtain the temperature and momentum dependence of the π meson as illustrated in Fig. 1, with which one can get the T dependence of the shear and bulk viscosities of the QCD matter [6].

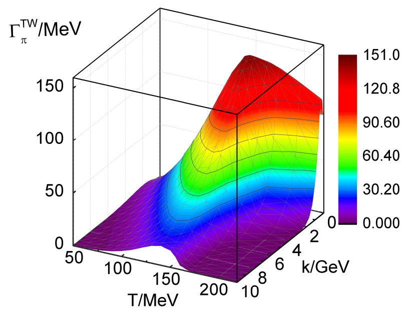

Figure 1: Momentum and temperature dependence of the pion thermal width (taken from Ref. [6]).

In short, we have given some properties of hadrons in SIM and shown that investigating hadron properties in SIM can provide information for not only the chiral phase transition but also the confinement–deconfinement one, and in turn, few-body method is of essential in studying the properties of SIM and QCD phase transitions.

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Probing the Standard Model with beta-decay experiments

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Precision measurements in nuclear beta decays provide sensitive tools to test the foundations and symmetries of the standard electroweak model and to search for exotic couplings presently excluded by the V-A theory in processes involving the lightest quarks [1]. The main aim of such measurements is to highlight deviations from the standard model predictions as possible indications of new physics. The sensitive parameters are often deduced from correlation studies between the very few bodies involved in the decay. This requires to perform very precise measurements using advanced technical methods, such as ion or atom traps installed on-line in radioactive nuclei production facilities. Data analysis also requires to generate the most realistic simulations, for which computing on GPU's may be unavoidable to take several processes into account at each incremented step. This enables to consider the relevant parameters of the experimental setup and their systematic effects on the measured quantities. Final state interaction involving the electron cloud, such as the shakeoff ionization process, can also play a significant role. The LPCTrap setup, installed at GANIL, comprises a recoil ion spectrometer which enables to address the study of this process. The decays of very light nuclei with only one or two electrons enable to test basic hypothesis of atomic models. More subtle dynamics must be considered when many electrons contribute to the global ionization yield. In the latter case, both Auger emission and e^- - e^- interactions have to be accounted for, which requires to develop more elaborate models. The study of $^{6}He^{1+}$, $^{19}Ne^{1+}$ and $^{35}Ar^{1+}$ decays has highlighted different behaviors [2,3], which invites to perform new experiments.

All these aspects will be discussed at the conference.

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The origin of the nucleon mass*

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It is often claimed that 98% of the nucleon mass is generated by quantum chromodynamics. The decomposition of the nucleon mass based on the trace of the energy-momentum tensor suggests that gluons play by far a dominant role [1]. About 25 years ago, Ji proposed another decomposition based on the energy component of the energy-momentum tensor, leading to a quite different picture [2].

Recently, we critically revisited these decompositions and argued that both overlooked pressure effects [3]. In particular we showed that Ji's decomposition, although mathematically correct, makes little sense from a physical point of view. We identify the proper mass decomposition along with a balance equation for the pressure forces.

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GW170817: constraining the nuclear matter equation of state

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The Physics of dense matter relevant to neutron stars (NSs) are poorly understood till date. Due to lack of detailed knowledge of the nuclear interaction at supra-normal densities, many theoretical model have been proposed. Inputs from astrophysical observations are crucial to constrain the nuclear interactions. Recent observation of GW170817 [1] opens a new window in the field of astronomy and astrophysics. In this present work, the constraints set on key parameters of the nuclear matter equation of state (EOS) by the values of the tidal deformability, inferred from GW170817, are examined by using a diverse set of Relativistic Mean Field (RMF) models and of Skyrme-Hartree-Fock (SHF) models [2]. The dimensionless tidal deformability parameter $'\Lambda'$ is found to be weakly or only moderately correlated with the individual key parameters of the EOS but it shows a strong correlation with specific linear combinations of the isoscalar and isovector key parameters of the EOS. In Fig. 1 we have plotted Λ for a $1.4\,M_\odot$ NS as a

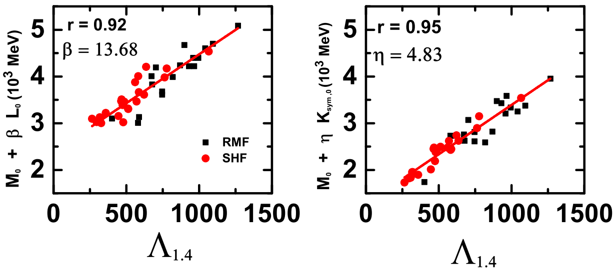

Figure 1

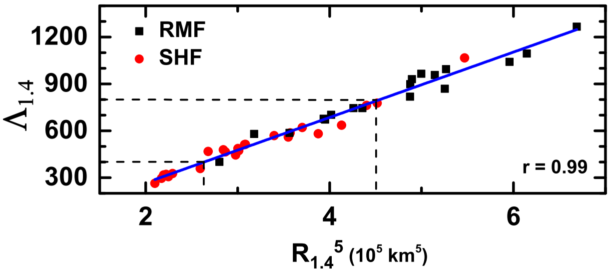

Figure 2

function of $M_0 + \beta L_0$ and $M_0 + \eta K_{sym,0}$. Where, M_0 is the slope of nuclear incompressibility. The L_0 and $K_{sym,0}$ are the slope and the curvature of the symmetry energy, respectively. The values of β and η are obtained to yield maximum correlations. Using those correlations and employing the bounds on $L_0 = 58.7 \pm 28.1$ MeV [3] and $\Lambda < 800$ (90% confidence) [1], the values of M_0 and $K_{sym,0}$ are in the range of 1972 to 2878 MeV and -141.0 to 19.78 MeV, respectively. Fig. 2 displays the variation of $\Lambda_{1.4}$ with NS radius $R_{1.4}^5$ corresponding to the canonical $1.4M_\odot$ NS. We find that $\Lambda_{1.4}$ is strongly correlated with $R_{1.4}^5$ with the Pearson correlation coefficient $r = 0.99$. The dimensionless tidal deformability, obtained within 90% (50%) confidence for GW170817, sets the radius of a canonical $1.4M_\odot$ neutron star to be $\lesssim$13.5(12.2) km [4]. These values of $R_{1.4}$ are in harmony with recent studies [5].

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Experimental analysis of few-body physics

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Recently the three-nucleon force effects (3NF) are considered to play an essential role not only in the few-nucleon systems but also in the exotic and heavier systems like neutron-rich nuclei and neutron stars. The main component of 3NF is considered to be a 2 pion-exchange between three nucleons with a Δ isobar excitation as an intermediate state. And now there are several 3NF models which have additional components. The ab-initio study of these 3NF models have been carried out via the three-nucleon bound states or scattering states basically. In these studies, the nucleon-deuteron (*Nd*) reactions have been playing important roles because they can provide various observables like spin- or energy- dependencies and they allowed us to reveal the detail features of 3NF from the comparisons between Faddeev calculations and highly precise data.

One of the remarkable studies is that the differential cross sections of the proton-deuteron elastic scattering are well reproduced by the introduction of 2 pion-exchange type 3NF at the intermediate energy regions. On the other hand, there are many observables which can not be explained by the Faddeev calculations including the 3NF, for instance, some spin observables and cross sections at higher than 200 MeV/A. These results indicate the lack of some components in modern 3NF models. To investigate the origin of these disagreements, proton-deuteron breakup reactions in some kinematical configurations and the elastic reactions in the higher energy regions have been measured recently.

On the other hand, the effects of isospin T=3/2 components of 3NF are considered to be key elements in the study of neutron-rich nuclei or neutron stars, nevertheless these effects could not be investigated via the *Nd* scattering. New researches through four-nucleon systems or 3n systems are just in the process to be carried out from both theoretical and experimental sides.

The recent states of experimental studies will be introduced in this talk.

Three two-species fermions with contact interactions.

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Properties of two identical particles of mass m and a distinct particle of mass m_1 in the universal low-energy limit of zero-range two-body interaction are studied. It is shown that for unambiguous formulation of the problem an additional parameter b, which determines the wave function near the triple-collision point, should be introduced for the mass ratio $\mu_r(L^P) < m/m_1 \le \mu_c(L^P)$ in the sectors of odd angular momentum L and odd parity P if the identical particles are fermions and in the sectors of even L and even parity if the identical particles are bosons. The critical values $\mu_r(L^P)$ and $\mu_c(L^P)$ are determined, in particular, $\mu_r(1^-) \approx 8.619$, $\mu_c(1^-) \approx 13.607$, $\mu_r(2^+) \approx 32.948$, and $\mu_c(2^+) \approx 38.630$. Within the framework of this formulation, dependence of the three-body bound-state energies on m/m_1 and b is calculated for $L \le 5$. A number of the three-body bound states is determined and presented in the form of "phase diagrams" in the plane of two parameters m/m_1 and b. To elucidate a role of the parameter b its correspondence to the three-body potentials is discussed. In addition, the three-body spectrum in a harmonic trap is considered.

Momentum Distributions and Short-Range Correlations in ^{3}He with Chiral Potentials

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We present a study of one- and two-nucleon momentum distributions and short-range correlations probabilities in ^{3}He, performed using a variety of modern potential models, ranging from the phenomenological Argonne v_{18} [1] and the meson-theoretic CD-Bonn [2] two-nucleon potentials, augmented or not by the Urbana IX [3] and Tucson-Merlbourne [4] three-nucleon interactions, respectively, to the most recent high-precision two-nucleon chiral potentials up to fifth order [5], again augmented or not by the leading three-nucleon force [6]. Within the chiral effective field theory approach, by studying both cutoff dependence and chiral order convergence, we will be able to estimate the theoretical uncertainty of our predictions. The relevance of our study for short-range correlation probabilities extracted from analyses of inclusive electron-scattering will be also addressed.

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Components of polarization-transfer to a bound proton in a deuteron measured by quasi-elastic scattering

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I will report measurements of the transverse (P_x and P_y) and longitudinal (P_z) components of the polarization transfer to a bound proton in the deuteron via the $^2H(\vec{e},e'\vec{p})$ reaction, over a wide range of missing momentum. The measurements were done at the Mainz Microtron (MAMI). A precise determination of the electron beam polarization reduces the systematic uncertainties on the individual components, to a level that enables a detailed comparison to a state-of-the-art calculation of the deuteron that uses free-proton electromagnetic form factors. We observe very good agreement between the measured and the calculated P_x/P_z ratios, but deviations of the individual components. Our results cannot be explained by medium modified electromagnetic form factors. They point to an incomplete description of the nuclear reaction mechanism in the calculation.

Key references for the work are [1] and [2].

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Single-State HORSE method for description of resonant states within the nuclear Shell Model

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We present a Single-State HORSE method [1, 2, 3] allowing us to obtain low-energy scattering phase shifts and resonance energy and width within the nuclear shell model. The Single-State HORSE technique is based on the general properties of the oscillator basis and on the HORSE (J-matrix) formalism in scattering theory; it utilizes general low-energy expansions of the S matrix including the poles associated with bound and resonant states.

We extended the Single-State HORSE method to the case of reactions involving charged particles [4]. The approach used here relies on the HORSE method generalization to the case of Coulomb scattering [5] and on the parametrization of the phase shifts in the low-energy region based on the analytic properties of Coulomb-modified partial-wave scattering amplitudes. This makes it possible to describe correctly the behavior of the phase shifts not only in the resonance region but also at energies tending to zero.

The Single-State HORSE approach is carefully verified using a model two-body problem with a Woods-Saxon type potential and is shown to be able to obtain accurate scattering phase shifts and resonance energy and width even with small oscillator bases.

Next the Single-State HORSE method is successfully applied to the study of the $n\alpha$ and $p\alpha$ scattering phase shifts and resonances based on the NCSM calculations of ^{5}He, ^{5}Li and ^{4}He nuclei with the realistic JISP16 and Daejeon16 NN interactions. Both JISP16 and Daejeon16 provide a good description of the $3/2^-$ and $1/2^-$ resonances in ^{5}He and ^{5}Li nuclei as well as of the $1/2^+$ non-resonant $n\alpha$ and $p\alpha$ phase shifts.

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Nucleon polarizabilities

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The scalar and spin electromagnetic polarisabilities of the proton and neutron are still not particularly well determined by Compton scattering experiments, with uncertainties ranging from somewhat less that 10% to over 100%. In the absence of free neutron targets, neutron properties must be extracted from light nuclei, particularly the deuteron and ^{3}He, but that requires a good understanding of the contribution of nuclear effects and two-body currents which substantially modify the cross sections.

Chiral effective field theory provides a unified framework for the analysis of the low-energy properties of both nucleons and light nuclei. World Compton scattering data has been used to give good constraints on the proton scalar polarisabilities α and β [1], with progress also being made on the spin polarisabilities [2] and prospects from a new generation of polarised scattering experiments [3, 4]. Progress is also being made on the theoretical and experimental front for Compton scattering from light nuclei [5, 6] and experiments are planned at both MAMI and HIγS. In this talk I will review progress in the field, and talk about future plans.

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Low-dimensional few-body processes in confined geometry of atomic and hybrid atom-ion traps *

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Impressive progress of the physics of ultracold quantum gases has stimulated the necessity of detailed and comprehensive investigations of collisional processes in the confined geometry of atomic and ionic traps. The traditional free-space scattering theory is no longer valid here and the development of the low-dimensional few-body theory including the influence of the confinement is needed. In our works we have developed quantitative models [1-4] for pair collisions in tight atomic waveguides and have found several novel effects in its application: the confinement-induced resonances (CIRs) in multimode regimes including effects of transverse excitations and deexcitations [2], the so-called dual CIR yielding a complete suppression of quantum scattering [1], and resonant molecule formation with a transferred energy to center-of-mass excitation while forming molecules [5]. Last effect was confirmed experimentally in [6]. Our calculations have also been used for planning and interpretation of the Innsbruck experiment where CIRs in ultracold Cs gas were observed [7]. Mention also the calculation of the Feshbach resonance shifts and widths induced by atomic waveguides [8]. In the frame of our approach we have predicted dipolar CIRs [9] which may pave the way for the experimental realization of, e.g., Tonks-Girardeau-like or super-Tonks-Girardeau-like phases in effective one-dimensional dipolar gases.

Recently, we have predicted the atom-ion CIRs [10] which are important for a hot problem of control the confined hybrid atom-ion systems having many promising applications [11]. We plan to present our new results, particulary, a calculation of the ion micromotion effect in the hybrid atom-ion systems [10,11], and to discuss perspectives in other low-dimensional few-body systems.

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A new *ab initio* approach for nuclear reactions based on the symmetry-adapted no-core shell model

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In this presentation, I will discuss a new *ab initio* approach for nuclear reactions that takes adavantage of the SU(3) symmetry and its relevance dynamics combined with the resonating group method that has been successfully applied to ab initio reactions of light nuclei [1, 2]. Indeed reaction theory with exact and approximate symmetries and their related group theoretical apparatus opens access to *ab initio* studies of reactions involving heavier and more exotic nuclei. With such an approach, we aim to describe nuclear reactions of astrophysical interest up to medium-mass region. In this model, the nuclear structure of the target and projectile is calculated by using a realistic nucleon-nucleon interaction and is based on the *ab initio* symmetry-adapted no-core shell model (SA-NCSM) [3, 4] which has provided results of energy and electromagnetic transition up through mass $A = 48$ and enables the description of spatially enhanced nuclear configurations. I will present the formalism that involves the expression of the norm and Hamiltonian kernels in the SU(3) symmetry-adapted basis, in addition to preliminary results for the n-α scattering reaction.

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Parton distribution amplitudes: revealing diquarks in the proton and Roper resonance

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Unravelling the structure of hadrons in terms of quarks and gluons remains today one of the main goal of hadron physics. Usually thought to be composed of few valence quarks, hadrons are actually much more complicated due to quantum field theory effects of pair creation and annihilation. The non-conservation of particle number can be partly overcome by working on the light front. There, hadrons can be expanded on a Fock basis, with state and wave functions of a given number of particles in momentum space. Were it necessary to use the complete set of Fock state to get an appropriate description of physical phenomenon, then hardly any connection could be made between experiment and theory. Fortunately, it is possible to connect some exclusive processes with to the hadron leading twist Parton Distribution Amplitude (PDA) thanks to collinear factorisation. Such PDA are obtained from the wave function of the lowest state of the Fock expansion, integrating out the transverse momentum degrees of freedom.

In this talk, I will describe our recent work [1] on the nucleon and Roper resonance PDA. We developed an algebraic model based on the numerical results obtained by solving the Faddeev equation. The latter show that diquark correlations play an significant role in the baryon structure. Assuming the formations of such diquark correlations, we computed the PDAs and compared their first moments with the available lattice data. I will also discuss the possibilities to compute the Nucleon Dirac Form Factors at large momentum transfer with our new PDA model.

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Description of scattering reactions of deuteron projectiles using the Gamow Shell Model with the Resonating Group Method

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The Gamow Shell Model (GSM) has been developed for several years to describe the nuclear structure of drip-line nuclei [1, 2]. Based on the use of the Berggren one-body basis, containing bound, resonant and scattering states, it comprises both continuum coupling at basis level and inter-nucleon correlations via configuration mixing. Initially devised to describe binding energies of weakly bound and resonant nuclei, it has been recently extended to a reaction framework using the Resonating Group Method (GSM-RGM) [3]. By combining the Berggren basis formalism with coupled-channel equations, it has been possible to calculate scattering and radiative capture cross sections of experimental and astrophysical interest [4, 5, 6]. Applications firstly considered a nucleon projectile, so that it would be useful to be able to treat cluster projectiles, so that one can study transfer reactions. GSM-RGM has thus been extended to the use of many-nucleon projectiles. Introductory calculations have been effected considering the ^{40}Ca(d,p) [7] and ^{4}He(d,d) reactions. The ^{6}Li nucleus has indeed only unbound excited states, so that continuum coupling is prominent therein. Future applications of experimental and astrophysical interest will also be discussed.

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Electron scattering experiments on light systems

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Electron-induced nuclear reactions on light nuclei are a subject of considerable interest, because they offer a perfect playground for testing and validating our description of nuclear structure and forces, as well as involved reaction mechanisms. The advances in the experimental techniques, allowing experiments with polarised beams and polarised targets, have given us a chance to complement the traditional cross-section measurements with the high-precision asymmetry measurements and investigate the properties of the nuclei that depend on the polarisation degrees of freedom. At the heart of this research are double-polarised quasi-elastic nucleon-knockout experiments on ^{2}H, ^{3}He and ^{12}C done in Mainz and at Jefferson Lab. In this presentation I will discuss new insights into the structure of ^{3}He gained by investigating reactions $^3\vec{\mathrm{He}}(\vec{e},e'd)$ and $^3\vec{\mathrm{He}}(\vec{e},e'p)$ in Hall A. Intriguing new results from measuring polarisation transfer ratios in $^2\mathrm{H}(\vec{e},e'\vec{p})$ and $^{12}\mathrm{C}(\vec{e},e'\vec{p})$ processes at the A1-Collaboration will be presented as well. These findings provide essential new input to the available few-body theories. However, they affect also experiments seeking to extract neutron information by utilising ^{3}He as an effective neutron target, as well as determinations of the neutrino properties with the ^{12}C based detectors.

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Kaonic Deuterium precision measurement at DAFNE: the SIDDHARTA-2 experiment.

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The SIDDHARTA-2 Collaboration aims to perform the first precision measurement of the X rays for the kaonic deuterium exotic atom transitions from the 2p to 1s level at the DAFNE Collider of the LNF-INFN. The 1s level of the kaonic deuterium is affected by the presence of the strong interaction , which shifts and broadens this level, with respect to the values defined by only the electromagnetic interaction.

The planned SIDDHARTA-2 measurement combined with the most precise measurement to date of the 2p->1s transition in kaonic hydrogen performed by SIDDHARTA in 2009 [1,2], will allow to extract of the isospin-dependent antikaon-nucleon scattering lengths, which are fundamental inputs for understanding the low-energy QCD theory in the strangeness sector, having a strong impact in particle and nuclear physics, as well as in astrophysics (equation of state for neutron stars).

In the presentation an overview of the SIDDHARTA-2 experiment, of the the scientific case, and of the future plans will be given.

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Construction of a local $\bar{K}N$-$\pi\Sigma$-$\pi\Lambda$ potential and composition of the $\Lambda(1405)$

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Few-body systems of an antikaon ($\bar{K}$) with nuclei are actively studied theoretically, as well as experimentally. For a quantitative discussion of such systems, it is necessary to prepare a reliable two-body meson-baryon interaction potential, to be combined with realistic nuclear forces and rigorous few-body techniques. Recently, a realistic single-channel $\bar{K}N$ potential is constructed [1], which equivalently reproduces the scattering amplitude of chiral SU(3) dynamics, constrained by the existing experimental data of the $\bar{K}N$ system [2, 3]. This potential is applied to study the kaonic nuclei up to seven-body systems [4], and to the accurate three-body calculation of the kaonic deuterium within eV accuracy [5]. While the single-channel $\bar{K}N$ potential is applicable in the $\bar{K}N$ threshold energy region, explicit treatment of the lower energy $\pi\Sigma$ and $\pi\Lambda$ channels can be important in few-body systems, in particular in the energy region near the $\pi\Sigma$ threshold.

In this talk, we present a $\bar{K}N$-$\pi\Sigma$-$\pi\Lambda$ coupled-channels potential, constructed on the basis of chiral SU(3) dynamics [6]. Several matching conditions are introduced to formulate an equivalent local potential that reproduces the coupled-channels scattering amplitudes resulting from chiral $\mathrm{SU}(3)_L\times\mathrm{SU}(3)_R$ meson-baryon effective field theory [2, 3]. In contrast to a previously constructed effective single-channel $\bar{K}N$ potential [1], the explicit treatment of the $\pi\Sigma$ channel yields a natural description of the low-mass pole as part of the two-poles structure of the $\Lambda(1405)$ resonance. The energy dependence of the potential can now be parametrized with a minimum of polynomial orders. To study the properties of the $\Lambda(1405)$ as a quantum-mechanical quasibound state, we derive the normalization condition of its wave function generated by the energy-dependent coupled-channels potential, using the Feshbach projection method. This framework provides an improved understanding of this system from the viewpoint of the compositeness of hadrons. With the properly normalized wave function, we demonstrate and confirm that the high-mass pole of the $\Lambda(1405)$ is dominated by the $\bar{K}N$ component.

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Performance of the FOREST/BLC spectrometer for study of the η-nucleon interaction via $\gamma d \to p\eta n$ reaction

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To investigate the nature of a baryon resonance which couple to a pair of a meson and a baryon, the study of a scattering process of the pair is useful. The $N(1535)$ is an excited nucleon (N) with negative parity and known to strongly couple to the η meson and nucleon. Although the ηN interaction is known to be attractive, the scattering length $a_{\eta N}$ and effective range $r_{\eta N}$ have large uncertainty. These parameters characterize the ηN interaction at low energies, therefore they can help us to accurately determine the pole position of $N(1535)$, which is an S-wave resonance near the ηN threshold [1]. Furthermore, the existence of exotic η-mesic nuclei depends on these values [2].

A new experiment of the η photoproduction reaction on the deuteron ($\gamma d \to p\eta n$) using energy-tagged photon beam is conducted at the Research Center for Electron Photon Science (ELPH), Tohoku University. This reaction includes ηn rescattering process and low-energy η can be produced when $E_\gamma \sim 0.94$ GeV, which is covered by the energy range of the ELPH photon beam. Two photons from η decay are measured by the 4π electro-magnetic calorimeter FOREST and the emitted proton is measured at 0°, where ηp or pn final-state interactions are suppressed due to their large relative momenta [3]. Hence ηn scattering contribution is expected to be enhanced.

To detect forward protons, a new magnetic spectrometer BLC was installed and the commissioning of data-taking was conducted. The maximum incident energy of the photon beam was 1.3 GeV. Charged particles emitted at 0° were detected and tracked. We will present the current status of the commissioning. Particle identification and resolving powers of the spectrometer will be also discussed.

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Three-nucleon force studies in $\vec{p} - d$ break-up reaction with BINA at 190 MeV

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The present knowledge of nuclear forces is not enough to describe exprimental data for systems which consist of more than two nucleons. Recent three-nucleon scattering experiments [1] have shown that the theoretical models based solely on nucleon-nucleon potentials fail to describe most of experimental results. A comprehensive study of three-nucleon force effects has been carried out at KVI in Groningen at various beam energies. In this paper, we present data of the $\vec{p} + d \longrightarrow p + p + n$ break-up reaction that were obtained using a 190 MeV polarized-proton beam impinging on a liquid deuterium target. The experiment was performed by exploiting BINA (**B**ig **I**nstrument for **N**uclear-polarization **A**nalysis), a detector system with a large angular acceptance and a high energy resolution. We present high-precision results of selected kinematical configurations and compare them with state-of-the-art Faddeev calculations with and without three-nucleon forces, the Coulomb force and relativistic effects. The comparison of these models with our data reveal discrepancies which point to deficiencies in the present description of three-nucleon potentials. Our results provide, therefore, an extensive database that will help to further investigate the structure of many-body forces.

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Conformality Lost in Efimov Physics*

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A general mechanism for the loss of conformal invariance is the merger of infrared and ultraviolet fixed points of an appropriate renormalization group flow and their disappearance into the complex plane [1]. In this talk, I will use the renormalization group perspective to discuss how the loss of conformal invariance occurs in the case of identical bosons at unitarity as the spatial dimension d is varied [2]. It is known that there are two critical dimensions $d_1 = 2.30$ and $d_2 = 3.76$ in the case of identical bosons at which there is loss of conformality as evidenced by Efimov effect in the three-body sector. For $d < d_1$ and $d > d_2$, the beta function of an appropriate three-body coupling constant has real roots that correspond to infrared and ultraviolet fixed points. As d approaches d_1 from below and as d approaches d_2 from above, the fixed points merge and disappear into the complex plane. For $d_1 < d < d_2$, the beta function has complex roots and the renormalization group flow for the three-body coupling constant is a limit cycle .

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A meson-baryon molecular interpretation for some Ω_c^0 excited states

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The recent observation by the LHCb collaboration of five narrow Ω_c^0 excited resonances decaying into $\Xi_c^+ K^-$ states [1] has triggered a lot of activity in the field of baryon spectroscopy aiming at understanding their inner structure, whether they can be understood within the quark-model picture, as more exotic multiquark states, or mainly qualify as dynamically generated quasi-bound states of an interacting meson-baryon pair.

In this talk I will present the results of a recent work [2] where we explore the possibility that some of the observed excited Ω_c^0 resonances could correspond to pentaquark states, structured as meson-baryon molecules. The interaction of the low-lying pseudoscalar mesons with the ground-state baryons in the charm +1, strangeness -2 and isospin 0 sector is built from t-channel vector meson exchange, using effective Lagrangians. The resulting s-wave coupled-channel unitarized amplitudes show the presence of two structures with similar masses and widths to those of the observed $\Omega_c(3050)^0$ and $\Omega_c(3090)^0$. The important observation is that the identification of these resonances with the meson-baryon bound states found in this work would also imply assigning the values $1/2^-$ for their spin-parity. An experimental determination of the spin-parity of the $\Omega_c(3090)^0$ would contribute to a better understanding of its structure, as the quark-based models predict its spin-parity to be either $3/2^-$ or $5/2^-$.

Several other works have also addressed the possible interpretation of some of the Ω_c^0 states seen at CERN as being quasi-bound meson-baryon systems. Particularly, the results found in [3] are qualitatively very similar to those presented in our work [2], and the model adopted in [4] produces states that can be related to the ones found in [2, 3], as well as be identified with some of the other LHCb resonances.

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Structure of Beryllium isotopes beyond the neutron dripline

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Dineutron decay is a forefront topic in nuclear structure that still lacks a firm experimental claim. The spontaneous emission of a dineutron should be favored in nuclei that are unbound with respect to two-neutron emission but bound with respect to single-neutron emission, such as ^{26}O [1]. A very interesting candidate can be found by adding two neutrons to the most neutron-rich Beryllium isotope, ^{14}Be, a well-known $2n$-halo nucleus.

In fact, tentative evidence has been proposed for dineutron decay in ^{16}Be [2]. A state of ^{16}Be was measured to be at 1.35 MeV above the ^{14}Be+n+n threshold, while no states were observed below this energy (above the ^{14}Be+n threshold) in ^{15}Be [3]. The rather low relative energy and angle between the two neutrons detected in the ^{14}Be+n+n channel was attributed to a signature of dineutron emission. However, a more standard scenario, the effect of the attractive n-n interaction in the final state, was found to explain as well the signal observed [4].

The intriguing nature of the phenomenon and the present experimental ambiguities have motivated recent theoretical calculations [5] and a new experimental campaign at RIKEN RIBF. The decay properties of ^{16}Be and the structure of ^{15}Be have been probed via the proton-knockout reaction from a ^{17}B beam. The combination of the high-intensity beam from RIBF, the active liquid-hydrogen target MINOS, the SAMURAI spectrometer, and the NEBULA neutron array let us probe the spectroscopy of both ^{15,16}Be isotopes over a wide energy range with high statistics and resolution. The analysis of n-n correlations is currently ongoing, and the first preliminary results will be presented.

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Scattering Problems of Two-Body Systems

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The complex scaling method (CSM) [1] is one of the well-established techniques in wide areas of physics, especially in resonance studies in nuclear physics. At the beginning, its advantage was mainly explained by the superior description of the resonances of the composite systems. Nowadays, it is successfully utilized for getting information on the unbound and scattering states in the observables.

In the present framework, the complex scaled orthogonality condition model (CSOCM) [2] and the extended completeness relation [3] are used. The scattering phase shifts have been investigated as important scattering quantities from the continuum level density (CLD) [4] obtained using the CSM.

The CSOCM can be used for obtaining scattering phase shifts of the many resonance system. In order to investigate effects of the many resonances for such system, we applied a simple schematic potential [5] for the $J^{\pi} = 0^{+}$ and 1^{-} partial waves. In addition, we discuss characteristics of the decomposed scattering phase shifts of the $\alpha + n$ system.

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The first unbound states in the $A = 9$ mirror nuclei ^{9}B and ^{9}Be

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Studies of mirror nuclei are important in understanding of the nuclear structure. However, in spite of considerable experimental and theoretical efforts, the location of the first excited state of the ^{9}B nuclei has not yet determined and the structures of the first excited $1/2^+$ states in mirror nuclei ^{9}Be and ^{9}B are still an open problem.

Recently, we investigated the structure of the first unbound state of ^{9}Be located just above the $\alpha + \alpha + n$ threshold energy applying the $\alpha + \alpha + n$ three-body model [1] and the complex scaling method (CSM) [2, 3]. The results indicate that the sharp peak observed just above the ^{8}Be+n threshold energy in the photo-disintegration cross section is well explained as a result due to the strong $E1$ strength coming from the ^{8}Be-n virtual state. The virtual state cannot be solved directly in the CSM, but recently, we showed that it is possible to extract the effect of virtual state from continuum solutions obtained using the CSM in a two-body system [4]. This virtual state in ^{9}Be is expected to be changed to a resonant state in ^{9}B because a barrier for the proton around the ^{8}Be core appears from the Coulomb interaction.

Various measurements of the first excited ^{9}B($1/2^+$) state have been reported ranging from $\mathrm{E_{ex}} = 1.16$ MeV using the ^{9}Be(^{3}He,t) reaction [5] to $\mathrm{E_{ex}} = 1.8$ MeV using the ^{10}B(^{3}He,α) reaction [6]. The situation is the same for theoretical side. There is a gap between the calculated values of energies and decay widths using different theoretical approaches. In some cases both experimental and theoretical methods have reported that a resonant state was not observed for the ^{9}B($1/2^+$). In addition, two close energies with decay widths at the $1/2^+$ state of ^{9}B are predicted in Ref.[7] with two different configurations between two states. In connection with above mentioned items, it is desirable to describe the first excited ^{9}B($1/2^+$) state under the correct treatment of the unbound states in connection with the ^{9}Be structure.

In this report, we present our recent results of the $1/2^+$ states obtained by changing the electric charge values of the valence nucleon in the complex scaled $\alpha + \alpha + N$ three-body model. This analytical continuation in coupling constant [8] of the valence nucleon gives a trace of poles from ^{9}Be to ^{9}B. Considering the virtual and resonance characters of the states for $A = 9$ system, we investigate the first excited $1/2^+$ state of ^{9}Be and ^{9}B mirror nuclei.

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Fragmentation dynamics of atomic and molecular dimers

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Atomic or molecular clusters constitute an intermediate step from gas phase to condensed matter. The properties of such systems under ion irradiation are of growing interest in the fields of atmospheric science, hadron-therapy or astrophysics. The presence of a surrounding environment may give rise to specific energy relaxation mechanisms depending on the cluster size and constituents.

We will focus on small clusters consisting of only two similar Ar atoms or two similar N_2 molecules. These weakly bound van der Waals dimers are produced in the supersonic expansion of a gas jet and irradiated by low energy keV ions delivered by the ARIBE/GANIL facility. We then use a COLTRIMS (COLd Target Recoil Ion Momentum Spectroscopy) set-up to measure in coincidence the three-dimension momentum vectors of the charged fragments produced in the collision. Each fragmentation channel is then carefully identified using momentum conservation laws.

For $(Ar)_2$, we found that the low electron mobility along the dimer results in an unexpected asymmetry in the charge repartition among the two ionic fragments [1]. Exotic relaxation processes such as RCT (Radiative Charge Transfer) or ICD (Interatomic Coulomb Decay) have also been identified and are responsible for charge or energy exchange between the two sites of the dimer. Moreover, by the reconstruction of the projectile impact parameter, we were able to evidence that highly charged projectiles mainly capture electrons from the nearest site of the dimer and to map the multiple electron capture probability as a function of impact parameter [2]. For molecular clusters, the role of the environment on molecular fragmentation has been investigated. It comes out that the presence of the second N_2^+ ion has small influence on both electron capture and molecular fragmentation dynamics. When comparing the fragmentation of monomers N_2^{n+} and dimers $(N_2)_2^{(n+1)+}$ cations, the main observation is a global shift of the KER spectrum towards high energies resulting from the additional Coulomb potential energy due to the neighbor N_2^+ ion [3].

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Ξ-hypernuclei at J-PARC

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We have measured an excitation energy spectrum of the $^{12}C(K^-,K^+)X$ reaction at 1.8 GeV/c with an energy resolution of 5.4 MeV (FWHM), which is the best energy resolution ever achieved in studying this reaction. The measurement was performed at the K1.8 beam line of the J-PARC hadron experimental hall by using the SKS spectrometer, as a pilot run of J-PARC E05 experiment. The K^- beam intensity at the primary proton beam power of 39 kW was typically 6×10^5/spill with 5.5-sec. beam cycle. The energy resolution was estimated from the peak observed in the $p(K^-,K^+)\Xi^-$ reaction from a 9.54-g/cm^2 CH_2 target. We took the data on the $^{12}C(K^-,K^+)X$ reaction with a 9.4-g/cm^2 C target for about 10 days. We have observed about 60k events of quasi-free Ξ^- production, and several tens of events in the bound region. We can see clear enhancements in the bound region above a flat background. Fitting to the enhancements with a few models suggest that the binding energy of $^{12}_{\Xi}Be$ would be larger than the previously estimated value of about 4.5 MeV.

Glauber model analysis for the ^{22}C nuclear radius

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A ^{22}C nucleus is the neutron dripline of carbon isotopes and is the heaviest two-neutron halo nucleus has been found so far. This nucleus is the so-called Borromean in which neither of the ^{20}C-n and n-n subsystems are bound and has attracted much attention not only to nuclear physics but also atomic physics in connection to the Efimov physics. However, the nuclear radius, which is one of the most basic properties of atomic nuclei, has been under discussion: The two recent interaction cross section measurements show the quite different ^{22}C radii, 5.4±0.9 fm [1] and 3.44±0.08 fm[2]. Since the nuclear radius has often used as one of the inputs to some theoretical models, this demands appropriate evaluation of the nuclear radius.

In this contribution, we present the examination of the determination of the nuclear radius of ^{22}C with total reaction cross sections to resolve the radius problem [3]. The nuclear radius of unstable nuclei has often been determined by the total reaction or interaction cross section measurement incident at several tens MeV to 1 GeV on a stable target nucleus such as ^{12}C and ^{1}H. Here the total reaction cross sections are calculated consistently within a reliable microscopic framework, the Glauber theory. The multiple-scattering processes within the Glauber theory is fully taken into account using a Monte Carlo technique.

Figure 1 clearly shows that our results reasonably agree with the interaction cross section data of ^{20}C on ^{12}C and ^{1}H targets, and the simultaneous reproduction of the two recent measured interaction cross sections of ^{22}C is not feasible within this framework .

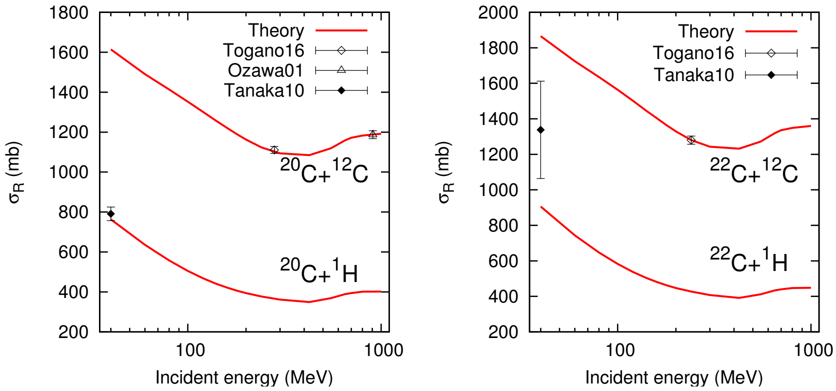

Figure 1: Total reaction cross sections of (left) ^{20}C and (right) ^{22}C on ^{12}C and ^{1}H targets as a function of incident energies. Experimental interaction cross section data are taken from Refs. [1, 2, 4].

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Positronium negative ions: the simplest three body state composed of a positron and two electrons

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One electron can bind to a positron to form a positronium (Ps) atom. Ps is a hydrogen like system composed of two leptions and its theoretical and experimental investigations have been performed actively for many years.

Another electron can further bind to Ps to form the positronium negative ion (Ps^-). Ps^- is the simplest three body system composed of three leptons. While this ion is similar to He and H^-, it is a weakly bound state composed of three particles with equal rest masses. Ps^- has been investigated by many theorists since Wheeler [1] predicted its existence in 1946. For example, its properties including binding energy and annihilation lifetime have been calculated precisely [2]–[5]. Its Feshbach resonances and shape resonances have also been predicted [6]–[8]. However, the experimental investigations have been scarce even after Mills [9] developed its formation method using a carbon thin film bombarded with slow positrons.

Recently, we have observed resonant photodetachment of Ps^- due to the shape resonance for the first time [10]. The development of efficient production method of Ps^- using alkali-coated surfaces [11] has enabled this observation.

In this presentation, recent developments of experimental investigations on Ps^- will be reviewed and future plans will be discussed.

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Tetramers of 2+2 bosons

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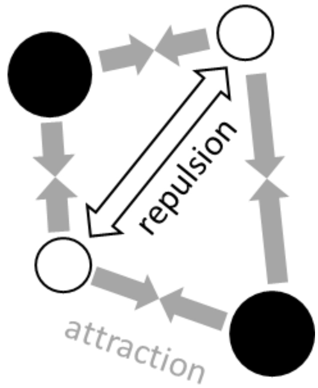
This study considers a system of two heavy bosons and two light bosons, where a short-range force attracts the bosons of different mass, while a short-range force repels the light bosons. This situation is motivated by the problem of impurities immersed in a Bose-Einstein condensate. The existence of four-body bound states in this system results from the competition between the attractive and repulsive forces.

In the limit of large mass ratios, both light bosons can mediate an Efimov attraction between the two heavy bosons, but their repulsion controls whether both or only one can contribute to the binding of the two heavy bosons. In the absence of repulsion, both contribute, and the energy spectrum consists of a superposition of two Efimov spectra with different scaling factors [1].



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Measurement for p–^{3}He elastic scattering with a 65 MeV polarised proton beam

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One of the most important topics of the nuclear physics is to describe various nuclear phenomena based on the nucleon-nucleon interactions combined with three-nucleon forces (3NF). 3NFs are the interactions acting among three nucleons. Their main ingredients are considered to be 2π-exchange type where Δ-isober excitations are in the intermediate state [1]. In the last decades, the study of 3NF effects has been extensively performed in three-nucleon scattering at intermediate energies ($E/A \gtrsim 60$ MeV) [2]. Rigorous numerical Faddeev calculations of the 3N scattering by using NN potentials as well as 3NF models have made it possible to compare the data to the theoretical calculations. As a result, the first evidence of 3NF effects has been found in the 3N scattering system.

As a next step, it should be interesting to see how 3NFs act in p–^{3}He scattering. In this system one could study 3NF effects in 4-nucleon scattering. Also one could approach to 3NF with the iso-spin channels of T=3/2. Note the 3NF with the iso-spin T=3/2 channels are expected to play important roles in neutron rich nuclei as well as neutron star [3, 4].

In order to study 3NF effects in p–^{3}He elastic scattering, we performed the measurement of the cross section and the proton analyzing power at 65 MeV with a polarized proton beam at Research Center for Nuclear Physics (RCNP), Osaka University. The gaseous ^{3}He target was bombard by a polarized proton beam, and scattered protons were detected by using the $E - \Delta E$ detectors which consisted of plastic and NaI(Tl) scintillators. Measured angles were $20° - 165°$ in the laboratory system ($26.9° - 170.1°$ in the center of mass system). The typical beam polarizations were 50 % throughout the experiment. We also measured the cross section for pp elastic scattering with the same experimental setup in order to estimate the overall systematic uncertainties.

In the conference, we will report on the obtained data combined with the theoretical calculations.

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One-proton emission of hypernuclei with time-dependent method

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In this contribution, one-proton (1p) radioactive emission under the influence of the Λ^0-hyperon inclusion is discussed [1]. Aim of this work is to invoke the interest to utilize the proton emission as a suitable tool to investigate the hypernuclear properties. I investigate the hyper-1p emitter, ${}^{6}_{\Lambda}$Li, with a three-body model (see Figure 1). For the 1p emission, time-dependent method is also utilized [2]. Two-body interactions for α-proton and α-Λ^0 subsystems are determined consistently to their resonant and bound energies, respectively. For a proton-Λ^0 subsystem, a contact interaction, which can be linked to the vacuum-scattering length of the proton-Λ^0 scattering, is employed.

As the result, a noticeable sensitivity of the 1p-emission observables to the scattering length of the proton-Λ^0 interaction is shown. The Λ^0-hyperon inclusion leads to a remarkable fall of the 1p-resonance energy and width from the hyperon-less α-proton resonance. For some empirical values of the proton-Λ^0 scattering length, the 1p-resonance width is suggested to be of the order of $0.1 - 0.01$ MeV. Thus, the 1p emission from ${}^{6}_{\Lambda}$Li may occur in the timescale of $10^{-20} - 10^{-21}$ seconds, which is sufficiently shorter than the self-decay lifetime of Λ^0, 10^{-10} seconds. By taking the spin-dependence of the proton-Λ^0 interaction into account, a remarkable split of the $J^\pi = 1^-$ and 2^- 1p-resonance states is predicted. It is also suggested that, if the spin-singlet proton-Λ^0 interaction is sufficiently attractive, the 1p emission from the 1^- ground state is forbidden. From these results, I conclude that the 1p emission can be a suitable phenomenon to investigate the basic properties of the hypernuclear interaction, for which a direct measurement is still difficult.

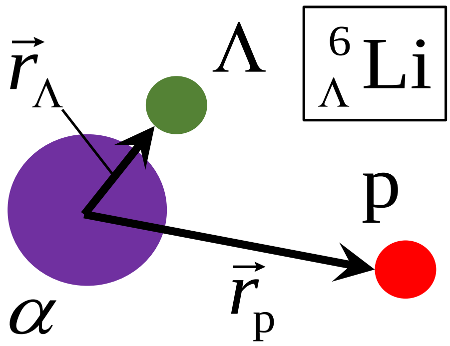

Figure 1: Three-body model of ${}^{6}_{\Lambda}$Li.

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Final results from the Jefferson Lab Qweak Experiment*

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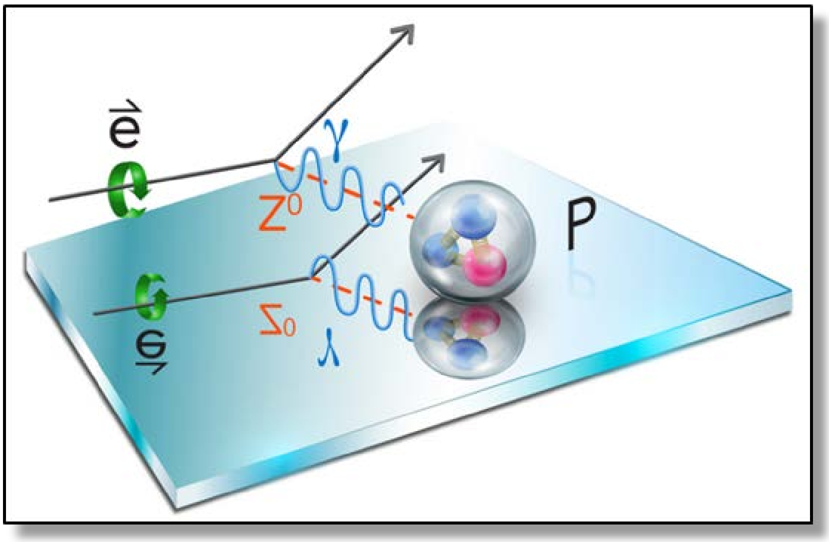
The Qweak experiment has completed the analysis and unblinded its final result to determine the weak charge of the proton by measuring the parity violating asymmetry in elastic e-p scattering at $Q^2 = 0.03$ (GeV/c)^2 with a total precision of less than 10 ppb. The experiment was carried out at Jefferson Laboratory in two data sets spanning 2010-2012, using longitudinally-polarized electrons of energy 1.16 GeV, a 35 cm long liquid hydrogen target, and custom detector apparatus. This determination of the proton's weak charge may be used to determine the running of the weak mixing angle to low Q^2 with a relative error of about a half percent. When combined with measurements from atomic parity violation, this measurement imposes a strong constraint on the values of the vector weak charges of the *u* and *d* quarks, C_{1u} and C_{1d}. Some of the backgrounds and corrections applied in the measurement will be discussed. The final results of Qweak will be presented, along with a discussion of the new constraints imposed by these results on additional parity-violating physics beyond the Standard Model.



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Relativistic effects in non-relativistic calculations of electroweak cross sections

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In general, ab initio calculations of nuclear lepton scattering cross sections, using realistic nuclear interactions, are performed within the non-relativistic (n.r.) framework. However, the comparison with experimental data is problematic when energy and momentum transfers become too high, like in the very interesting quasi elastic regime with momentum transfers $q \geq 500$ MeV/c. A partial solution to this problem is the inclusion of relativistic corrections to the charge and current operators, but the quantum mechanical dynamical treatment is still non-relativistic. We will present a strategy that tries to minimize this problem, without renouncing to the use of ab initio methods. This consists in performing the n.r. calculations in a reference frame, the active nucleon Breit (ANB) system, where all nucleon momenta are limited by $q/2$ [1]. In a further step the obtained results are transformed to the laboratory (lab) system. The transformation is relativistically correct but requests interpolations of the response functions in order to limit computational costs to a reasonable level.

We have applied this strategy to calculate the electron scattering cross section of ^{4}He, within the ab initio Green Function Monte Carlo Method (GFMC) [2, 3]. For the above mentioned interpolations we have developed a novel algorithm, based on the concept of first-kind scaling.

In particular we will discuss the rather strong frame dependence of the $^4\mathrm{He}(e, e')$ lab frame response functions obtained through GFMC calculations in various reference frames. We will show how such a frame dependence can be drastically reduced by the use of the two-fragment model introduced in Ref. [1]. In fact this model leads to significant modifications of the response functions for all considered frames, with exception of the ANB frame. Furthermore, we will illustrate that a very good agreement is obtained between theoretical and experimental $^4\mathrm{He}(e, e')$ cross sections for a variety of kinematical setups. This offers a promising prospect for the data analysis of neutrino-oscillation experiments that requires an accurate description of nuclear dynamics where relativistic effects are accounted for.

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Nuclear Reaction near the Three-Body Thresholds

-a theory of low-temperature nuclear translation- *

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We propose a new theory of low-temperature nuclear translation *via* the Efimov-like energy levels by a three-body reaction, where new three type of cluster-cluster potentials with a long range potential tail are introduced. These potentials satisfy the unitary limit with the scattering length: $a \to \infty$. Such a long range potential occurs near the three-body break up threshold (3BT) and the quasi two-body threshold (Q2T) in the three-body systems [1]. One of the well-known long range potentials: $1/r^2$ is proposed by Efimov at the 3BT in 1970 [2].

Recently, we proposed a general particle transfer (GPT) potential in the three-body systems, which gives a potential form of $V(r) = -V_0(2a)^{2\gamma+2}/r(r+2a)^{2\gamma+2}$ with parameters a and γ [3]. The GPT-potential has an attractive long range potential of $1/r^n$ for the long range: $a \ll r$, while a Yukawa-type potential for short range: $r \ll a$. If we adopt $\gamma = -1/2$, the potential has $1/r^2$-type potential which is obtained at the Q2T. These long range potentials are an attractive potential, and then they diminish the repulsive Coulomb potential in the range of a certain distance. Therefore, two clusters could come close each other in comparison to the usual short range cluster-cluster potential case.

If and only if, these clusters set in array on a special material with adequate field, they could reproduces shallow bound states as an Efimov-like states. In the end, the Efimov-like bound states could fall down to the ground state after certain life-time. Therefore, the present nuclear reaction could be called a "slow reaction" or a low temperature reaction compared with the usual "fast reaction" or the hot reaction by an accelerator.

The lower temperature reaction could be useful to shorten the life-time of the radioactive nuclei such as ${}^{137}_{55}$Cs($7/2^+$) of the life time (Lf)=30.07years, and also ${}^{135}_{55}$Cs($7/2^+$) of Lf=2.3×10^6years, by using the reactions ${}^{137}_{55}$Cs($7/2^+$:Lf=30.07y)+d+d $\to$ ${}^{141}_{57}$La($7/2^+$:Lf=3.92h), and ${}^{135}_{55}$Cs($7/2^+$:Lf=2.3×10^6y)+d+d $\to$${}^{139}_{57}$La($7/2^+$: stable), and also ${}^{135}_{55}$Cs($7/2^+$:Lf=2.3×10^6y)+4d $\to$${}^{143}_{59}$Pr($7/2^+$:Lf=13.57d).

It is very difficult to measure the Efimov-like states near the thresholds, however, such bound states could be down to the deeper states in certain life-time. The process contributes the creation of the fusion energy. If an effort could be paid for "tuning the range" within the *rms* radius of the shallow bound state, the confinement of the fuel into such a material could be performed effectively for making Efimov-like bound states.

Finally, it should be stressed that one of criterion for the Efimov effect is the existence of the two-body unitary limit. However, the three-body Born term of AGS equation at the 3BT, and the three-body Born term of the quasi two-body Lippmann-Schwinger equation at the Q2T indicate $1/r^2$-type potentials which generate the divergence of the quasi two-body scattering length. This is the most important feature just below the 3BT and the Q2T [1].

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Poincaré covariant light-front spectral function and transverse momentum distributions

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Poincaré covariant spin-dependent spectral function, $\mathcal{P}^{\tau}_{\mathcal{M},\sigma'\sigma}(\tilde{\boldsymbol{\kappa}}, \epsilon, S)$, and spin-dependent momentum distributions were defined in Ref. [1] within the light-front (LF) Hamiltonian dynamics, starting from the LF wave function for a three-body system with spin $\mathcal{M}$ and polarization vector $\mathbf{S}$. The spectral function is defined through the overlaps between the ground state wave function of the three-body system and the tensor product of a plane wave of LF momentum $\tilde{\boldsymbol{\kappa}}$ for one of the particles in the intrinsic reference frame of the cluster [1,(23)] and the state which describes the intrinsic motion of the fully interacting two-particle spectator subsystem. The mentioned tensor product allows one to fully take care of macrocausality and to introduce a new effect of binding in the spectral function.

In this contribution it will be shown that in valence approximation :

i) a linear relation exists between the correlator and the spectral function

$$\Phi^{\tau p}_{\alpha,\beta}(p,P,S) \;=\; \frac{2\pi\ (P^+)^2}{(p^+)^2\ 4m}\ \frac{E_S}{\mathcal{M}_0[1,(23)]}\ \sum_{\sigma\sigma'} \left\{\ u_\alpha(\tilde{\mathbf{p}},\sigma')\ \mathcal{P}^{\tau}_{\mathcal{M},\sigma'\sigma}(\tilde{\boldsymbol{\kappa}},\epsilon,S)\ \bar{u}_\beta(\tilde{\mathbf{p}},\sigma)\ \right\} \quad , \qquad (1)$$

where $\mathcal{M}_0[1,(23)]$ is the free mass of the cluster;

ii) the spin-dependent momentum distributions are to be evaluated as integrals on the relative intrinsic momentum k_{23} of the interacting spectator pair

$$n^{\tau}_{\sigma\sigma'}(x,\mathbf{p}_\perp;\mathcal{M},\mathbf{S}) \;=\; \frac{2(-1)^{\mathcal{M}+1/2}}{(1-x)} \int dk_{23}\ \ \{\mathcal{Z}^{\tau}_{\sigma\sigma'}(x,\mathbf{p}_\perp,k_{23},L=0,\mathbf{S}) \;+\; \mathcal{Z}^{\tau}_{\sigma\sigma'}(x,\mathbf{p}_\perp,k_{23},L=2,\mathbf{S})\} \quad (2)$$

where L is the angular momentum in the orbital angular momentum decomposition of the one-body off-diagonal density matrix.

The six T-even transverse momentum distributions can be obtained through Eq. (1) and one finds that the linear equalities proposed in Ref. [2] between the transverse parton distributions, i.e.

$$\Delta f(x,|\mathbf{p}_\perp|^2) = \Delta'_T f(x,|\mathbf{p}_\perp|^2) \;+\; \frac{|\mathbf{p}_\perp|^2}{2M^2}\ h^{\perp}_{1T}(x,|\mathbf{p}_\perp|^2) \qquad\qquad g_{1T}(x,|\mathbf{p}_\perp|^2) = -h^{\perp}_{1L}(x,|\mathbf{p}_\perp|^2) \qquad (3)$$

hold exactly in valence approximation when the contribution to the transverse momentum distributions from the angular momentum $L = 2$ is absent.

As far as the quadratic relation proposed in Ref. [2] is concerned, in our approach it does not hold, even if the contribution from the angular momentum $L = 2$ is absent, because of the presence of $\int dk_{23}$ in the expressions of the transverse momentum distributions.

Furthermore, in this contribution preliminary results for the EMC effect in ^3He will be presented. Encouraging improvements were already obtained with respect to the non-relativistic results using average values for k_{23} [3], and we are going to perform the full LF calculation.

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Imaging the partonic structure of the nucleon

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I will discuss different kinds of parton distributions, which allow one to obtain a multidimensional picture of the partonic structure of the nucleon. I will use the concept of generalized transverse momentum dependent parton distributions and Wigner distributions [1, 2], which combine the features of transverse-momentum dependent parton distributions and generalized parton distributions [3]. I will show examples of these functions, with focus on the role of the spin-spin and spin-orbit correlations of quarks in the nucleon [4].

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Relativity in few-hadron systems: analysis of baryon electromagnetic transition form factors in the Covariant Spectator Theory

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Electron scattering is a successful tool to reveal the microscopic structure of the nucleon N and its excited states N^* [1]. Dilepton production in relativistic heavy-ion reactions probe how the N^* excited states decay to and radiate in the highly dense medium. Superficially, these methods appear unrelated. However, they are deeply connected since they explore the same physical systems in different space-like and time-like ranges of photon virtualities, thereby providing complementary information on baryonic structure.

Baryon transition form factors (TFFs), in both the space-like and time-like regions, constitute the common ground of the two methods. What makes the information contained in baryon TFFs so challenging is the interplay between the microscopic quark-gluon structure and the hadronic states to which the baryonic resonances couple in their decays. How exactly do excited baryons couple to pions and vector mesons and the photon? What is the evolution of the coupling with Q^2, the squared momentum transfer?

The answers to these questions crucially influence both space-like and time-like regimes, in electron-scattering and dilepton production reactions, respectively, which have to be matched smoothly at $Q^2 = 0$. Understanding the role of vector mesons in electromagnetic transitions from electron scattering, in turn, strongly impacts on medium effects probed by di-electron emission. This link is explored in this talk, where TFFs are seen as a tool for the quest of medium modifications of strongly interacting matter.

We therefore explore the constraints from electron scattering to calculate TFF in the timelike region. We review results of the Covariant Spectator model [2] for the TFFs of several $\gamma^* N \to N^*$ transitions [3, 4]. We discuss the role of the valence quarks and the meson cloud excitations for different resonances N*. In general the results are in good agreement with the empirical JLab data for $Q^2 > 2$ GeV^2. Finally, we present the extension of some TFF from the space-like (in electron-scattering) to the the time-like (in dilepton production) regime. This extension recently enabled the first extraction of the $\Delta(1232)$ Dalitz decay branching ratio by the HADES collaboration [5].

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The *basic model* of Nuclear Theory: from Atomic Nuclei to Infinite Nuclear Matter

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A major goal of nuclear theory is to explain the wealth of data and peculiarities exhibited by nuclear systems in a fully microscopic approach. In such an approach, which we refer to as the basic model of nuclear theory, the nucleons interact with each other via many-body (primarily, two- and three-body) effective interactions, and with external electroweak probes via effective currents describing the coupling of these probes to individual nucleons and many-body clusters of them. These effective interactions and currents are the main inputs to *ab-initio* methods that are aimed at solving the many-body Schrödinger equation associated with the nuclear system under consideration. In this talk, I will review recent progress in Quantum Monte Carlo calculations of low-lying spectra and electroweak properties of light nuclei as well as nucleonic matter equation of state. Emphasis will be on calculations based on chiral effective field theory approach.

Universal relations for heteronuclear few-body systems*

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The Efimov is one of the most fascinating features of few-body physics. It refers to the appearance of discrete scale invariance in few-body systems that display a large two-body scattering length. The scaling factor associated with this discrete scaling symmetry is 22.7 for Bosons but can be very different for systems with distinguishable particles that have different masses.

I will recent discuss results for systems with two identical particles and a third one that has a differet mass. I will discuss how corrections due to the finite range can be included [1] and how a finite temperature impacts the measurability of recombination features that are the experimental signatures of Efimov physics [2].

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Pion effects in N and Δ masses and strong form factors

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Three-quark configurations $\{QQQ\}$ have proven not to be sufficient for a proper description of baryon ground and resonant states. Rather mesonic degrees of freedom are needed in addition. Especially for baryon resonances the coupling to (mesonic) decay channels is essential in order to account for their decay properties [1, 2].

We have constructed a relativistic coupled-channels quark model that allows to include mesonic (decay) channels explicitly. It provides for a consistent framework to describe baryons and their excitations as bound ground states and decaying resonances with finite widths.

So far we have managed to consider explicit pionic effects by coupling to $\{QQQ\pi\}$ channels. In particular, we have studied in a consistent approach the influence of pion dressing on the N mass as well as the Δ resonance energy and hadronic decay width; all of these values are described in good agreement with experimental data. At the same time we have obtained a microscopic quark-level description of the strong form factors at the $NN\pi$, $N\Delta\pi$, and $\Delta\Delta\pi$ interaction vertices. The corresponding results compare reasonably well with parametrizations used in phenomenological (meson-exchange) models available from the literature, such as, e.g., in refs. [3, 4].

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Laser spectroscopy of muonic atoms and ions: Charge radii and polarizabilities of the lightest nuclei

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In light muonic atoms and ions, the atomic electrons are replaced by a single negative muon μ^-. Due to the large muon mass, $m_\mu \approx 200\, m_e$, and the correspondingly 200 times smaller Bohr orbit, nuclear structure effects on atomic energy levels are vastly enhanced, by a factor $200^3 \approx 10$ millions.

We have performed laser spectroscopy on the 2S-2P transitions ("Lamb shift") in muonic hydrogen, deuterium, and helium-3 and -4 ions, with surprising results. Our value of the proton [1] and deuteron [2] charge radii are, for example, ten times more accurate than the corresponding world averages from regular atoms and electron scattering [3]. At the same time, however, our radii are 5-6 standard deviations smaller than the CODATA world average. This discrepancy has been coined the "proton radius puzzle".

New data on muonic helium-3 and -4 will also yield tenfold improved charge radii. All these charge radius determinations depend crucially on accurately calculated nuclear polarizabilities.

Several groups have pushed the calculations to exciting accuracies in the 1% range or better, for the deuteron [4, 5, 6, 7, 8, 9, 10], for muonic helium-3 [11] and -4 [12]. For a summary, see [13].

Today, the accuracy of the calculated nuclear polarizabilities limits the accuracy of the charge radii deduced from muonic deuterium and helium-3 and -4. For the deuteron, a combination of measurements in electronic and muonic H and D yields an *experimental* value of the deuteron polarizability contribution [2], which is three times more accurate than the calculated value, and 2 standard deviations larger [9, 10].

Finally, I will give an update on the proton radius puzzle. New measurements in hydrogen agree [14] and disagree [15] with the muonic proton radius.

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Universal physics of two neutrons and one flavored meson in pionless effective theory

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We present an exploratory qualitative investigation of the two- and three-body universal physics associated with the s-wave three-body system consisting of a cluster of two neutrons and one flavored meson, i.e., either an antikaon K^- or a D^0 meson, with total spin-isospin $J = 0, I = 3/2$ [1]. The technique of extrapolation to unphysical quark masses between the strange and the charm flavors, provides a natural mechanism to tune the meson-neutron interaction close to resonant conditions. In the two-body sector, we show that the meson-neutron scattering length becomes infinitely large in an unphysical region of the quark mass in the so-called *zero coupling limit* (ZCL) of the Weinberg-Tomozawa contact interactions in the coupled channel system with subthreshold decay channels neglected. Likewise in the three-body sector, employing a leading order *pionless* cluster effective field theory [2, 3] with *real* meson-neutron scattering lengths as input, we confirm an approximate limit cycle renormalization group behavior (with quasi-log-periodicity) of the three-body coupling as a function of a sharp momentum cut-off introduced in the system of STM integral equations [4]. This indicates that despite the smallness of the meson-neutron scattering lengths in the real world, Efimov effect can be manifest in the three-body system when the meson-neutron scattering lengths are extrapolated to the unitary limit. Consequently, by varying the sharp cut-off we explore the possibilities of existence of three-body Efimov-like bound state formation. In particular, our analysis in the ZCL scenario indicates that a plausible D^0nn ground state trimer may be realized within the EFT framework with a cut-off lying much below the pion threshold. While for the K^-nn system, no physically realizable mechanism in the context of a low-energy EFT can generate sufficient interaction strength to form Efimov trimers.

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Measurements of differential cross sections and analysing powers of the three-body break-up channel in deuteron-deuteron scattering at 65 MeV/nucleon

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In this contribution, the results of a detailed analysis of data obtained in deuteron-deuteron scattering at intermediate energies will be presented. The goal is to rigorously investigate three-nucleon force (3NF) effects in the four-nucleon scattering process. To achieve this, we measured differential cross sections and a rich set of vector and tensor analysing powers for various configurations of the three-body break-up channel of $^2\mathrm{H}(\vec{d}, dp)n$. The data were obtained at KVI using a polarised deuteron beam with a beam energy of 65 MeV/nucleon and a liquid deuterium target in combination with a 4π detection system carrying the name **B**ig-**I**nstrument for **N**uclear-Polarization **A**nalysis, (BINA). This work extends the results from an earlier study reported in Ref. [1]. In particular, additional kinematical configurations and spin observables were analysed and obtained. We discuss the analysis procedure, including a thorough study of the systematic uncertainties, compare the data with earlier results, and present new polarisation data.

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Hypernuclear spectroscopy with heavy ion beams: the present status and the perspective

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Nuclear spectroscopy with heavy ion beams and fixed nuclear targets has recently become a powerful tool to study sub-atomic nuclei with strangeness, so called hypernucleus. The first HypHI (**Hyp**ernuclei with **H**eavy **I**on) experiment at GSI was performed with a ^{6}Li beam bombarding a carbon target at 2 AGeV. The experimental approach was developed to measure and study hypernuclei produced in the projectile rapidity region of the nuclear collisions. Such Λ-hypernuclei are produced by the coalescence between a Λ hyperon produced in the mid-rapidity region of the participant zone and a projectile spectator fragment. The HypHI collaboration demonstrated the feasibility of the spectroscopy of hypernuclei produced in ion-induced reactions with the successful observations of the Λ hyperon and ${}^3_\Lambda$H and ${}^4_\Lambda$H hypernuclei [1]. Several other results showed indications of a possible bound state of two neutrons and one Λ hyperon, ${}^3_\Lambda$n or nnΛ [2]. However, recent theoretical calculations have shown that such a state is unlikely bound [3, 4, 5]. Additionally, the obtained results reported the shorter lifetime of the ${}^3_\Lambda$H and ${}^4_\Lambda$H compared to their structure models [1, 6], which have implications on the theoretical models of the hypernuclear structure.

With this current experimental approach for the hypernuclear spectroscopy, the accuracy and statistics need to be improved. The experimental method also has to be further developed with different detection techniques and beams at higher energies.

A new project to study hypernuclei has been proposed at GSI: it will employ the WASA central detector, currently at COSY in Jülich and under transportation to GSI, for pion measurement combined with the high resolution fragment separator, FRS, for measuring decay residues. The project has been already approved and experiments with WASA+FRS will be performed in coming years. The project will then continue with the Super-FRS at FAIR [7]. Another novel development at higher energies is in progress for the future heavy ion accelerator facility in China, High Intensity heavy ion Accelerator Facility, HIAF. It will open possibilities to study double-strangeness hypernuclei with heavy ion beams and fixed targets. The HIAF will also enable hypernuclei spectroscopy with its fragment separator with a similar fashion to the experiment with WASA+FRS at GSI.

These future perspectives at GSI/FAIR and HIAF will be discussed after an highlight of the current results and status.

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High-precision nucleon-nucleon potentials from chiral EFT

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Ab initio calculations in few- and many-body systems require precise two-nucleon forces as input. We present new nucleon-nucleon (NN) potentials [1] up to fifth order in chiral effective field theory, whose adjustable parameters have been fitted to the 2013 Granada database [2] of experimental NN scattering data. We employ a new local regularization scheme for long-range forces in momentum space which does not distort the long-range behavior of the interaction and allows for a systematic extension to three-nucleon forces and currents. Furthermore, the contact interaction part of the potentials is studied. We discuss the removal of redundant contact interaction terms at fourth order which can be eliminated by means of suitably chosen unitary transformations. Compared to our previous potentials [3, 4], the removal of the redundant contact interactions leads to softer potentials, which is a welcome feature for few-body calculations. Last but not least, we study the inclusion of sixth order contact interactions in F-Waves and their effects on the two-nucleon system. The resulting potentials at fifth order yield an excellent description of NN scattering data below the pion-production threshold previously only achieved by high-quality phenomenological potentials while at the same time allowing the inclusion of consistent many-body forces and currents derived from chiral EFT.

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Are the chiral based $\bar{K}N$ potentials really energy-dependent?*

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It is shown, that the energy dependence of the chiral based $\bar{K}N$ potentials, responsible for the occurrence of two poles in the $I = 0$ sector, is the consequence of applying the on-shell factorization introduced in [1]. When the dynamical equation is solved without this approximation, the second, unphysical, pole disappears. Accordingly, an energy-independent $\bar{K}N$ potential was derived, which supports only one pole in the region of the $\Lambda(1405)$ resonance. The potential, being energy-independent, is suitable for standard quantum mechanical calculations in $n > 2$ systems, including coordinate space variational approaches, where the energy-dependence leads to serious difficulties.

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Exploring the p-n interaction close to the drip-line in the fluorine isotopic chain.

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Understanding the boundaries of the nuclear landscape and the origin of magic nuclei throughout the chart of nuclides are overarching aims and intellectual challenges in nuclear physics research. Studying the evolution of binding energies for the ground and first few excited states in atomic nuclei from the valley of stability to the drip line is essential to achieve these endeavors. In the oxygen isotopes, recent experiments have shown that the drip line occurs at the doubly magic ^{24}O. The role of tensor and three-body forces was emphasized to account for the emergence of the N=16 gap at ^{24}O and the "early" appearance of the drip line in the oxygen isotopic chain, respectively.

On the other hand, with the exception of ^{28}F and ^{30}F, which are unbound, six more neutrons can be added in the fluorine isotopic chain before reaching the drip line at ^{31}F. One can therefore speculate that the extension of the drip line between the oxygen and fluorine, as well as the odd-even binding of the fluorine isotopes, arise from a delicate balance between the two-body proton-neutron and neutron-neutron interactions, the coupling to the continuum effects, and the three-body forces.

Within this context, we have investigated the evolution of the residual interaction between the ^{26}F and the ^{28}F nuclei, that were studied at RIKEN during the SAMURAI21 experiment. It required a complex and innovative set of detector systems with neutron walls, gamma-ray detectors, drift chambers, time of flight detectors associated with the detection of recoil ions in a spectrometer and an active target. I propose to present the results on the structure of the ^{26}F unbound states populated via neutron knockout from ^{27}F secondary beam as well as the ground and first excited states of the unbound ^{28}F, populated via knockout reactions from ^{29}F and ^{29}Ne secondary beams at 250 MeV/nucleon. Our results complete previous studies on the ^{26}F, where bound excited states [1] and unbound states populated via proton knockout from ^{27}Ne [2] have already been investigated. Moreover our results on the ^{28}F highly improve and complete previous studies [3] due to the high statistic and the high resolution achieved with the active target used during the experiment. Our results shed light on the evolution of the residual interaction when adding two neutrons to the $d_{3/2}$ shell from ^{26}F to ^{28}F.

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Looking back, looking forward

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I shall present some reminiscences of Few-Body conferences, starting from the 70s, and discussions with some founders of the earlier Few-Body meetings, who stressed the stimulating virtues of their interdisciplinary character.

For years, the field was somewhat dominated by few-nucleon systems. This is still an important topics, but the methods there have dramatically evolved, in particular with the onset of effective theories.

The physics of hadrons has become an important chapter of Few-Body conferences, especially for exotics involving heavy flavors, with sometimes much focus on quark dynamics, and more recently, an impressive effort devoted to its reformulation at the hadronic level.

The physics of very-weakly bound systems, initiated some decades ago by Thomas and Efimov, has attracted many newcomers in our conferences, and stimulated sophisticated developments of both experimental and theoretical methods.

Finally I will present a kind of bloopers, an anonymous list of examples of absent-mindedness errors that I have encountered in my carrier. I thank the authors for giving the opportunity to the young generation to improve on the past work.

Time Evolution of a light Atom and Two heavy Dipoles in Two Dimensions

We study a three-body system, formed by a light particle and two identical heavy dipoles, in two dimensions in the Born-Oppenheimer approximation. We calculate the three-body spectrum for a repulsive dipole-dipole interaction and investigate the three-body solutions as functions of strength and dipole direction. Avoided crossings occur between levels localized in the emerging small and large-distance minima, respectively. The characteristic exchange of properties like mean square radii are calculated. Simulation of quantum information transfer may be suggested. For large heavy-heavy particle repulsion all bound states have disappear into the continuum. The Time evolution of the three body energies and mean square radii are computed for a time dependent potential. The two different evolutions imaginary and real time are studied in this presentation.

Universal Phillips lines for identical and distinguishable particles

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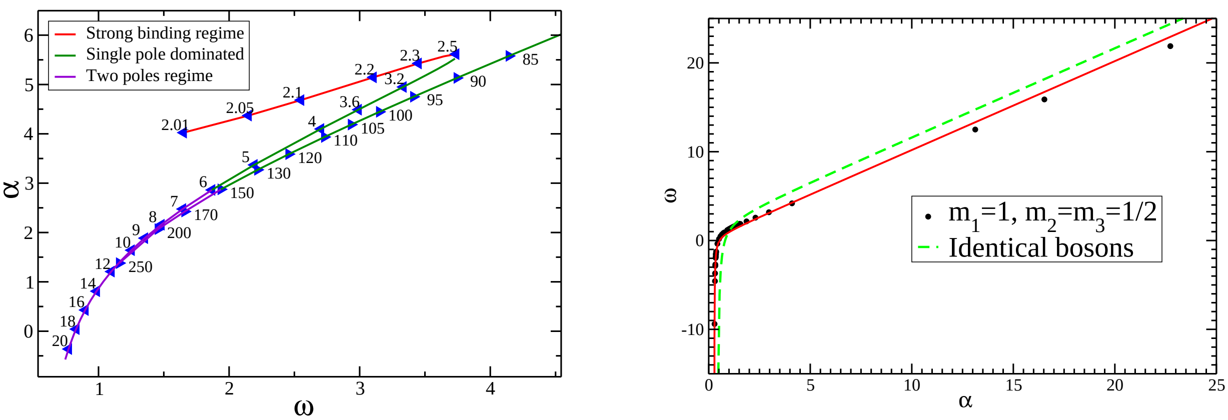
One of the most interesting results in quantum few-body problem – the discovery of the three-body interaction universal regime – was obtained by Vitaly Efimov [1] in 1970. About the same time, a linear correlation between neutron-deutron scattering length and the energy of the triton bound state was brought to the attention of few-body community by A.C. Phillips [2]. This correlation is known as the Phillips line. The nature of this linear correlation remained somewhat mysterious for almost 20 years until Efimov and Tkachenko had suggested that the linearity results from observing some complicated non-linear relationship in very small scale [3]. A direct connection between the Efimov effect and the Phillips line has been revealed by the author in [4], where a universal modification of the Phillips line was proposed, and the corresponding universal curve was constructed for the case of three identical bosons (see Fig. 1a). Unlike the original Phillips line, the universal version is constructed in terms of dimensionless variables

$$\alpha \equiv a_3\sqrt{-2m_{12}E_2}/\hbar,$$
$$\omega \equiv 1/\sqrt{E_3/E_2 - 1},$$

where E_2 is the energy of the lowest two-body threshold, E_3 is the energy of the near-threshold three-body bound state, m_{12} is the reduced mass of the two-body subsystem and a_3 is the particle-dimer scattering length. Here we shall discuss the universal Phillips lines for distinguishable particles (Fig. 1b) and their properties.



(a) Identical bosons

(b) Distinguishable particles

Figure 1: Universal Phillips lines for identical bosons and particles of different masses.

The universal Phillips lines can be useful in testing few-body computer codes, checking theoretical results for consistency and identifying the universal interaction regime.

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Evaluation of correlations in nuclear matter by using spectral expansion for the in-medium propagator*

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The wave-packet diagonalization technique for solving scattering problems in free space is generalized to finding two-body correlations in infinite nuclear matter [1]. In the approach, the effective in-medium Hamiltonian is introduced which corresponds to the total in-medium propagator. After employing a continuum discretization procedure in the stationary wave-packet basis, explicit spectral expansions for the above operators can be evaluated. So that, the total propagator and subsequently the in-medium T-matrix at many energies and relative momenta can be found from a single diagonalization procedure for the effective Hamiltonian matrix in the basis chosen. The developed technique occurred to be very effective within the mean field Brueckner–Hartree–Fock framework where it simplified self-consistent iterations of a single-particle self-energy and equation of state [1].

The approach is applicable to a more general case when the hole-hole continuum is taken into consideration and the in-medium propagator has the so-called pphh form [2]. The effective Hamiltonian is non-Hermitian and may have pairs of eigenstates with complex energies signaling about the pairing instability. It is shown [2] that these states can be used for a treatment of pairing in-medium and give an important contribution to the in-medium T-matrix. In particular, momentum dependencies of pairing gaps in definite spin-angular channels can be reconstructed from the corresponding eigen functions of the effective Hamiltonian instead of solving the conventional gap equations for these channels [2] (see Fig. 1).

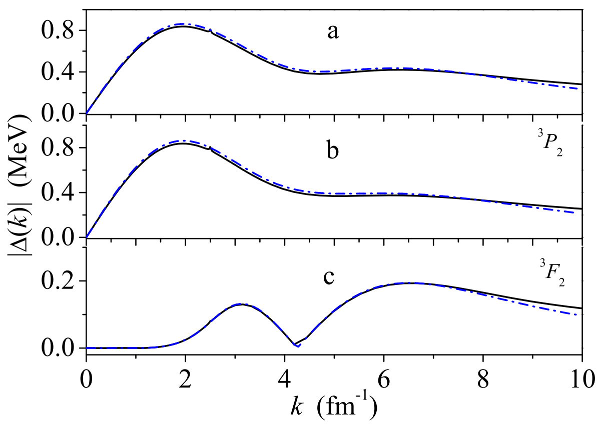

Figure 1: Absolute values of the total (a) and partial (b and c) pairing gaps for the coupled $^3PF_2$ channel in neutron matter at $k_F = 2.5$ fm^{-1} calculated from the effective Hamiltonian eigen function (dash-dotted curve) in comparison with the solutions of the corresponding gap equation (solid curves).

The diagonalization technique allows to separate forward- and backward-propagating parts of the T-matrix explicitly which is useful for the general Self-Consistent Greens Function (SCGF) framework. An extension of the developed approach to account of three-body in-medium correlations is discussed.

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Fate of the neutron-deuteron virtual state as an Efimov level*

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The emergence of Efimov levels in a three-body system is investigated near the unitarity limit characterized by resonating two-body interaction. The triton was one of the three-body systems studied by Efimov [1]. No direct evidence of Efimov levels was found as triton is the only physical bound state in this system. However, this system supports a virtual state which is evident from the modified effective range expansion (mERE) [2]. We show that the virtual state evolves into a shallow bound state emerging as an excited triton as we drive the system towards unitarity. We provide a model-independent analysis at low energy by formulating a consistent effective field theory for neutron-deuteron scattering. We provide a theoretical derivation for the empirically derived mERE. The results presented are universal to atomic, nuclear and particle physics though we considered a particular system to study the emergence of the Efimov levels.

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Relativistic high-precision methodologies for atomic calculations

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We have developed a broadly applicable method and a corresponding atomic code for predicting properties of systems with a few valence electrons to good precision [1]. This approach is based on the combination of configuration interaction (CI) and the all-order linearized coupled-cluster methods. The quantum electrodynamics corrections were directly incorporated into the CI+all order method in Ref. [2]. The effective three-particle interactions between valence electrons, which are induced by the core polarization, were studied in Ref. [3]. The CI+many-body perturbation theory codes were documented and made available for the scientific community in Ref. [4].

This CI+all-order method has been applied to the study of numerous atoms and ions with a few valence electrons including highly-charged ions [5], superheavy elements with $Z > 100$ [6] and negative La^- ion [7]. The method has been applied to the calculation of the ionization potentials, removal energies, electron affinities, transition wavelengths, electric-dipole, electric-quadrupole, electric-octupole, magnetic-dipole, magnetic-quadrupole, and magnetic-octupole transition rates, branching ratios, lifetimes, hyperfine A and B constants, electric-dipole, magnetic-dipole, electric-quadrupole static and dynamic polarizabilities, hyperpolarizabilities, field shifts, specific mass shifts, long-range interaction C_6 and C_8 van der Waals coefficients, parity-violating amplitudes, electron electric-dipole moment enhancement factors, and sensitivity coefficients to the variation of the fine-structure constant and the violation of local Lorentz invariance (see [8] for a complete list of relevant publications). Such properties are required in many current applications including studies of fundamental interactions and searches for physics beyond the Strandard Model of elementary particles [9], analysis of astrophysical data, plasma science, atomic clock research, actinide chemistry, studies of quantum degenerate gases, production of ultracold molecules, quantum information, dark matter searches, and others. We also developed methodologies to evaluate the accuracy of the resulting recommended data.

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Complex-Range Gaussians as a Basis for Treatment of Charged Particle Scattering*

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We suggest a new technique towards solving scattering problems with charged particles. The method is based on the Wave-Packet Continuum Discretization (WPCD) approach and the Coulomb wave-packet (CWP) formalism [1]. CWPs are constructed as integrals of regular Coulomb wave functions over discretization intervals and thus represent normalized states in continuum. An evident advantage of the CWP formalism is a possibility to adjust a discretization mesh to the problem in question†. On the other hand, exact CWPs can be evaluated only numerically which represents some inconvenience in practical calculations. Thus, we employ here some special representation for the Coulomb wave-packets, the so called complex-range Gaussian basis (CRGB) [3]. The real-valued functions of this basis are constructed from Gaussians with complex scale parameters, so that they oscillate in coordinate space and are very well suited to approximate wave functions of excited and continuum states (see Fig. 1).

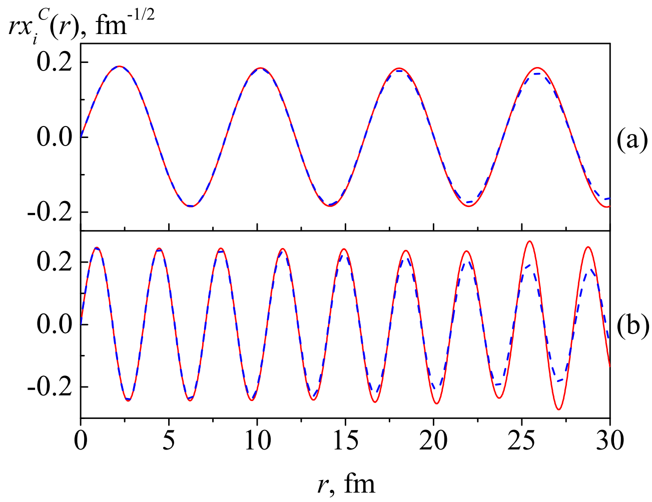

Figure 1: Coordinate behavior of the exact Coulomb wave-packets (dashed curves) and their approximations (solid curves) in the CRGB at $E = 10.15$ MeV (a) and $E = 50.6$ MeV (b).

With the developed technique, off-mass-shell elements of the Coulomb-nuclear T-matrix can be found in a wide energy region from a two-fold diagonalisation procedure for the total and Coulomb Hamiltonian matrices on the CRGB. The efficiency of the method is illustrated with calculations of partial phase shifts for nucleon and deuteron elastic scattering off alpha particles where its accuracy and convenience are demonstrated clearly.

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†For example, recently CWPs have been successfully employed for a calculation of cross sections for the antiproton impact ionization of the hydrogen atom at very low antiproton incident energy (few keV) in the close-coupling approach [2].

Few-body systems in Minkowski space

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In recent years, a novel approach for addressing the dynamics directly in the physical space, namely the Minkowski space, has receiving great interest, and many efforts have been dedicated for demonstrating its effectiveness in dealing with the non perturbative regime, even in presence of spin degrees of freedom. The dynamical equation to be solved is the well-known Bethe-Salpeter equation [1], that allows one to describe an interacting systems within a quantum-field-theory framework, in its full glory, and the so-called Bethe-Salpeter amplitude represents its solution. To get actual solutions, one introduces the Nakanishi integral representation [2,3,4,5] of the Bethe-Salpeter amplitude, obtaining in this way a viable formal tool for achieving the desired goal.

The technique will be briefly illustrated by presenting the outcomes for two-body systems without and with spin degrees of freedom, as well as the main features of calculated dynamical quantities, like momentum distributions, that necessarily live in the Minkowski space, and not addressable in a consistent way in the Euclidean space. The role of the spin degrees of freedom will be also discussed, in view of the possible relevance in other fields of application.

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Three-electron bound states in conventional superconductors*

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We expand the Cooper problem [1] by including a third electron in an otherwise empty band. The other two electrons, both restricted outside of an inert Fermi sea, are in a lower band. Such a two-band structure can occur in a recently developed pump-probe experiment in solid state physics [2]. The effective interaction between a pair of electrons is assumed to be attractive, due to the dominance of the electron-phonon interaction over the screened Coulomb repulsion [3]. Assuming the zero total momentum of the system and also the singlet spin-state for the inter-band electrons, we derive a system of two coupled integral equations describing the system in momentum space.

We demonstrate the formation of a three-electron bound state in a conventional superconductor when all electrons are mutually interacting. Furthermore, when the two inter-band electrons are noninteracting, while the intra-band electrons attractively interact, we demonstrate the formation of a three-electron bound state, provided that the intra-band coupling constants are below a critical value. In the latter case and for fermions with highly effective mass ratios, and also for the Debye energy possessing much larger values, we show that the number of the three-body bound states will be increases, however, unlike the standard Efimov effect [4], it will remain finite.

Finally, from the lower-band perspective where the inter-band electrons are noninteracting, the formation of a three-electron bound state can be interpreted as a pairing mechanism for the inter-band electrons, that is induced by the third electron.

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Observation of new neutron resonances in ^{17,19}C

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Intermediate-energy nucleon knockout reactions in inverse kinematics offer unique tools to investigate in-medium correlations of nucleons [1, 2] as well as for spectroscopy, often, of nuclei far from stability [3, 4]. This study focuses on new neutron resonances in ^{17}C and ^{19}C, found, respectively, by neutron-knockout (from ^{18}C) and proton-knockout (from ^{20}N) channels at $\sim$250 MeV/nucleon on Carbon. The SAMURAI spectrometer [5] at RIKEN-RIBF was utilized for the measurement, which was based on the invariant mass method involving detection of a neutron and a charged fragment from in-flight decay of the knockout residue. The new states were observed above one-neutron (S_n) (E_x $\sim$1.55 MeV in ^{17}C) and three-neutron (S_{3n}) thresholds (E_x $\sim$6.02 MeV in ^{19}C), in the one-neutron decay channels. An analysis based on a shell model and an eikonal reaction model, taking into account the resonance energy, population strength, and decay property, is made to characterize their microscopic structures. Since the region of the neutron-rich carbon isotopes represents a frontier of *ab initio* structure calculations including continuum and three-body forces [6], the new information from the present study provides critical testing grounds for them.

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Universality and the Coulomb interaction

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The Efimov effect has been studied extensively in cold atoms systems, where it is possible to observe experimentally [1][2]. But originally Efimov proposed the effect for nuclei [3], an area where progress has been hampered by complications involving the Coulomb force. It is difficult to disentangle the influence of the Coulomb force, which is long-range, from the short-range force that is needed to produce the Efimov effect.

We explore how the Efimov spectrum is influenced by the Coulomb force by adding a Coulomb potential to a Gaussian potential. The Gaussian potential can be regarded as the leading order term in an EFT expansion of any short-range potential.

For increasing strength of the Coulomb potential we expect a transition from the Efimov regime to a regime that is dominated by the Coulomb force. We use the Gaussian expansion method [4] to numerically calculate spectra with different strengths of the Coulomb coupling.

The universality of the resulting spectra is reduced and a second parameter in addition to the scattering length is needed to describe a physical system even in leading order. In addition we analyse the structure of the states and how it changes with increasing strength of the Coulomb potential. This is discussed in light of the spectra.

We then investigate nuclear systems and analyse how well they fit the universal theory we developed.

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Threshold Effects and the Line Shape of the $X(3872)$ in Effective Field Theory*

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Latest measurements suggest that the $X(3872)$ mass lies less than 200 keV away from the $D^0\bar{D}^{0*}$ threshold [1, 2], reenforcing its interpretation as a loosely-bound mesonic molecule [3–5]. This observation implies that in processes like $D^0\bar{D}^0\pi^0$ production, threshold effects could disguise the actual pole position of the $X(3872)$ [6]. In this talk, we propose a new effective field theory for the $X(3872)$ using D^0, $\bar{D}^0$ and π^0 degrees of freedom [7]. The D^{0*} enters as a $D^0\pi^0$ p-wave resonance, assuming Galilean invariance to be an exact symmetry. That allows for a comprehensive study of the influence of pion interactions on the $X(3872)$ width. We present relations between the mass of the $X(3872)$, its width, and its line shape in $D^0\bar{D}^0\pi^0$ production up to next-to-leading-order. Our results provide a tool for the extraction of the $X(3872)$ pole position from the experimental data near threshold.

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Hyperon and hypernuclear physics with PANDA at FAIR

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The future PANDA experiment at FAIR [1] is a next-generation experiment which will shed light on some of the most challenging, unresolved problems of contemporary physics. Many of these are related to the strong interaction in the confinement domain and manifest in our poor understanding of the nucleon: despite a century of rigorous research, we neither understand its size [2], its mass, its spin [3], nor its inner structure [4]. Another question is why our Universe consists of matter and not antimatter. One piece of the latter puzzle is to find out whether charge conjugation and parity symmetry (CP) can be violated in baryon decays [5].

In the first phase of PANDA, the focus will be on hyperons. The basic question is: *"What happens if we replace a light quark in a nucleon with a heavier one?".* We use hyperons as a diagnostic tool to find answers to the aforementioned questions.

The production of hyperons involves the creation of a heavy (s, c, b) quark-antiquark pair, a process where the energy scale is governed by the mass of the produced quark. The mass of the strange quark coincides with the scale where quarks are confined into hadrons. Strange hyperons therefore provide a window to the strong interaction in a domain where our understanding remains scarce.

The weak, self-analysing decay of hyperons gives access to spin observables. These are of interest for many reasons; for example as a test of CP violation in baryon decays, the role of spin in strong interactions and hyperon electromagnetic structure.

In hypernuclear physics, strangeness provides an additional degree of freedom. Hypernuclei give unique possibilities to study nucleon-hyperon and hyperon-hyperon interactions, which in turn give insight into e.g. neutron stars.

The upcoming PANDA experiment will be a strangeness factory where a multitude of aspects of hyperon and hypernuclear physics will be studied. In this talk, I will outline the hyperon- and hypernuclear physics programmes at PANDA.

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The problem of cluster separability in relativistic few-body systems

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A convenient framework for dealing with hadron structure and hadronic physics in the few-GeV energy range is relativistic quantum mechanics. Unlike relativistic quantum field theory, one deals with a fixed, or at least restricted number of degrees of freedom while maintaining relativistic invariance. For systems of interacting particles this is achieved by means of the Bakamjian-Thomas construction, which is a systematic procedure for implementing interaction terms in the generators of the Poincaré group such that their algebra is preserved. Doing relativistic quantum mechanics in this way one, however, faces a problem connected with the physical requirement of cluster separability, as soon as one has more than two interacting particles. Cluster separability, or sometimes also termed "macroscopic causality", is the property that if a system is subdivided into subsystems which are then separated by a sufficiently large spacelike distance, these subsystems should behave independently. More formally, the Poincaré generators should become a sum of the subsystem generators upon separation of the subsystems. In the present contribution we will discuss the problem of cluster separability and its physical implications on the electromagnetic structure of bound-state currents and then try to sketch, how it may be resolved. Although it is known for quite some time [1], how mass operators and, in the sequel, Poincaré generators with correct cluster properties can be constructed for interacting few-body systems, the problem of cluster separability is usually ignored in practical applications. The solution of the cluster problem rests mainly on unitary transformations by means of, so-called, "packing operators". In the present contribution we will give an explicit construction of such packing operators for three-particle systems consisting of distinguishable particles. This should pave the way for practical applications in which correct cluster properties may be important.

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Compelete set of deuteron Analyzing Powers for dp Elastic Scattering at 70–300 MeV/nucleon and Three-Nucleon Forces

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Few-nucleon scattering at intermediate energies ($E/A \gtrsim$ 100MeV) is one attractive approach to investigate the dynamical aspects of three-nucleon forces (3NFs), such as momentum and/or spin dependences. Direct comparison between the data and the rigorous numerical calculations based on bare nuclear potentials provides information of 3NFs. So far large 3NF effects are theoretically predicted and experimentally confirmed in the cross section minimum for dp scattering at $\sim$ 100 MeV/nucleon. With the aim of clarifying roles of the 3NFs in nuclei the experimental programs with polarized deuterons beams at intermediate energies are in progress at RIKEN RI Beam Factory (RIBF) [1]. We have measured all deuteron analyzing powers (iT_{11}, T_{20}, T_{21}, and T_{22}) for deuteron–proton (dp) elastic scattering at 70–300 MeV/nucleon, typically in step of 50 MeV/nucleon.

The vector and tensor polarized deuteron beams were accelerated by three cyclotrons, AVF, RRC and SRC. The measurement of deuteron analyzing powers for elastic dp scattering was carried out using the polarimeter BigDpol installed at the extraction beam line of the SRC. The deuteron beams bombarded a polyethylene (CH_2) target in the scattering chamber. Scattered deuterons and recoil protons were detected by plastic scintillators in kinematical coincidence conditions.

The obtained high precision data are compared with the results of three-nucleon Faddeev calculations based on the nucleon-nucleon (NN) potentials; *i.e.* CD Bonn, Argonne V_{18}, Nijmegen I, and II, alone or combined with the Tucson-Melbourne'99 and the Urbana IX 3NFs. Large discrepancies between the pure NN theory and the data, which are not resolved even by adding the current 3NFs, are found at the c.m. backward angles for almost all the deuteron analyzing powers with increasing an incident energy. In the conference the comparison between the data and the calculations based on the χ EFT potentials [2] will also be presented.

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Quasi-bound state in the $\bar{K}NNN$ system

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The attractive nature of $\bar{K}N$ interaction due to the existence of subthreshold $\Lambda(1405)$ reconance has stimulated theoretical and experimental searches for K^- bound states in different systems. The interest in few-body systems was stimulated by calculations, which predicted deep and relatively narrow quasi-bound K^- -nuclear states. Many theoretical calculations devoted to the lightest possible system $\bar{K}NN$ have been performed since then, using different methods: Faddeev equations with coupled channels, variational methods, and some others, see a review [1] and references therein. All of them agree that a quasi-bound state in the K^-pp system exists but they yield quite diverse binding energies and widths.

The experimental situation is unsettled as well: several candidates for the K^-pp state were reported by different experiments. However, the measured K^- binding energies and decay widths of such state differ from each other and, moreover, are far from all theoretical predictions. Due to this new experiments are being planned and performed.

Detection of the heavier four-body $\bar{K}NNN$ system could be easier than in the case of $\bar{K}NN$ since direct scattering of K^- on three-body nuclei (such as ^{3}He or ^{3}H) can be performed. Some theoretical works were devoted to the question of the quasi-bound state in the $\bar{K}NNN$ system with different quantum numbers [2, 3], but more accurate calculations within Faddeev-type equations are needed. The reason is that only these dynamically exact equations in momentum representation can treat energy dependent $\bar{K}N$ potentials, necessary for the this system, exactly.

We will solve four-body Faddeev-type AGS equations [4] in order to study the quasi-bound $\bar{K}NNN$ systems. We will use our experience with the three-body AGS calculations, described in [1], and our two-body potentials, constructed for them. In particular, three models of the $\bar{K}N$ interaction will be used: the separable potentials having one- or two-pole structure of the $\Lambda(1405)$ resonance and a chirally motivated model. All the three potentials describe low-energy K^-p scattering and $1s$ level shift of kaonic hydrogen with equally high accuracy. This will allow us to study the dependence of the four-body results on the two-body input.

In our three-body calculations [1] we took the coupling between the $\bar{K}N$ and $\pi\Sigma$ channels into account explicitly and solved AGS equations with coupled $\bar{K}NN$ and $\pi\Sigma N$ channels. But a reliable calculation of a four-body problem is much harder task than a three-body one. That is why we will use the exact optical $\bar{K}N$ potential, which is energy-dependent, corresponding to three our antikaon-nucleon potentials with coupled channels. We shown [1] that the one-channel three-body calculation with such potential is a very good approximation to the problem with coupled channels and assume that it is true for the four-body case.

We will also construct and use a separable expansion of the three-body amplitudes, entering the kernels of the four-body equations, in order to reduce the dimension of the system of integral equations [5].

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Tetra-neutron system populated by RI-beam induced reactions*

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Study of multi-neutron systems is one of fundamental subjects in nuclear physics. We have found a candidate resonant tetraneutron in an exothermic double-charge exchange reaction ^{4}He(^{8}He,^{8}Be) at 190 A MeV[1]. Production mechanism with kinematical consideration including relevant reaction process is introduced, where amounts of energy and momentum transfers in the reaction are emphasized. An analysis procedure on the four-body continuum system is presented and nuclear forces relevant for formation are discussed. Recent experimental results are also shown.

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Tetraneutron resonance in the Single-State HORSE approach

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A low-lying resonance in the system of four neutrons (tetraneutron) was recently first observed by Kisamori *et al.* [1]. To the best of our knowledge, a theoretical description of this resonance was presented only in our paper [2]. In Ref. [2], we used the JISP16 NN interaction and a recently proposed Single-State HORSE formalism [3] extended to the case of democratic decays which is able to extract resonance energies and widths from the results of the No-Core Shell Model (NCSM) calculations.

A further development of the Single-State HORSE formalism together with new results obtained with various models of inter-nucleon interactions in extended NCSM model spaces will be presented.

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A simple tool to study many-body forces

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The envelope theory [1, 2], also known as the auxiliary field method, is a technique to compute approximate solutions of a quantum system with N identical particles. It has been generalized for various systems with arbitrary kinematics and one- or two-body potentials [3, 4]. The basic idea is to replace the Hamiltonian H under study by an auxiliary Hamiltonian $\tilde{H}$ which is solvable, the eigenvalues of $\tilde{H}$ being optimized to be as close as possible to those of H. The method is easy to implement since it reduces to find the solution of a transcendental equation. Recently, its accuracy has been tested for eigenvalues and eigenvectors by computing the ground state of various systems containing up to 10 bosons [5, 6]. We show here that the envelope theory can be extended to compute the eigensolutions of a system of identical particles with a type of many-body forces often used in phenomenological models.

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Analytic model of a multi-electron atom

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The choice of the initial approximation for the single-electron wave functions (SEWF), plays an important role in modern quantum chemistry, both in the framework of the density functional theory or the solution of the Schrödinger equation. It is well known that the numerical solutions of the Hartree-Fock (HF) equations provide the best possible zeroth-order approximation for SEWF. The inclusion of many HF configurations (MCHF) or application of various post-HF methods [1] allows one to include corrections due to correlation effects.

However, despite the great efficiency of modern numerical algorithms [1], simple analytical approximations still play an important role for many applications, where there is no need for extremely high accuracy, but a simple algorithm of repeated calculations of atomic characteristics is required. For example, the models based on, e.g., the Thomas-Fermi or multi-parametric screening hydrogen [2] approximations are widely used in computational plasma and X-ray physics [2], crystallography [3] or semiconductors physics [4]. In addition, the simplest possible inclusion of screening corrections in various cross sections like bremsstrahlung or pair production is required for later usage in particle-in-cell computer codes for simulation of strong laser-matter interaction, where computational efficiency is crucial.

In the present work [5] we suggest a new basis set of fully analytical SEWF, which on the one hand provides a sufficiently accurate *analytical* zeroth-order approximation and on the other hand allows one to construct regular perturbation theory (RPT) for the inclusion of higher-order corrections. Our basis set includes the hydrogen-like wave functions with a single-variational parameter, namely the effective charge Z^*, which is identical for all SEWF of a given atom. The fact that the effective charge is identical for all SEWF is the principal difference of our approach in comparison with the inclusion of the multi-parametric screening corrections or the quantum defect method.

The identical effective charge for all wave functions automatically provides the complete and orthonormal basis and, consequently, renders the transition into the secondary-quantized representation natural. We have demonstrated that the *analytical* zeroth-order approximation contains the whole spectrum of a multi-electron atom and constructed a perturbation theory series, which converges fast with the rate $\sim 1/10$. In addition, we stress here that the accuracy of our results does not depend on the number of electrons in an atom, i.e., our approximation is uniformly available for all atoms or ions. Moreover, the results via second-order perturbation theory, are comparable with those via MCHF.

Finally we provide a software package, which allows automated calculation of the observable characteristic of multi-electron atoms. Our results in the zeroth-order approximation are *fully-analytical* and provide better qualitative and quantitative description in comparison with the Thomas-Fermi model, thus allowing to substitute the latter in all actual applications.

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Search for Deeply Bound Kaonic Nuclear States by AMADEUS. *

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Deeply Bound Kaonic Nuclear States are currently one of the hottest topics in nuclear and hadronic strangeness physics, both from experimental and theoretical points of view. The existence of bound kaonic nuclear states of K^-, also called kaonic nuclear clusters, was firstly predicted in 1986 [1]. The phenomenological investigations, resulted in deeply bound nuclear states with narrow widths and large binding energies which can reach 100 MeV in kaon-nucleon-nucleon system (K^-pp), being a consequence of the strongly attractive K^- - proton interaction. Recent theoretical studies, based on different methods are giving a wide range of possible values for the binding energies of the kaonic nuclear states, ranging from few MeV up to about 100 MeV [2, 3, 4, 5]. Therefore, in order to clarify this issue, experimental data are needed. The research would be very important in understanding the fundamental laws of the Nature and Universe. It can have important consequences in various sectors of physics, like nuclear and particle physics as well as astrophysics. The binding of the kaon in nuclear medium may impact on models describing the structure of neutron stars (Equation of State of neutron stars) [6, 7] including binaries which are expected to be sources of the gravitational waves. Investigation of stable forms of strange matter like DBKNS in extreme conditions would be helpful for a better understanding of elementary kaon - nucleon interaction for low energies in the non-perturbative quantum chromodynamics (QCD) and in consequence, would contribute to solve one of the crucial problems in hadron physics: hadron masses, hadron interactions in nuclear medium and the structure of the dense nuclear matter.
The AMADEUS group has developed a method having a high chance for discovery of DBKNS corresponding to K^-pp, K^-ppn and K^-ppnn kaonic nuclear clusters and their decay to Λp, Λd and Λt, respectively. The method is based on the exclusive measurement of the momentum, angular and invariant mass spectra for correlated Λp, Λd, Λt [8]. Possible DBKNS may be produced with K^- stopped in helium or carbon and then decay into considered decay channels. The experiment was carried out with very high precision and high acceptance by AMADEUS using the KLOE detector itself as an active target (2004-2005) as well as with dedicated high purity graphite target (2012) and using low-energetic negatively charged kaon beam provided by DAΦNE collider located in National Laboratory in Frascati (Italy). The poster will present status of the data analysis.

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Search for the η-mesic helium in proton-deuteron and deuteron-deuteron reactions.

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The existence of η-mesic nuclei in which the η meson is bound in a nucleus by means of the strong interaction was postulated already in 1986 [1] but it has not been yet confirmed experimentally. The discovery of this new kind of an exotic nuclear matter would be very important as it might allow for a better understanding of the η meson structure and its interaction with nucleons [2, 3]. The search for η-mesic helium is carried out with high statistics and high acceptance with the WASA detector, installed at the COSY accelerator in the Research Center Jülich [4, 5, 6, 7]. The search is conducted via the measurement of the excitation function for selected decay channels of the ^{4}He-η and ^{3}He-η systems. The talk will include description of the experimental method used at WASA and the status of the data analysis. We will emphasize new results from the search of ^{3}He-η mesic nucleus via non-mesonic decays.

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Pairing correlations play crucial roles in atomic nuclei and in quantum many-body physics in general. They are responsible for the odd-even staggering observed in the binding energy of atomic masses, for the fact that all even nuclei have a $J=0^+$ ground state, and for their small moment of inertia as compared to a rigid body. More generally, pairing correlations imply a smoothing of the level occupancy around the Fermi energy surface, an enhancement of pair transfer probabilities, as well as a superfluid behavior in the nuclear rotation and vibration. Transition from BCS (Bardeen Cooper-Schrieffer) to BEC (Bose-Einstein Condensation) pairing correlations has been evoked from the modelling of the interior to the surface, respectively, of some neutron-rich nuclei [1]. Despite its tremendous importance, the real observation of the decay of paired nucleons is very scarce, as difficult to evidence.

In the present work, we used the high-energy nucleon knockout reactions $^{19}N(-1p)^{18}C^*$ and $^{21}O(-1n)^{20}O^*$ at GSI/R3B as a `piston' to suddenly promote neutron pairs of ^{18}C and ^{20}O, respectively, into the $^{16}C+n+n$ and $^{18}O+n+n$ continuum. Dalitz plots and correlation functions are used to analyze triple correlations in these systems over a decay energy up to 12 MeV above the corresponding two-neutron emission thresholds. An attempt is made to link these observables to the role of the reaction mechanism and to the pairing configurations of ^{18}C and ^{20}O, where the four neutrons above the ^{14}C and ^{16}O cores may be coupled in pairs or in tetra neutron configurations. The correlation between the two neutrons in ^{18}C is the largest ever observed in any quantum system [2].

In a second experiment, we studied the neutron correlations in the unbound nucleus ^{28}F, using a similar Dalitz analysis. The goal was to search for a possible existence of a di-neutron state (connected to the BEC transition), and see if the Ikeda conjecture, proposed to account for the presence of narrow cluster states around the corresponding energy thresholds, can be extended to neutron clusters above the two-neutron separation energy. This nucleus was produced at RIKEN/SAMURAI in the neutron and proton knockout reactions from ^{29}F and ^{29}Ne radioactive beams, respectively.

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Masses and structure of heavy quarkonia and heavy-light mesons in a relativistic quark model in Minkowski space*

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We use the Covariant Spectator Theory (CST) [1, 2] to calculate the masses, vertex functions, and decay constants of heavy and heavy-light mesons, described as quark-antiquark bound states. The CST two-body bound-state equation is similar to the Bethe-Salpeter equation, an integral equation formulated in Minkowski space with a kernel of two-particle irreducible Feynman diagrams describing the quark-antiquark interaction, except that the relative-energy loop integration is carried out by taking only the residues of the quark propagator poles into account. Cancelations between the omitted kernel pole contributions make sure that the equation has the correct limit when one quark becomes very heavy, which makes it particularly suitable to describe unequal-mass mesons.

The quark-antiquark dynamics is described through a kernel with an adjustable mixture of Lorentz scalar, pseudoscalar, and vector linear confining interactions, together with a Lorentz-vector one-gluon-exchange kernel. Although in principle scalar and pseudoscalar interactions break chiral symmetry, our formalism allows us to include such interactions and still satisfy the constraints of chiral symmetry, which will be of great importance when we extend our calculations to the light quark sector. Since the Lorentz structure of the confining interaction is not well known, varying the weights of the different structures allows us to study the sensitivity of meson properties to the Lorentz structure of the kernel, and to find out if a particular combination is preferred.

The inclusion of an unscreened linear confining interaction in momentum space required the development of special analytical and numerical techniques, which can be thoroughly tested in the nonrelativistic domain, where the exact solutions are known in some cases. Our method [3] turned out to work very reliably, leading to numerically stable results with both the nonrelativistic confining potential and the relativistic generalization we use in the meson calculations. In particular, we are able to calculate higher radially excited states, of which a fair number have been measured in bottomonium and charmonium.

We performed a series of fits to the heavy and heavy-light meson spectrum, and found that very good agreement can be achieved by adjusting a small number of global model parameters [4, 5]. We also found that the decay constants are highly sensitive to details of the calculated vertex functions. Some of these decay constants have been measured with high precision, and can be used to constrain the high-momentum behavior of our kernel. I will discuss what conclusions can be drawn from our results, especially about the Lorentz structure of the kernel.

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Differential cross section for deuteron breakup in collision with proton - measurements at intermediate energies.

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Reactions in three-nucleon systems at intermediate energies, between 50 and 200 MeV/nucleon, attract attention due to theoretically predicted sensitivity of the observables to subtle effects of the dynamics beyond the pairwise nucleon-nucleon force, so-called three nucleon force (3NF). Precise measurements in the sector of elastic nucleon-deuteron scattering show importance of 3NF for correct description of the cross section data, though at energies above 100 MeV/nucleon the currently available models of 3NF do not produce effects sufficiently large to cure discrepancy between the data and calculations [1]. Complementary studies are conducted in the sector of ^{1}H(d,pp)n and ^{2}H(p,pp)n breakup reactions, characterised with the 3-body final state, rich in kinematic configurations differing in sensitivity to dynamical effects. Each experiment studying large phase space of the reaction provide numerous data, however, their interpretation is involved, since the differential cross section is sensitive to Coulomb interaction between protons, 3NF and relativistic effects. So far the Coulomb effects have been confirmed, and the 3NF shows already its importance at energies as low as 65 MeV/nucleon [1, 2]. There are also strong hints of discrepancies between data and theory at energies close to 200 MeV/nucleon. Systematic (in beam energy) set of data is necessary to single out the 3NF and relativistic effects.

The experimental studies of the breakup reaction with the BINA detector at KVI, the Netherlands [1, 2] are continued with the same detection system at CCB Krakow, Poland. The status of data analysis will be shown and the preliminary results obtained at proton beam energy of 108 MeV will be discussed.

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Universality in few-body systems*

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We explore ground state properties of quantum few-body systems which consist of one, two or three different atom species. Stability of different clusters consisting of spin-polarized hydrogen, helium, neon, argon, alkali and alkaline earth isotopes is determined and their structure is analyzed. The study of realistic systems is supplemented by model calculations in order to fill gaps and test influence of the interaction potential model. For selected masses and interaction models exact ground-state estimates are obtained by the diffusion Monte Carlo method and pure estimators.

Often special emphasis is given on a universality of quantum two- and three-body halo states [1, 2, 3], which prefer more to be in classically forbidden regions of space. Using dimensionless measures of the binding energy and cluster size, studied atomic clusters are compared to other known halos in different fields of physics. Different characteristic scaling lengths, which make size-energy ratio to be universal, are tested. As the scaled binding energy decreases, scaled size of samba and tango type trimers separate from Borromean type [3].

Here we make a step forward and extend size-energy universality to four- and five-body systems, starting with halo systems and tracking their behavior when going far away from the halo region toward strongly bound systems. In addition, connections between $(N+1)$- and (N)-body scaling relations are considered.

Among structural properties we emphasize helium dimers and trimers which can be compared [4] with the most recent experimental results [5, 6, 7] obtained by Coulomb explosion imaging of diffracted clusters, and helium-alkali pentamers [8] which already indicate behavior noticed in nanodroplets.

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Narrow resonance $N^*(1685)$ and η photoproduction*

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In this talk, we present recent results of the investigation on η photoproduction off the neutron, i.e. $\gamma n \to \eta n$, employing an effective Lagrangian approach and a Regge method. We focus on the bump structure at $\sqrt{s} = 1.685$ GeV, which appears mainly in the neutron channel. This phenomena is often called neutron anomaly. There are various interpretations on this bump structure: For example, it can be understood as an interference effects between $S_{11}(1535)$ and $S_{11}(1650)$. However, in this presentation, we will regard the bump structure as the $N^*(1685)$ resonance, which was put forward from the chiral quark-soliton model. Since the neutron anomaly can be easily explained by the difference of the transition magnetic moments of the neutron and proton, it is of great interest to consider this $N^*(1685)$ to describe the $\gamma n \to \eta n$ reaction. Moreover, the narrow width is also well explained by the chiral quark-soliton model. Assuming this bump structure as N*(1685), we include it in the present work. We present the results of the total and differential cross sections, and the helicity-dependent ones in comparison with recent experimental data from the CB-ELSA/TAPS and A2 collaborations.

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Studies of validity of quasiclassical approach to three-body decays

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Conventional method of width determination for resonant states, such as elastic phase shift energy dependence, or via S-matrix pole position in the complex energy plane could be technically complicated for very small widths $\Gamma \ll E$. Therefore studies of radioactive decays require specific methods for the decay width determination. Among them are "natural" width definition via WF with pure outgoing asymptotics [1], Kadmensky type integral formulas [2], and quasi-classical approach of Gamow type [3].

Use of quasi-classical approach of Gamow type for the decay width evaluation

$$\Gamma \sim \exp\left[-\int_{r_1}^{r_2} p\, dr\right] ,$$

require reduction of few-body problem to a single-channel formalism of some form, where Gamow integral over the sub-barrier trajectory $\{r_1, r_2\}$ can be defined. Here both the validity of the few-body problem reduction and the applicability of the quasiclassical approximation for barriers of specific shape can be questioned.

Formalism of the Gamow type has been repeatedly used in the recent years for determination of three-body decay widths (e.g. [3, 4]). We examine the validity of this approximation by example of the width of the first excited $3/2^-$ state state of ^{17}Ne, which is known to decays via so-called "true" two-proton decay mechanism. The width of this state is important for determination of the astrophysical capture rate for ^{15}O$+p+p \rightarrow {}^{17}$Ne$+\gamma$ reaction [5]. Theoretical calculations of this width so far has produced considerable controversy [6, 3, 2, 4]. Recently this issue was revisited experimentally [7] providing improved limits for the width value and looking for realistic methods to further improve measurements of this quantity. This activity also urges improved theoretical treatment of the case.

Our results question validity of the widths obtained in [4].

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Symmetry motivated electron-based approach to the Standard Model

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We consider unexpectedly accurate relations between nucleon masses and the electron rest mass.

From CODATA evaluation [1] one can find that the shift of the neutron mass value relative to $115\delta - m_e$ is equal to δm_n=161.56(6) keV which accounts an integer ratio $\delta m_N/\delta m_n$=8·(1.0001(1)) with nucleon mass splitting δm_N=1293 keV. It was considered as a fine structure with the period 161 keV=$\delta m_N/8$.

This approach beyond the Standard Model starts from the observations:
1) pion's mass splitting δm_π=4594 keV is close to $9m_e$=4599 keV. Hence the doubled value of pion's β-decay energy is close to the CODATA period δ=$16m_e$.
2) Empirical relations found by Y. Nambu and A. Hautot $\mathrm{m}_N = m_\mu + 6m_\pi$ and $m_\pi/m_\mu = 17/13$, respectively, allow to introduce the period of $(m_\pi + m_\mu)/(17{+}13)$=8174 keV, very close to δ=8176 keV. Masses m_μ, m_π, m_N, f_π=130.7 MeV and ΔM_Δ=147 MeV=$(m_\Delta - m_N)/2$ are close to nδ (with n=13,16-18,115, where n is a number of the period δ).

Discreteness in differences ΔM between 137 particle masses from PDG-2016 was found [2,3]. Maxima at 17 MeV=2δ, 48 MeV=6δ, 104 MeV=m_μ, 142 MeV=m_π, 445-462 MeV close to M_q=$3\Delta M_\Delta$ (close to the initial constituent quark mass in NRCQM), 1687 MeV=$12m_\pi$, 3370 MeV=$24m_\pi$, 3959 MeV=$9\mathrm{M}_q$ and 4425 MeV=$10\mathrm{M}_q$ were observed. Stable intervals ΔM=m_π, $12m_\pi$ and $24m_\pi$ appear in the particles containing the charm quarks, while intervals ΔM=$9\mathrm{M}_q$ and $10\mathrm{M}_q$ - in the particles containing the beauty quarks.

Discreteness with CODATA parameter δ=$16\mathrm{m}_e$ extended up to the higher energies. The lepton ratio L=$\mathrm{m}_\mu/\mathrm{m}_e$=207 was found between vector boson masses M_Z, M_W and constituent quark masses M_q, $\mathrm{M}"_q$=$3f_\pi$ as well as long-range correlation with δ in values of the scalar and the top-quark masses [4,5].

We come to the conclusion that during the description of the hadronization process [6] consideration of the symmetry motivated discreteness based on the electron (CODATA relations) should be taken into account [7].

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Study of a 5-alpha cluster candidate with the 22Ne(p,t) and 22Ne(p,3He) reactions

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A study performed with the K600 magnetic spectrometer and a 60 MeV beam of protons from the SSC cyclotron facility at iThemba LABS in South Africa, has indicated the existence of a tentative candidate for a 0^+ 5-alpha cluster state at E_x = 22.5 MeV in ^{20}Ne [1]. This state was populated by the ^{22}Ne(p,t)^{20}Ne transfer reaction on a gas target of ^{22}Ne. The present experiment follows up on this study, with the ^{22}Ne(p,t)^{20}Ne reaction this time explored at 80 MeV and with a wider range of scattering angles, including at forward angles to enhance low-spin states, thereby ensuring that the spin and parity can be reliably ascertained. In addition to this, the ^{22}Ne(p,^{3}He)^{20}F reaction was also employed to verify the nature of isobaric analogue states which were observed in a region near to the 5-alpha candidate in ^{20}Ne, by looking for these states in an analogue nucleus. This additional reaction was included to ensure that the low-spin states in the region of the candidate at E_x = 22.5 MeV are well understood, and also to verify that the E_x = 22.5 MeV state itself has an isospin of T = 0. Results from this study at E_p = 80 MeV will be presented.

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Investigating 16O above the 4-alpha breakup threshold *

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The p + ^{15}N reaction was used to probe the ^{16}O nucleus at excitation energies of E_x = 12.4 to 15.5 MeV, using a proton beam at energies of E_p = 0.33 to 3.80 MeV from a 5MV Van de Graaff accelerator. Being above both the alpha and proton break-up thresholds of ^{16}O, the relative strengths of alpha and gamma decay from this region is of vital importance to the ratio of $^{16}O/^{12}C$ during the CNO cycles of massive stars, which in turn influences to the abundances of elements at a later stage of a star's life. The 0_6^+ state received special attention, since it is the primary candidate for the 4-alpha cluster state in ^{16}O, and known to have a strong alpha-decay component. Recent experimental evidence has pointed to a $2^+/3^-$ state at E_x = 15.046 MeV which may have interfered with measurements of the 0_6^+ state in the past [1]. This state was also thoroughly investigated. The decays were studied using an array of four DSSD detectors around a target of $C_{15}N$. This setup also allows for a clean measurement of gamma-ray decays by looking at particle energies. Preliminary results from this experiment will be presented.

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Discrete scaling and scattering properties from atom-dimer collision *

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A new perspective to detect the Efimov-like discrete scaling, as suggested in [1], is reported by considering low-energy scattering data in experiments with ultra-cold binary mixtures having strong mass asymmetries. For that one could investigate low-energy scattering observables that can emerge from experiments involving condensed atomic mixtures such as Lithium and Caesium or Lithium and Ytterbium [2]. The discrete scaling behavior is identified in the energy dependence of atom-molecule elastic cross-section in mass imbalanced systems, when having the collision of a heavy atom with mass m_H with a weakly-bound dimer formed by the heavy atom and a lighter one with mass $m_L \ll m_H$. Approaching the heavy-light unitary limit the $s-$wave elastic cross-section will present a sequence of zeros/minima at collision energies following closely the Efimov geometrical law. The emergence of this scaling is shown explicitly by applying the adiabatic Born-Oppenheimer approximation to the low-energy two-atomic species atom-dimer collision, in which the colliding atom is the heavy particle.

Next, by considering a more general imbalanced-mass three-body systems, where the mass asymmetry is less pronounced, I am also reporting some characteristics results obtained in a recent investigation [3], considering the collision of one of the species against the dimer formed by the remaining two atoms. In this case, we are extending to the scattering region a previous study on three-body weakly-bound molecules [4]. The corresponding scattering properties given by $s-$wave atom-dimer cross-sections and absorption parameter are illustrated for different combinations of helium-4 (^{4}He), isotopes of lithium (^{6}Li and ^{7}Li), and sodium (^{23}Na). As a three-body system near the unitarity is governed by the Efimov physics, being not sensible to details of the interaction, in our approach we consider two-body separable, zero- and finite-ranged potentials, with the two and three-body bound-state energies fixed by the available data and model results [5].

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A comprehensive measurement of differential cross sections and analysing powers in the proton-deuteron break-up channel at 135 MeV

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A detailed description of nuclear forces is essential for understanding the properties of nuclei and the dynamics in few-nucleon scattering processes. Although observables in the two-nucleon systems can be obtained with unprecedented precision using modern two-nucleon potentials, the same potentials are not able to describe the three-nucleon systems. The need for an additional three-nucleon potential became evident when comparing three-body scattering observables and light-nuclei binding energies with state-of-the-art calculations [1]. In this work, the analysing powers (A_x and A_y) and differential cross sections are presented for the proton-deuteron break-up reaction studied with using a polarised-proton beam at 135 MeV impinging on a liquid-deuterium target. For the experiment we used the Big Instrument for Nuclear-polarisation Analysis (BINA) at KVI, the Netherlands. BINA is composed two main parts, a forward wall to detect protons that scatter between 10°-35° and a backward ball covering polar angles between 32°-160°. With this setup, we recently expanded our measurements of cross sections and analyzing powers from earlier presented result [1]. In particular, we measured for the first time A_x for a large range in the kinematical S-curve, polar and azimuthal angles of the two outgoing protons.

Cross section and analysing power data are compared to predictions from Faddeev calculations that are based on modern two-nucleon and three-nucleon potentials. Our polarisation data are reasonably well described by calculations for kinematical configurations at which the three-nucleon force effect is predicted to be small. However, striking discrepancies are observed at specific configurations, in particular in cases when the relative azimuthal angle between the two protons becomes small. The aim is to significantly extend the worlds database in the three-nucleon scattering system as a benchmark to eventually confine the structure of the three-nucleon interaction. In this contribution, some of these configurations along with the analysis techniques will be discussed.

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Three-nucleon force contribution to the distorted-wave theory of (d,p) reactions

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In the last two decades rapid advances have been made in the implementation of the three-nucleon force (3NF) in nuclear structure calculations and its importance for various nuclear properties has been demonstrated. However, another large branch of nuclear physics – direct nuclear transfer reactions - is still based exclusively on Hamiltonians with two-body interactions only. These reactions are studied experimentally in many radioactive beam facilities, such as ISOLDE (CERN), RIKEN (Japan) or TRIUMF (Vancouver), to provide an important source of knowledge about single-particle nuclear structure and, more recently, to serve as a testing ground for ab-initio theories, in which the 3NF is often included.

In this talk I will present the first calculations of the 3NF contribution to the distorted-wave theory of (d,p) reactions [1]. I will discuss the qualitative difference between this contribution and the contribution from two-nucleon force only. This difference arises because of a new type of nuclear matrix elements which nuclear structure theory never dealt with before. I will discuss the challenges of the 3NF treatment in the distorted-wave theory and present a few (d,p) cross sections for double-magic nuclear targets calculated in the distorted-wave Born approximation using the contact 3NF whose strength has been fixed by the chiral effective field theory at the next-to-next-to-leading order. Introducing a 3NF into distorted-wave theories will pave the way to a consistent comparison of spectroscopic factors, calculated in ab-initio theories with 3NF, with those deduced from experiments with the help of reaction theory in which 3NF are included as well.

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Radiative $^3He(^2H,\gamma)^5Li$ capture at astrophysical energy and its possible role in accumulation of ^6Li at the BBN

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We see the interest to the radiative capture reactions in the isobar-analogue channels $^3He(^2H,\gamma)^5Li$ and $^3H(^2H,\gamma)^5He$ is due to following two main reasons. The new data may be found in [1] on their application in the diagnostics of nuclear fusion efficiencies of $^2H(^3H,n)^4He$ and $^2H(^3He,p)^4He$ reactions used for study of tokamak plasmas in experiments on JET and ITER. The latest data on plasma diagnostics are presented in [2].

These reactions are also parts of nucleosynthesis chain of the processes occurring on the early stage of stable stars formation, as well as possible candidates for the overcoming of the well-known problem of the $A = 5$ gap in the synthesis of light elements in the primordial Universe [3].

There is an "unambiguous" opinion: due to the smallness of the cross section of the $^3He(^2H,\gamma)^5Li$ reaction, it does not contribute to the astrophysical processes [4]. However, this statement is not entirely true, since the rate of this reaction is not negligible. In addition, we consider a possible scenario for astrophysical processes of ^6Li formation involving a short-lived ^5Li isotope.

The radiative $^3He(^2H,\gamma)^5Li$ capture is considered on the basis of the modified potential cluster model (MPCM) [5] and new results are obtained for dipole $E1$ and $M1$ transitions, taking into account the mixing of the doublet and quartet spin channels, both in scattering states and for the bound ground state. The potentials of the intercluster interaction were constructed on the basis of the description of the known scattering phase shifts and the main characteristics of the ground state (GS) of ^5Li. The total cross sections of the $^3He(^2H,\gamma)^5Li$ capture at energies from 5 keV to 5 MeV in c.m. are calculated on the GS of ^5Li. For the astrophysical S-factor and the rate of this reaction, obtained in these calculations, simple analytic parametrizations are proposed.

The parametrization of the cross sections for the $^3H(^3He,\gamma)^6Li$ and $^5Li(n,\gamma)^6Li$ processes of radiative capture is carried out. Corresponding the rates of these processes were calculated, their parametrization was performed, and a comparison with the $^3He(^2H,\gamma)^5Li$ and $^4He(^2H,\gamma)^6Li$ capture reactions rate was made.

On the basis of comparisons of the rates of these reactions and the prevalence of light elements, it is assumed that the two-step process $^2H + {}^3He \to {}^5Li + \gamma$ and $n + {}^5Li + \gamma \to {}^6Li + \gamma$ can make a definite contribution to the production of ^6Li at the BBN at least at temperatures T_9 of the order of unity. In this temperature range the number of neutrons has not yet begun to decrease, and the number of ^2H and ^3He nuclei is already reaching its maximum, which leads to increase in the reaction yield $^2H + {}^3He \to {}^5Li + \gamma$.

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Energy-momentum tensor for unpolarized proton target*

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The discovery of the relation between the quantum energy-momentum tensor (EMT) and General Parton Distributions [1, 2] provides a unique way to study the EMT of the nucleon [3,4].

It was shown that the expectation value of the EMT for an unpolarized proton target in the forward limit has the same structure as that of a perfect fluid [5]. The generalization of this result to a more general class of frames [6] leads to a more general EMT structure similar to that of an anisotropic perfect fluid density in the Breit frame. In this case additional terms can be related to the internal energy and transverse/radial pressure inside an unpolarized proton target.

We illustrate these results using current phenomenological knowledge of the EMT form factors.

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Astrophysical S-factor of the direct $\alpha(d,\gamma)^6$Li capture reaction in a three-body model

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Astrophysical S-factor of the direct $\alpha(d,\gamma)^6$Li capture reaction is evaluated in a three-body model [1, 2]. The final ^{6}Li nucleus is described as a bound state of $\alpha + p + n$ in the Hyperspherical Lagrange mesh method. At the long-wavelength approximation, E1 transitions are forbidden between isospin-zero states. Hence E1 radiative capture is strongly hindered in reactions involving N = Z nuclei but the E1 astrophysical S factor may remain comparable to, or larger than, the E2 one. It is shown that the theoretical estimation for the isovector E1 capture due to the small isovector component of the final ^{6}Li nucleus with a norm square of order 10^{-3} is dominant at low astrophysical energies. The E2 S-factor is estimated with the three body wave function with corrected asymptotics at a distance of 5-10 fm.

The astrophysical S factor computed in the three-body model is in a very good agreement with the recent low-energy experimental data of the LUNA collaboration [3] (see Fig. 1). This confirms that a correct treatment of the isovector E1 transitions involving small isospin-one admixtures in the wave functions should be able to provide an explanation of the data without any adjustable parameter. The exact-masses prescription which is often used to avoid the disappearance of the E1 matrix element in potential models is not founded at the microscopic level and should not be used for such reactions [2].

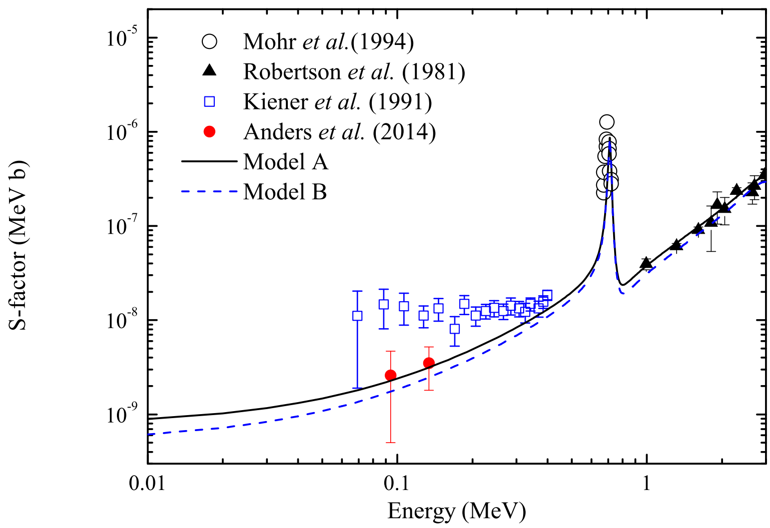

Figure 1: Astrophysical S factor within the three-body model in comparison with experimental data. Model A(B) is based on the Kukulin *et al.* (Kanada *et al.*) αN potential

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Few-body insights of multiquark exotic hadrons

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Quark model calculations have played a pivotal role in the description of few-body system for the last 40 years. Starting from the seminal works by Appelquist [1] and Eichten [2] about the structure of the charmonium it is fair to state that our current understanding on the hadron structure would not have been possible without the abundance of quark model results accumulated during these decades.

Our aim in this talk is to illustrate the description of systems made of up to six quarks and antiquarks in the framework of the quark model and to evaluate the important, and sometimes misunderstood, role played by some of the hypothesis usually considered in the literature.

Systems made of more than three quarks are the simplest systems where color dynamics can be observed and studied. Therefore, the fundamental role played by the few-body color structure when describing multiquark states will be addressed in detail. A typical, usually unjustified, hypothesis is to neglect one, or many, color vectors in favor of a single color state. An often overlook consequence of this hypothesis is the fact that then the threshold is no longer a solution of the hamiltonian, and therefore special care has to be taken to distinguish bound and unbound states. This hypothesis, together with the additional assumption of discarding the antisymmetrization of the wave function components, is largely responsible of the belief that the quark model predicts a proliferation of bound multiquark states. We will prove that such conclusion is nothing more than an artifact caused by such hypothesis.

Multiquark states have been advocated to explain recent experimental data in the heavy-light sector, and there are already speculations about multiquarks containing only heavy quarks and antiquarks. With a rigorous treatment of the few-body problem in current quark models, full-charm and full-beauty tetra-quarks are found to be unbound. Thus their stability should rely on more subtle effects that are not included in the simplest picture of constituent quark models.

We will show that the variational and Born-Oppenheimer approximations are able to give energies very close to the exact ones obtained with more complex state-of-the-art numerical techniques. Following on this, the Hall-Post inequalities also provide very useful lower bounds that help to exclude the possibility of stable tetra-quarks for some mass ratios and some color wave functions. We will also carefully analyze the consequences of widely used approximations in the heavy quark sector, as it is the diquark assumption

With respect to the dynamics, probably the most interesting effect is the delicate interplay between chromoelectric and chromomagnetic interactions. Such competition may be able to produce hidden-charm pentaquarks which lie below the lowest threshold for spontaneous dissociation while playing the opposite role in the six-body sector, eliminating any possibility of obtaining bound or metastable six-body states.

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Four-body continuum with 3N-forces

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The four-nucleon continuum is of particular interest in order to test the accuracy of our present knowledge of the nucleon-nucleon (NN) and three-nucleon (3N) interactions and also since many four-nucleon reactions are important for astrophysics, energy production, and studies of fundamental symmetries. We present a study of the effect of 3N forces in various four nucleon reactions as $p - {}^3$He, $p - {}^3$H, $n - {}^3$He, and $d - d$ for energies below the breakup threshold in three subclusters. The calculations are performed solving the four-body quantum mechanical problem using the Kohn variational principle and the hyperspherical harmonics (HH) technique [1] and considering NN and 3N interactions derived from chiral effective field theory, taking fully into account of the Coulomb repulsion between the protons.

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Microscopic studies of alpha clustering in light nuclei*

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Starting from the first principles, we conduct a triple-alpha clustering study of ^{12}C. Along with a number of structural questions we explore the decay amplitudes for the direct and sequential processes, discussing the intermediate alpha-alpha configuration of ^{8}Be. For this study we put forward a new approach, Ref. [1], that is based on the configuration interaction technique combined with the Resonating Group Method. The new microscopic method involves antisymmetrization over all nucleons, and maintains translational invariance. Our approach is applicable to various types of clustering, and under appropriate approximations reduces to well-established previously used techniques. We illustrate the power of the approach using other applications to alpha clustering in ^{8,10}Be and in ^{20}Ne.

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Measurement of ^{3}He analyzing power for $p - {}^3$He elastic scattering at 70 MeV

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The three-nucleon force (3NF) is essentially important to clarify various nuclear phenomena, such as the binding energy of light mass nuclei [1], the equation of state of nuclear matter [2] and few-nucleon scattering systems [3]. With the aim of exploring the properties of the 3NF in four-nucleon scattering systems we are planning the measurement of p–^{3}He scattering with the polarized ^{3}He target at intermediate energies ($E/A \geq 65$ MeV).

We developed the polarized ^{3}He target for the measurement of ^{3}He analyzing power. Polarized ^{3}He was produced by the spin-exchange optical pumping (SEOP) method. In this method, ^{3}He was polarized by a two step process. First, Rb vapor is polarized by optical pumping with circularly polarized light in the presence of static magnetic field. Second, the polarization of Rb atom is transferred to ^{3}He nuclei by spin-exchange interaction. To measure the ^{3}He polarization and control the spin directions of ^{3}He nucleus, we used the adiabatic fast passage–NMR (AFP–NMR) method. We obtained the absolute value of the ^{3}He polarization and calibrated the NMR signal by the electron spin resonance (ESR) measurement of Rb. We obtained ^{3}He polarization of about 20 %.

Using the polarized ^{3}He target, we performed the measurement of ^{3}He analyzing power with 70 MeV proton beams at the Cyclotron and Radioisotope Center (CYRIC), Tohoku University. Proton beams were injected to the target, and scattered protons were detected by using $E-\Delta E$ detectors which consisted of plastic and NaI(Tl) scintillators. Measured angles were from 35° to 110° in the laboratory system ($47^\circ - 129^\circ$ in the center of mass system). During the experiment, we measured the ^{3}He polarization and flipped the spin directions of ^{3}He nucleus by using the AFP–NMR method. We extracted ^{3}He analyzing power by measuring the asymmetry of elastically scattered protons from the polarized ^{3}He target.

In the conference we will report results of this experiment.

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Nuclear short-range correlations - The contact relations

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The main focus of our research is the study of nuclear short-range correlations (SRCs), i.e. the implications of finding two nucleons close to each other inside the nucleus. Such correlations were studied extensively in the last few decades, but full understanding of their implications is still missing. For this purpose we use a new theoretical tool, called the nuclear contact formalism, originally designed for atomic systems, to find direct relations between different nuclear quantities and the probability of finding two nucleons in a close proximity inside the nucleus. One of the main assumptions behind this theory is the possibility to describe such a pair of nucleons as an isolated two-body system. It reveals the importance of few-body subsystems for the full understanding of heavy nuclei.

In order to use this method, significant changes in the original formalism had to be made. These necessary modifications were recently introduced [1], and the generalized nuclear contact formalism can be now used to study nuclear SRCs. So far, we were able to describe using this theory several nuclear quantities and reactions that are related to two-body short-range correlations. For example, a new asymptotic relation between the one-body and two-body momentum distributions was derived and verified using available ab-initio numerical data [1]. Additionally, Levinger's quasi-deuteron model for the nuclear photo-absorption cross section was rederived using the contact formalism. As a result, a surprising relation between the photo-absorption cross section and the nuclear momentum distributions was revealed and verified numerically [2, 3]. We were also able to extract the values of the dominant nuclear contacts for $A \leq 40$ nuclei, which are a measure for the number of correlated pairs in the different channels [4]. The nuclear contacts are also directly related to the Coulomb sum-rule [5].

Recently, we utilized the contact formalism to study exclusive electron scattering experiments, which are one of the main experimental tool for studying nuclear SRCs. Preliminary results show a good description of available experimental data. Our analysis also provides predictions for future experiments.

The nuclear contact formalism seems to become a powerful tool for studying nuclear SRCs. It reveals the implications of few-body subsystems on the full description of heavier nuclei, and deepens our understanding of nuclear SRCs.

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The quest for new data on the Space Star Anomaly in pd breakup

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Even though the development of the theories providing a precise description of few-nucleon interactions is well advanced, certain inconsistencies between experimental data and theoretical predictions are still to be resolved. One of the most intriguing discrepancies observed in the proton-deuteron breakup reaction is known as the Space Star Anomaly [1]. It concerns a very special geometrical configuration, where the momentum vectors of the reaction products are of the same length. What is interesting, the experimental evidence shows that the effect marks its presence at low energies (7.5-13 MeV/nucleon) [2], to the contrary to the inconsistencies attributed to the so-called three-nucleon force.

Unfortunately, the highest energies analysed with this respect were 19 MeV [3] and 65 MeV [4]. Therefore due to a poor coverage of the energy range it was not possible to draw clear conclusions about the source of the effect. The measurement and the calculations at 65 MeV show lack of the Space Star Anomaly at this energy and, on the other hand, enhanced sensitivity to relativistic effects [5]. Systematic studies in the domain of energy and for various orientations of the star relatively to the beam direction are important for better understanding of the process dynamics. The Big Instrument for Nuclear-polarization Analysis (BINA) [6, 7], currently at the Cyclotron Centre Bronowice (CCB) in Cracow, is one of the detectors well suited for such studies. The research programme of the experiment aims i.a. at providing some additional data on the Space Star cross-sections.

In this contribution, the thorough description of the Space Star Anomaly effect will be presented. The latest theoretical predictions based upon Refs. [8, 9] will be compared with each other and with the very first preliminary data points for the star configuration obtained with the BINA experimental setup for the beam energies $\geq$ 50 MeV/nucleon, as the next step in the research programme started recently [10].

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Three-nucleon continuum reactions with semilocal coordinate-space regularized chiral forces*

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Solving three-nucleon (3N) scattering exactly in a numerical sense up to energies below the pion production threshold allows one to test the 3N Hamiltonian based on modern nucleon-nucleon (NN) potentials and three-nucleon forces (3NF's). At higher energies (above ≈ 60 MeV) for some observables large 3NF effects are predicted when using (semi)phenomenological models such as TM [1] or Urbana IX [2], combined with standard NN interactions (AV18 [3], CDBonn [4], NijmI and II [5]). Some nucleon-deuteron (Nd) elastic scattering cross sections and polarization data support these predictions. In some other cases, however, defects of the (semi)phenomenological 3NF's are demonstrated [6]. Relativistic effects are found to be small for the elastic scattering cross section and negligible for spin-observables at higher energies [7]. The discrepancies at high energies, which remain even when Urbana IX or TM 3NF's are included, point to the importance of short-range contributions to the 3NF. Application of improved, semilocal coordinate-space regularized chiral NN interactions up to N^4LO order of chiral expansion [8] combined with N^2LO 3NF's [9] supports conclusions obtained with standard forces. It can be expected that an application of consistent chiral NN and 3NF's up to N^3LO [10, 11] will play an important role in understanding of elastic scattering and breakup reactions at higher energies.

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Strong decays of p wave heavy mesons in $HH\chi PT$

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In this work, we studied the strong decays of the famous narrow mesons $D^*_{s0}(2317)$, $D'_{s1}(2460)$ and their bottom partners within the framework of heavy hadron chiral perturbation theory. Up to next-to-leading order in $1/\Lambda_\chi$, by a fit to the three experimentally measured widths of the p wave heavy mesons, the chiral symmetry-breaking coupling constants are extracted. The single-pion decay widths for the excited charmed strange mesons are estimated to be $\Gamma(D^*_{s0}(2317) \to D^+_s \pi^0) = 9.2 \pm 2.3\, KeV$ and $\Gamma(D'_{s1}(2460) \to D^{*+}_s \pi^0) = 9.0 \pm 2.1\, KeV$, meanwhile the widths for their beauty partners are also given under the heavy quark symmetry. Our results are consistent with the experimental constraints and comparable with other theoretical predictions. Besides, the numerical analysis shows that the chiral-symmetry corrections to the widths of the bottom mesons are relatively more significant compared to those of their nonstrange partners.

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Positronium scattering from hydrogen and helium atoms at low energies

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We investigate the elastic scattering of Ps-H and Ps-He below the Ps($n = 2$) excitation threshold using the confined variational method with explicitly correlated Gaussians as basis functions [1, 2]. As an extension of the work in the reference [2], we calculate phase shifts for the elastic Ps-H scattering for partial waves $1 \leq \ell \leq 3$. We expect that the Ps-H calculation is to determine the contribution of the mixed symmetry terms to phase shifts for partial waves $\ell > 2$ and to resolve the convergence problems that occur in the calculations of Woods et al. for ${}^{1,3}D$ with the S-matrix complex Kohn variational method [3]. For the Ps-He scattering below the excitation threshold of Ps($n = 2$), we compute phase shifts, pick-off annihilation rates, and momentum-transfer cross sections for partial waves $\ell \leq 3$ to resolve the huge discrepancies between theory and experiment [4].

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Study of multi-neutron systems with SAMURAI

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$Multi-neutron\ systems$ (^3n, ^4n, ^6n, ...) have been drawing the attention of nuclear physicists around the globe for decades. But no firm conclusion has been drawn despite many experimental and theoretical efforts. These multi-neutron systems, whether existing as bound or low-lying resonances, have fundamental importance in nuclear physics [1, 2, 3, 4, 5]. They provide the possibility to investigate "*purely*" the nuclear forces which is free from Coulomb interaction, and serve as the most stringent test of our knowledge of the nuclear force. They are also essentially important for our understanding of neutron-rich nuclear matter, neutron star, and the evolution of the universe [6].

New measurements on Multi-neutron systems have been performed at $RIBF$ of $RIKEN$ in 2017/July, taking advantage of the high-performance $SAMURAI$ spectrometer and large neutron detection arrays [7]. Different methods have been applied in the series of experiments, which will provide complementary information on the properties of these multi-neutron systems. Now the data analysis is in progress, and some preliminary results will be discussed in the present talk.

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Energy spectra of excitons in square quantum wells*

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The electron-hole bound states (excitons) in the semiconductor quantum wells (QW) are remarkable examples of a Coulomb systems, in which the external potential of the heterostructure plays a role of "the third particle", thus effectively making such a system to be a three-body one. The exciton states and the exciton-light coupling in heterostructures with QWs have been experimentally and theoretically studied for several decades [1, 2, 3]. The quality of heterostructures is continuously growing and experimental samples with excellent properties have recently become available in many laboratories. Measurements of the reflectance spectra of the high-quality heterostructures show that the accurate data on the exciton energies and radiative as well as nonradiative broadenings can be easily obtained [4, 5]. In this context, the high quality of samples requires the improved precision of theoretical modeling of the exciton states and resonances. Therefore, such problems gradually draw attention of the few-body community [6, 7].

In this report, we present the results of the accurate modeling of the exciton states as well as the corresponding radiative decay rates. The energies of the ground and excited states of excitons in GaAs-based finite square QWs of various widths and alloy compositions are calculated. This type of QWs is widely experimentally and theoretically studied now as a model heterostructure. Determination of the exciton states is achieved by studying the three-dimensional Schrödinger equation for the exciton in a QW and analysing the spectrum of the respective Hamiltonian. The eigenvalue problem is solved numerically using the finite-difference discretization scheme [5] and properly taking into account the discontinuities of the material parameters at the interfaces of the QW [8]. We show that the numerical method is asymptotically exact, thus it allows us to obtain accurate exciton states for a wide range of QW widths and potential profiles [9]. The calculated bound states of electron-hole pairs in GaAs/AlGaAs and InGaAs/GaAs QWs are classified according to their quantum-confinement and Coulomb nature. The accurate radiative decay rates for the calculated *s*-like exciton states are obtained for QW widths up to 100 nm. Calculated data are confronted with the experimental reflectance spectra measured for high-quality InGaAs/GaAs heterostructures with QWs. The calculated values are in good agreement with the experimental data.

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Potential splitting approach for Faddeev-Merkuriev equations: application to e^+–H and e^+–He$^+$ multichannel scattering*

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The three-particle multichannel Coulomb scattering problem with rearrangement channels is treated by the potential splitting approach [1] incorporated into the framework of Faddeev-Merkuriev equations [FME] [2]. In contrast to [3] where the integral equations formalism has been used, we operate with the differential form of the FME. Coulomb potential splitting into the long-range tail part and the short-range core part is performed in two-body configuration space, reducing the number of FME splitting parameters [4] drastically. For this kind of splitting procedure we have developed a method of fine tuning the splitting radius in order to optimize the calculations for the given energy region. Using the FME allows us to produce results that are uniformly accurate for elastic scattering, excitations, relaxations and rearrangements.

We present the results of our detailed calculations of scattering characteristics in the systems e$^+$–H and e$^+$–He$^+$ with zero total angular momentum. We calculate all possible cross-sections in the low-energy region which admits up to seven open channels including the rearrangement channel of the positronium formation. All resonances of the e$^+$–H system obtained and approved previously by a number of authors [5, 6, 7] are clearly reproduced in the calculated cross sections, which demonstrates that our results are highly accurate and consistent. In the cross sections of the e$^+$–He$^+$ system we see no sign of resonances reported in papers [8, 9]. Alternatively, the exterior complex scaling approach has been used for calculating resonant energies in the e$^+$–H and e$^+$–He$^+$ systems. These calculations confirmed our results for the resonant structures found by solving the FME directly.

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Studies of the $\bar{K}NN$ bound state via the exclusive analysis of the in-flight (K^{-}, n) reaction at J-PARC

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A bound system of a nucleus and an anti-kaon, so-called kaonic nucleus, has been studied extensively to establish the possibility that a meson could be a component of the nucleus. Existence of the kaonic nucleus has been examined both theoretically and experimentally, but full understanding for the binding energy and width have not yet been reached due to the lack of understanding of the $\bar{K}N$ interaction in the energy range below the $\bar{K}N$ threshold, even in the two-body systems. Many experimental searches with a variety of reactions have been performed, but understanding of kaonic bound states remains still preliminary and controversial, even in the simplest system, $\bar{K}NN$ bound state.

We performed an experimental study of the $\bar{K}NN$ bound state via the in-flight $K^{-} +\ ^{3}$He reaction at the J-PARC hadron experimental facility. In this reaction, a neutron inside the ^{3}He target is kicked out to forward direction with a momentum brought from the incident kaon, where the kaon is bound around two residual protons with low momentum transfer about 200 MeV/c. Under this kinematical condition, a $\bar{K}NN$ bound state is expected to be formed with relatively large cross section owing to high sticking probability of low momentum kaon. Furthermore, the kinematics of the in-flight reaction and exclusive decay analysis help to reduce the background such as other nucleon or hyperon resonances production reaction, and one- or two-nucleon absorption processes. The produced state is reconstructed by invariant-mass of detectable decay modes, non-mesonic Λp mode (2-body decay) and mesonic $\pi\Sigma p$ mode (3-body decay), by using a cylindrical detector system surrounding the ^{3}He target. The emitted neutron is not directly detected but kinematically identified by using the missing-mass method.

From analysis of the non-mesonic Λp decay mode, two clear peaks were observed below and above the $\bar{K}NN(= 2370$ MeV) threshold in the invariant-mass spectrum. The peak (A) above the $\bar{K}NN$ threshold can be considered as kinematical structure which comes from quasi-elastic kaon absorption process, because the peak position moves higher with increasing momentum transfer ($q = |\vec{p}_{K^{-}} - \vec{p}_{n}|$). On the other hand, the peak (B) below the $\bar{K}NN$ threshold doesn't have such a dependence; the peak seems to be a kind of resonant state which has strangeness $S = -1$ and baryon number $B = 2$. By fitting the observed spectrum based on assuming the S-wave $\bar{K}NN$ bound state, we found that the binding energy of the peak is about 50 MeV. In the mesonic $\pi\Sigma p$ decay mode, we observed $\Lambda(1405)$ production events in the $\pi^{\pm}\Sigma^{\mp}$ invariant-mass spectrum with a cross section of about 100 μb, which is about 10 times larger than the $\bar{K}NN$ bound state production observed in Λp decay mode. We also observed that there is a yield below the $\bar{K}NN$ threshold in the $\pi\Sigma p$ invariant-mass spectrum, which is the same energy region as the observed resonance state in the Λp decay mode analysis.

We will discuss more detailed results from studying the $\bar{K}NN$ bound state in the both mesonic and non-mesonic decay modes, and analysis of observed peak in the Λp decay mode such as decay angular distribution to determine the spin-parity of the state.

$\pi J/\psi - D\bar{D}^*$ potential described by the quark exchange diagram

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Exotic hadrons reported in the heavy flavor sector have been one of the interesting topics in hadron and nuclear physics [1, 2]. Especially near the thresholds, the heavy quark symmetry inducing the mass degeneracy of heavy hadrons provides (i) the one pion exchange being the driving force of nuclei, and (ii) the many channel-couplings. Such effects are expected to produce an attraction and the hadron-hadron bound states, called hadronic molecules, near the hadron-hadron thresholds. On the other hand, an existence of thresholds induces the cusp structure which may be misinterpreted as a physical resonance [2]. Hence, careful analysis of the scattering is needed near the thresholds.

In order to discuss the dynamics near the thresholds, the hadron-hadron interaction is very important, while the high-precision interaction is not established yet in the heavy flavor sector. In Ref. [3], the Lattice QCD simulation by HALQCD indicates the importance of the $\pi J/\psi - D\bar{D}^*$ potential which is given by the charm quark (hadron) exchange process. Such interaction must be very short range interaction, but the mechanism is not understood yet. As for the standard method, the meson exchange potential has been introduced in the hadron interaction. However, the $\pi J/\psi - D\bar{D}^*$ potential should be described by the D meson exchange, where the interaction range is about 0.1 fm. The interaction range is smaller than the hadron size, typically 1 fm. Then, the D meson exchange picture would not be validiness.

Understanding the $\pi J/\psi - D\bar{D}^*$ potential is important in the studies of the Exotic hadrons which couples to a quarkonium. To describe this potential, we introduce the quark exchange process instead of the meson exchange one. The meson-meson scattering is described by the Born-order quark exchange diagram [4]. The meson wavefunctions and the quark interaction are given by the constituent quark model, where the parameters are fixed to reproduce the meson mass spectra. In this study, the cross section and the energy dependent potential for the $\pi J/\psi - D\bar{D}^*$ process are computed. We find that the hyperfine (spin-spin) and linear potential terms of the quark interaction plays an important role, while the coulomb one plays a minor role. We also find the difference between the results of the D meson exchange and the quark exchange calculations.

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Approximate sum rule for the electric dipole moment of light nuclei

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The measurement of the electric dipole moment (EDM) is an excellent test of the standard model of particle physics, and the detection of a finite value is signal of a new source of CP violation beyond it. Among systems for which the EDM can be measured, light nuclei are particularly interesting due to their high sensitivity to new physics [1]. In this talk, we examine the sensitivity of the EDM of several light nuclei to the one pion-exchange nucleon-nucleon interaction within the cluster model. We suggest an approximate sum rule for the nuclear EDM.

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Efimov effect in D spatial dimensions in AAB systems *

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The existence of the Efimov effect is drastically affected by the dimensionality of the space in which the system is embedded. The effective spatial dimension containing an atomic cloud can be continuously modified by compressing it in one or two directions. In the present talk I will show, for an AAB system formed by two identical bosons A and a third particle B, the dimensionsality D for which the Efimov effect can exist for different values of the mass ratio $\mathcal{A} = m_B/m_A$. A prediction for the Efimov discrete scaling factor, $\exp(\pi/s)$, as a function of a wide range of values of $\mathcal{A}$ and D will be given [1]. I will also show a framework to study the three-body problem while the dimensionality of the system is changed continuously [2].

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Relation between scattering amplitude and Bethe-Salpeter wave function inside interaction range

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We discuss an exact relation between the two-particle scattering amplitude and the Bethe-Salpeter (BS) wave function inside the interaction range in quantum field theory [1]. The reduced BS wave function, which is defined by the BS wave function inside the interaction range, plays an essential role in the relation. The half off-shell scattering amplitude can be obtained from the relation as well as the on-shell scattering amplitude. Based on the relation, it is shown that the solution of Schrödinger equation with the effective potential, which is determined from the BS wave function inside the interaction range, gives a correct on-shell scattering amplitude only at the momentum where the effective potential is calculated, while wrong results are obtained from the Schrödinger equation at other momenta. It is also presented that the relation can be regarded as the LSZ reduction formula using the BS wave function.

Furthermore, we present the lattice QCD calculation for the on-shell and half off-shell scattering amplitudes using the relation in the S-wave $I = 2$ two-pion channel [2]. From the calculation it is confirmed that the scattering length obtained from the relation agrees with the one from the finite volume formula.

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Potential splitting approach for atomic and molecular systems*

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An approach based on splitting the reaction potential into a finite range part and a long range tail part to describe few-body scattering in the case of a Coulombic interaction is presented [1, 2]. The solution to the Schrödinger equation for the long range tail of the reaction potential is used as an incoming wave. This reformulation of the scattering problem into an inhomogeneous Schrödinger equation with asymptotic outgoing waves makes it suitable for solving with the exterior complex scaling technique [3]. The validity of the approach is analyzed from a formal point of view and demonstrated numerically.

The potential splitting approach is illustrated with calculations of scattering processes in atomic and molecular systems. We have considered the electron scattering on the hydrogen atom and the positive helium ion in energy regions where resonances appear. We compared our calculated values with other results [4], and with the accurate data for electronhydrogen elastic scattering in the vicinity of resonance states [5]. The relative difference is found to be less than 10^{-3}.

We have also studied the scattering processes in the $H^+ - H_2^+$ system. This system has been considered as the three-body system with one-state electronic potential surface. The potential was calculated *ab initio* for intermediate inter-proton distances while for short and large distances analytical representations were constructed. The analytical representation for large distances is vital for the application of the exterior complex scaling method. Elastic cross sections were calculated and analyzed.

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Study of helium and lithium atomic systems with the discrete variable representations

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Quantum systems consisting of helium and lithium atoms have remarkable features. They are characterized by rather weak interactions between the particles, and by the wave functions spreading over large distances exceeding the radius of the Bohr orbit in tens and hundreds times. In some of these systems, conditions for the existence of Efimov states are nearly fulfilled. Due to above mentioned peculiarities, accurate calculations of the binding energies and the wave functions of these systems are complicated and require essential computational effort [1, 2, 3, 4].

The computational complexity can be reduced with the use of the discrete variable representation (DVR) [5]. In the DVR, specific functions, so-called discrete delta-functions, are used as the basis functions. DVR-functions equal to zero in all integration points except of the only one. This property substantially speeds up computations of the matrix elements of the Hamiltonian.

The binding energies and wave functions have been obtained for He_2, ^{7}Li–He, ^{6}Li–He, He_3, ^{6}Li–He_2, and ^{7}Li–He_2 systems. Different DVR-techniques have been used for calculations, their applicability and performance have been compared. The results for lithium systems have been compared to available data [6, 7, 8], and the existing discrepancies between them are carefully analysed.

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Bethe-Salpeter approach to three-body bound states with zero-range interaction

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We present results for the solution of the Bethe-Salpeter equation (BSE) for three bosons with zero-range interaction [1], using: (i) Wick-rotation, (ii) Light-front projection and (iii) direct integration in Minkowski space. The input to the BSE is the two-body scattering length and there is no necessity to regularize the equation in the ultra-violet and the Thomas collapse is absent. We have computed the three-body binding energies, Bethe-Salpeter amplitudes and light-front wave functions. We study different regimes of the three-boson system by increasing the strength of the two-body interaction via the scattering length, which is changed from small negative values to positive values passing the unitary limit, where it is infinite. With a weak two-body interaction the three-body system is unbound, for stronger two-body interaction a Borromean three-body bound state appears. For even stronger two-body interaction another physical (excited) state appears, found previously in light-front calculations [2, 3]. Comparing to the light-front approach the four-dimensional three-boson BSE implicitly incorporates three-body forces of relativistic origin, which are attractive and increase the binding energy.

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XYZ mesons at BESIII*

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With its unique data samples at energies of 3.8–4.6 GeV, the BESIII experiment made a significant contribution to the study of charmonium and charmonium-like states, i.e., the XYZ states. We report new measurements on the charged charmoniumlike states $Z_c(3900)$ and $Z_c(4020)$, on the $X(3872)$ decays, and on the cross-sections of $e^+e^- \to \pi\pi J/\psi$, $\pi\pi h_c$, $\omega\chi_{cJ}$, $\eta J/\psi$, and ηh_c, and the vector structures in these final states. We also present data from BESIII that may further strengthen the study of the XYZ and conventional charmonium states, and discuss perspectives on future experiments.

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S-wave elastic scattering of o-Ps by H_2 at low energies

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The confined variational method [1] is applied to investigate the low-energy elastic scattering of ortho-positronium from H_2 by first-principles quantum mechanics. The work extends the *ab-initio* theoretical description of the scattering of a composite projectile from a one-center target to a multi-center target. Describing the correlation effect with explicitly correlated Gaussians, we obtain accurate S-wave phase shifts and pick-off annihilation parameters for different incident momenta. By a least-squares fit of the data to the effective-range theory, we determine the S-wave scattering length, $A_s = 2.02a_0$, and the zero-energy value of the pick-off annihilation parameter, $^1\mathrm{Z}_{\mathrm{eff}} = 0.1839$. The obtained $^1\mathrm{Z}_{\mathrm{eff}}$ agrees well with the precise experimental value of 0.186(1) [2] and the obtained A_s agrees well with the value of $2.1(2)a_0$ estimated from the average experimental momentum-transfer cross section for Ps energy below 0.3 eV[3].

Table 1: Confining potential parameter G, $\delta^T_{ep} = \langle \delta^T(\mathbf{r}_{e^-} - \mathbf{r}_{e^+}) \rangle$, phase shift δ_0, and pick-off annihilation parameter $^1\mathrm{Z}_{\mathrm{eff}}$ for Σ_g o-Ps-H_2 scattering at different k. Experimental values of $^1Z_{\mathrm{eff}}$ are listed for comparison. Numbers in parentheses give the uncertainty in the last digit.

k (a_0^{-1})	G	δ^T_{ep}	δ_0 (rad)	$^1Z_{\mathrm{eff}}$
0.06094	2.15×10^{-6}	1.7876×10^{-6}	−0.1196	0.1736
0.08275	2.27×10^{-6}	4.7048×10^{-6}	−0.1527	0.1688
0.099993	1.7717×10^{-4}	8.4677×10^{-6}	−0.1846	0.1665
0.0	Effective-range theory			0.1839
Exp. at 77.4 K [4]				0.197(3)
Exp. at 250 K [4]				0.195(5)
Exp. at 293 K [4]				0.193(5)
Exp. at 293 K [2]				0.186(1)

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Few-body dissociation of relativistic light nuclei in nuclear track emulsion

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Events of dissociation of relativistic nuclei in nuclear track emulsion (NTE) allow a holistic investigation of “cold” ensembles of lightest nuclei. So far, with regard to fine structure dissociation of relativistic nuclei, the NTE technique remains the only means providing unique completeness of such observations at the best angular resolution and as well as a sufficient statistical provision. Moreover, full-bodied studies of light nuclear structure require reconstruction of relativistic decays of the unstable ^{8}Be and ^{9}B nuclei. Feasibility of such studies in electronic experiments is not visible at all. The cluster structure of light nuclei and the role of the unstable ^{8}Be and ^{9}B nuclei in them is studied in the BECQUEREL project (http://becquerel.jinr.ru/) on the basis of NTE layers longitudinally exposed at the JINR Nuclotron to relativistic Be, B, C and N nuclei, including radioactive isotopes [1]. Recent advances are highlighted [2,3]. On the practical side series of experiments with newly reproduced samples NTE has confirmed prospects of NTE in low and high energy nuclear studies [5].

Recently it is suggested to search in relativistic ^{12}C dissociation for α-particle triples in the second excited state 0^+_2 of the ^{12}C nucleus (the Hoyle state). The started study of the Hoyle-state (HS) in dissociation is setting new limit of NTE use. Being performed in contrast to relativistic energy of 3α-ensembles and minimum possible energy stored by them such observations would clearly demonstrated HS as a full-fledged and sufficiently long-lived nuclear-molecular object. Probably, not only single but also pair- and even triple-wise combinations of α-particles that are close to ^{8}Be might be observed to reflecting the HS structure in less distorted way. It can be expected that ^{8}Be and HS will become reference points to search for more complex states of dilute nuclear matter in dissociation of heavier relativistic nuclei. The current experiment task is to search for several hundreds of 3α-events in NTE pellicles and measure the angles of α-particles in the relevant ranges with a resolution allowing reconstructing decays of the unstable ^{8}Be nucleus and HS (example in Fig.). HS events are observed in dissociation $^{12}\mathrm{C} \rightarrow 3\alpha$ at 4.5 *A* GeV/*c* and 1 *A* GeV/*c* ^{12}C nuclei with a contribution preliminary estimated to be of the order of 10%. Thus, the first data on relativistic HS are encouraging.

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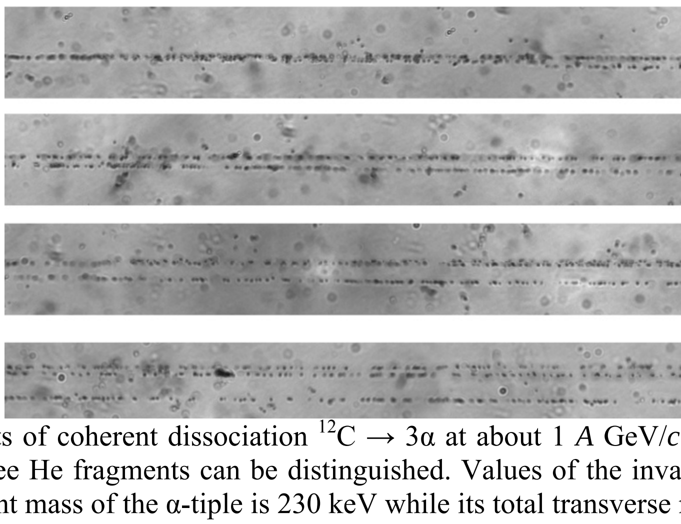

Fig. Sequential shots of coherent dissociation $^{12}\mathrm{C} \rightarrow 3\alpha$ at about 1 *A* GeV/*c* (from top to bottom); when moving from the vertex three He fragments can be distinguished. Values of the invariant mass of the α-pairs are 57, 60 and 270 keV. Invariant mass of the α-tiple is 230 keV while its total transverse momentum 111 MeV/*c*.

Imaging of few-body nuclear systems in nuclear track emulsion

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In spite of the fact that nuclear track emulsion (NTE) was developed more half a century ago, it still remains a universal and cost-efficient detector. The application of NTE is especially well grounded where tracks of nuclear particles cannot be reconstructed using electronic detectors. At the JINR Nuclotron the BECQUEREL experiment [1] is performed a program of irradiation of NTE stacks in the beams of relativistic isotopes of beryllium, boron, carbon and nitrogen, including radioactive ones to study their cluster structure. Charge-topology distributions of final states have an individual character appearing to be some kind of a signature of the isotope under study. The NTE technique allows one to observe the 3D images of few-body ensembles originated in peripheral collisions and explore the fragmentation of the relativistic nuclei down to the most peripheral interactions - nuclear “white” stars [2].

The competitive character of the novel NTE is proved in measurements of slow α particles and heavy ions (summarized in [3]). The possibility of α spectrometry was verified and the atom drift effect is established in measurement of decays of 60 MeV ^{8}He nuclei implanted in NTE [4]. Correlations of α particles in splitting of ^{12}C nuclei by 14.1 MeV neutrons [5] as well as ^{7}Li and ^{4}He nuclei produced in ^{10}B breakup by thermal neutrons in boron-enriched NTE [6] are studied. NTE samples were irradiated with slow Kr and Xe ions [7,8]. Surface irradiations of NTE samples were performed with automatic movement of the ^{252}Cf source [9].

Recently, samples of reproduced NTE were also irradiated with 2.5 and 160 GeV muons (started in [10]). Such irradiation allows one to study few-body fragmentation under the action of an electromagnetic probe [11]. Multiphoton exchange or virtual photon–meson transformations can serve as the fragmentation mechanisms. It was established that the breakup of carbon nuclei into trios of α particles has a nuclear diffraction rather than electromagnetic character. Thus, the connection of high energy and low energy nuclear physics appears.

Classic observations of fundamental importance presented in “The Study of Elementary Particles by the Photographic Method” by C. H. Powell, P. H. Fowler and D. H. Perkins can serve as a model of clarity in our time. Our research is implemented in keeping with this tradition by state-of-art means. The rich collection of videos and images of the nuclear few-body processes gathered at the Web site is presented [1]. In terms of applications they are relevant for the development of advanced systems of automatic search for nuclear interactions, as well as for university education.

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Characteristics of ^{6}Li nucleus cluster photodisintegration reactions*

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For nuclear astrophysics the $\alpha d \rightarrow {}^{6}\mathrm{Li}\gamma$ reaction represents a special interest as a unique source of formation of ^{6}Li nuclei in the Big Bang [1]. Its study is important for thermonuclear applications as well. The matter is that a resonance in αd-scattering at α-particles energy in laboratory system of 2.109 MeV (E_{α}= 0.7 MeV in system of inertia center) is an only process as a result of which α-particles with energy less than 3.7 MeV (products of *dt*- and d^{3}He-synthesis) will effectively interact with the main components of *dt*- and d^{3}He-plasma in early generation thermonuclear facilities [2]. The resonance corresponds to the known level of 3^{+} in ^{6}Li nucleus, a decay of which is accompanied with a typical radiation with E_{γ}= 2.186 MeV [3]. The cross section of $\alpha d \rightarrow {}^{6}\mathrm{Li}\gamma$ reaction in this resonance equals 150 nb and it is one of the series of resonances suggested for γ-diagnostics of thermonuclear deuterium-tritium plasma [2].

For the theory of photonuclear reactions the processes of two-particle photodisintegration of light self-conjugate nuclei (N = Z) with formation of particles with zero isotopic spin like $^{4}\mathrm{He}(\gamma, d)d$, $^{6}\mathrm{Li}(\gamma, d)\alpha$, $^{16}\mathrm{O}(\gamma, \alpha)^{12}\mathrm{C}$ and other are of peculiar interest. Cross sections of the reactions mentioned are extraordinarily small since according to selection rule by isotopic spin, the E1-transitions in the case of $\Delta T = 0$ are strongly suppressed and the E2-multipoles begin to play the determinative role, here a magnitude of the E2-multipole, in its turn, is defined by the kinematic factor of suppression which is included in operators of electromagnetic transitions. By the reason of small values of cross sections the processes were investigated insufficiently from experimental point, particularly, in the near-barrier range.

On the base of potential theory of light nuclei cluster photodisintegration the characteristics of ^{6}Li nuclei cluster photodisintegration reactions are considered in the range of low and intermediate energies. At low energies the important role of E1-multipole and its interference with E2-multipole were considered. The essential point is the different character of interference of E1- and E2-amplitude for the direct and inverse reactions. If for the direct reaction the interference at scattering in forward semisphere has a constructive character, then in backward semisphere the interference of E1- and E2-amplitudes – is deconstructive one. For the inverse reaction the interference has an opposite character: in forward semisphere it is deconstructive, and in backward semisphere it is constructive. In the energy range above several MeV the E2-multipole becomes to be dominating. The effect of appearance of the node structure of the wave function of relative motion has been considered in the characteristics of ^{6}Li cluster photodisintegration reaction with polarized and non-polarized photons.

Because of the difference in potential barrier penetrability the E1-multipole appears in the astrophysical range where the interference effects of E1- and E2-multipoles in the angular distributions of particles are the strongest ones. For the direct photonuclear reactions the analysis of angular distributions of particles has been enlarged with calculations of asymmetry appearing in case of processes with linearly polarized photons, exactly in this characteristic all peculiarities of (γ, *d*) reaction on ^{6}Li nucleus are revealed especially clearly: appearance of the cluster E1-multipole, its interference with E2-multipole; the node character of wave function of nucleus.

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S-factor and scattering-parameters from ^{3}He + ^{4}He $\rightarrow$ ^{7}Be + γ data*

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The reaction $^3\mathrm{He} + {}^4\mathrm{He} \rightarrow {}^7\mathrm{Be} + \gamma$ is important in the production of neutrinos in the Sun and lithium in the Big Bang, but its rate at solar energies has not been measured directly. We use the next-to-leading-order (NLO) amplitude in an effective field theory (EFT) for $^3\mathrm{He} + {}^4\mathrm{He} \rightarrow {}^7\mathrm{Be} + \gamma$ to perform the extrapolation of higher-energy data to solar energies. At NLO the EFT parameters are the s-wave scattering length, a_0 and effective range, r_0, the asymptotic behavior of ^{7}Be and its bound excited state, and two short-distance contributions to the $E1$ capture amplitude. We perform a Bayesian analysis of the radiative capture data below 2 MeV and obtain the multi-dimensional posterior pdf of these parameters. The EFT calculation reproduces total S-factor and branching-ratio data well (see Fig. 1) and yields $S(0) = 0.578^{+0.015}_{-0.016}$ keV b: consistent with other recent evaluations [1, 2], but with a smaller error bar [3].

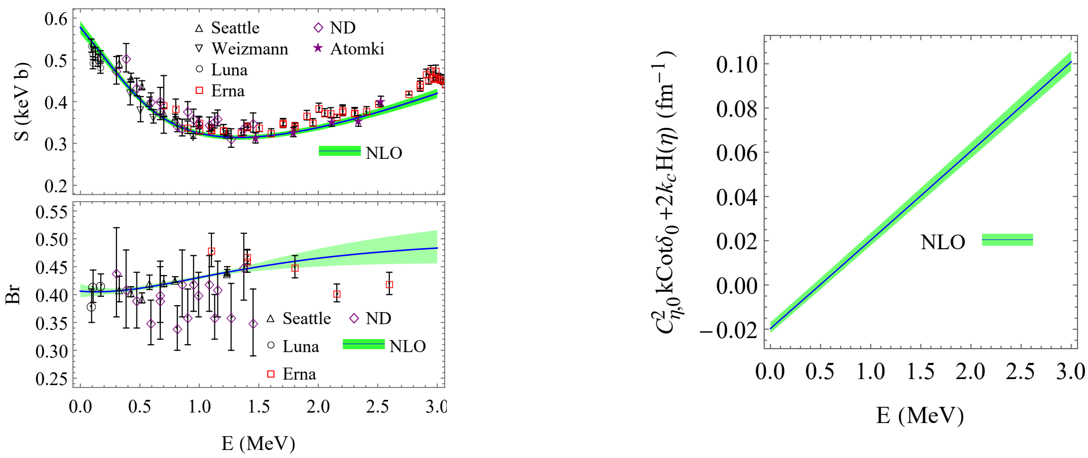

Figure 1: Left: Total S-factor and branching ratio, with data sets indicated in the legend. The green band is the 68% interval from our NLO analysis, the blue line is the mean. Right: ^{3}He-^{4}He effective-range function extracted from radiative-capture data at NLO; the green band denotes the 68% interval.

It has long been known that ^{3}He-^{4}He scattering properties play an important role in this capture S-factor—much more so than in cases such as $^7\mathrm{Be}(p, \gamma)$ [4]. We invert this usual understanding and employ the extant radiative capture data to obtain a tight constraint on a (non-linear) combination of the ^{3}He-^{4}He scattering length, the effective range, and the short-distance piece of the capture matrix element [3]. The corresponding result for the ^{3}He-^{4}He effective-range function, shown on the right of Fig. 1, will be tested by future high-quality measurements of ^{3}He-^{4}He scattering at low energies, e.g. [5].

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The pseudoscalar glueball puzzle*

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We report the new analysis of the mixing mechanism for pseudoscalar mesons and glueball which is introduced by the axial vector anomaly. We demonstrate that the physical mass of the pseudoscalar glueball does not favor to be lower than 1.8 GeV if all the parameters are reasonably constrained [1]. This conclusion, on the one hand, can accommodate the pseudoscalar glueball mass calculated by Lattice QCD, and on the other hand, is consistent with the high-statistics analyses at BESIII that all the available measurements do not support the presence of two closely overlapping pseudoscalar states in any exclusive channel. Such a result is in agreement with the recent claim that the slightly shifted peak positions for two possible states $\eta(1405)$ and $\eta(1475)$ observed in different channels are actually originated from one single state with the triangle singularity interferences [2, 3]. By resolving this long-standing paradox, one should pay more attention to higher mass region for the purpose of searching for the pseudoscalar glueball candidate.

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Exploring few- and many-body physics with an ultracold Bose-Fermi mixture of a large mass imbalance

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Magnetic Feshbach resonance is one of the most powerful tools in the field of quantum gases to study few- and many-body physics. One of the interesting questions is that how do few- and many-body states interplay with each other.

In this talk I will present our experimental efforts towards investigating the interplay between the Efimov states of three particles and the many-body polaron state of a Bose-Einstein condensate (BEC) in an ultracold mixture of fermionic ^{6}Li and bosonic ^{133}Cs atoms. I will discuss the nature of Feshbach resonances and summarize our exploration of the enhanced Efimov scenario [1] in our large-mass-ratio mixture. Then I will focus on spectroscopic study of a few ^{6}Li atoms immersed in a ^{133}Cs BEC where the hybridization of the Efimov and the polaronic states is favored [2].

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A three-body system in two dimensions

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One of the most intriguing phenomena of few-body physics is the Efimov effect [1], which manifests itself in an infinite number of weakly bound three-body states if at least two of the three two-body subsystems exhibit a single s-wave resonance.

We present the energies and wave functions of purely quantum-mechanical bound states in the system of three particles in two dimensions provided: (i) the system consists of a light particle and two heavy ones, and (ii) the heavy-light short-range potential has a s-wave [2] or p-wave resonance [3]. Furthermore, we explore the scaling of the three-body energies depending on the shape of the two-body interaction potential.

Our results are based on a numerical scheme utilizing spectral methods [4, 5] which enables us to discretize the stationary Schrödinger equation in function space achieving exponential convergence. We solve the resulting eigenvalue problem with the Data Vortex supercomputing system.

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Probing three-body collisions induced by a charge impurity in an ultracold gas*

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Investigating atom-ion interactions in hybrid setups merging a cold atom trap and a cold ion trap has revealed to be one of the novel developments of research on ultracold matter. Beside elastic or inelastic binary collisions, charge exchange, or three-body collisions, the formation of cold molecular ions has been directly observed by one group [1], while they are predicted to be created in most experiments of this kind [2].

Here we present a joint theoretical and experimental investigation of the formation of cold $RbBa^+$ molecular ions induced by the presence of a single Ba^+ ion immersed in a dense ($\approx 10^{12}$ atoms/cm^3) cloud of ultracold Rb atoms [3]. The experiment reveals formation rates compatible with a three-body collision facilitated by both the high atomic density and the long-range interaction between Ba^+ and Rb. The molecular ions are detected destructively by photodissociation provoked by the relatively intense 1064 nm laser used in the dipole trap beam [3].

In order to model the photodissociation mechanism, the potential energy curves and all the relevant permanent and transition electric dipole moments are calculated in a semiempirical methodology which has been already used in our group to describe a number of diatomic systems [4]. Both atoms are represented as one-electron systems, where the valence electron is moving in the field of a relativistic effective core potential with a core-polarization potential correction. The $RbBa^+$ electronic structure is thus reduced to an effective two-electron problem. The remaining two valence electrons are considered to calculate the Hartree-Fock and the excitation determinants, in an atom-centered Gaussian basis set, through the usual self-consistent field methodology. Finally, a full configuration interaction is achieved.

With these data we computed the state-to-state absorption cross section, $\sigma_{\Lambda vj}(\nu)$, of a $RbBa^+$ ro-vibrational level (vj) in the Λ electronic state, induced by a laser with frequency ν, towards accessible electronic states Λ', reaching continuum states with angular momentum j' and energy $\hbar k$. The main photodissociation channels are identified, and the results indicate that the lifetime of the molecular ions is strongly limited by the presence of laser light in the experiment, in agreement with the findings of Ref. [5]. The implementation of these results in a Monte-Carlo model allows to decipher the vibrational distribution of the created molecular ions, thus giving insight on the details of the originating three-body collision.

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Production of hypernuclei and strange particles in spallation reactions at a few GeV using an intranuclear cascade approach

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Motivated by a renewed interest of hypernucleus studies, strangeness degree of freedom was implemented in the intranuclear cascade model INCL.

INCL takes care of the first stage of reactions between a nucleon (or a light cluster) and a nucleus at energies from a few tens of MeV up to a few GeV. After emission of fast particles, a hot remnant nucleus is produced and then another model, combined to INCL, treats its de-excitation (the Abla model in our case).

INCL was known as a reliable model in the non-strange sector for energies up to 2-3 GeV [1] and, after 2010 with implementation of the multiple pion emission, up to $\sim$15 GeV [2, 3]. Since at those energies other particles can play a (smaller) role, on the one hand, and, on the other hand, new experiments on hypernuclei in several facilities are in progress or planned, K's, Λ's and Σ's have been added as participant particles in INCL. Most important reactions involving these particles are also included. Concerning hypernucleus production, the de-excitation code Abla was also upgraded with evaporation of Λ's and fission of hypernuclei (hyper-fission).

Main ingredients will be discussed and results compared to experimental data will be shown. Kaon spectra obtained from experiments with several targets and at different energies show good agreements most of the time. Role of the Δ-induced Kaon production will be discussed and other specific channels mentioned. While much less data exist on Λ spectra, data from the HADES collaboration were used and here also the results are very encouraging, especially compared to other models. The main remaining discrepancy was analysed and will be explained. Finally, hypernucleus production rates will be compared to the very rare existing data. In addition, we put constraints on the Λ-nucleus potential by combining those experimental data to our calculation results.

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Nuclei wading in the nucleons sea: Exploring light nuclei beyond proton drip line

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The boundaries for nuclear stability against particle emission are called drip lines. Beyond the drip lines, the particle emission time τ is usually very short, shorter than 10^{-21} seconds. Unbound nuclei are observed as broad resonances with an energy uncertainty $\Delta\mathrm{E} = \frac{\hbar}{2\Delta t} \sim 1$ MeV. Unbound nuclei are interesting in many ways:

- Some unbound nuclei play an important role in nuclear astrophysics, that is the case of ^{8}Be in the triple alpha reaction, and ^{2}He in the *pp*1 reaction chain. The extreme case of ^{19}Na [1], involved in a two-proton capture reaction, will be presented.

- The inverse reaction of the two-proton capture is the two-proton radioactivity. The same models are used to calculate the two processes. The study of ^{18}Na, the intermediate nucleus in the two-proton radioactivity of ^{20}Mg, will be presented [2].

- The symmetry of mirror nuclei is often used in nuclear astrophysics. The unknown properties of a neutron deficient nucleus can be deduced from the known properties of its mirror nucleus. Unbound nuclei are perfect cases to study the effect of the coupling with continuum. Could it be possible to measure some changes in the effective nucleon-nucleon interaction between mirror nuclei? The case of ^{16}F - ^{16}N, described as a core plus one proton and one neutron, will be presented [3].

- The generalized conjecture of Ikeda says that the coupling to a nearby particle/cluster decay channel induces particle/cluster correlations in nuclear wave functions. It is claimed in Ref. [4] that this conjecture holds for all kinds of cluster states including unstable systems like dineutron, or ^{8}Be. We observed a narrow resonance in the unbound nucleus ^{15}F [5], located well above the one proton emission barrier, but just above the two-proton emission threshold. This state could be an example of induced two-proton correlation.

- Tunnelling through the Coulomb barrier is a purely quantum effect. Pushed to its extreme limits, some questions remains. In the case of the unbound nuclei, what is the decay law of the particle emission, exponential? Search for γ-transition in ^{15}F will be discussed.

All these unbound nuclei were measured using the resonant elastic scattering technique and radioactive beams. This technique will be presented.

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Pion valence momentum distributions: response to massive effective gluons

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We study the response of the pion valence momentum distribution to the variation of the effective gluon mass by solving the ladder Bethe-Salpeter equation in Minkowski space. We resort to the Nakanishi integral representation of the Bethe-Salpeter amplitude and light-front projection[1]. The dynamical model has a quark-gluon vertex form factor, constituent quarks and a coupling constant given by the pion mass. The mass scales of the model are chosen to be around Λ_{QCD}, and the effective gluon mass between $\sim \Lambda_{QCD}/10$ and Λ_{QCD} [2]. In our covariant model the pion light-front wave function has, besides the valence state, an infinite number of Fock-components built by a $q\bar{q}$ and any arbitrary number of effective gluons, in correspondence the valence probability is found to be unexpectedly small being about 30 to 40%. The valence wave function responds to the gluon effective mass: the longitudinal momentum distributions tends to be wider and the transverse one extend to higher momentum when the effective gluon becomes heavier. Our work, although limited to study the valence properties, raises the question on how the higher Fock-components of the pion wave function contribute to the quark momentum distributions, as states with more constituents should bring sizeable contributions indicated by the small occupation of the valence state.

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Hidden-charm and bottom meson-baryon molecules coupled with five-quark states

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The LHCb collaboration has recently reported evidence of two pentaquark states. We have constructed a classification scheme for pentaquark states and tried to describe them as compact objects [1]. The hidden-charm pentaquark states have been also described as meson-baryon molecules with coupled channels for $\bar{D}^{(*)}\Lambda_c$ and $\bar{D}^{(*)}\Sigma_c^{(*)}$ [2] and recently, for the first time, we have discussed the interplay between compact and molecular components [3]. Important predictions are also given for bottom meson-baryon molecules coupled with five-quark states [3].

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New studies of short-range correlations and the EMC effect

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The atomic nucleus is one of the most complex strongly-interacting many-body Fermionic systems in nature. A main challenge in describing nuclei is understanding the short interparticle part of the nuclear wave function. Recent high-energy proton and electron scattering experiments show that short-range interactions between the nucleons form correlated, high-momentum, neutron-proton pairs, known as Short-Range Correlations (SRC). There measurements suggest that these correlations account for 20% of the nucleons in the nucleus, and 60-70% of the kinetic energy carried by nucleons in nuclei, thereby having large implications to the modification of the bound nucleon structure function and more.

I will present results from new studies of short-ranged correlations in nuclei and the EMC effect, with emphasis on measurements of neutron-rich nuclei. I will also discuss the development of new effective theories for describing short-ranged correlations, the way in which they relate to experimental observables, and the emerging universality of short-distance and high-momentum physics in nuclear systems.

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Bosonic drops with two- and three-body interactions close to the unitary limit

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Saturation properties of bosonic drops are directly linked to the short-range repulsion of the two-body interaction of the particles. We will focus on the behavior of bosonic drops in which the two-body state is close to the unitary limit and will analyze the evolution of the ground state energy with the number of particles. Close to the unitary limit the two-body and three-body systems show a particular behavior as they are well inside the Efimov window. In particular the three-body spectrum shows a disctrete scale invariance. Furthermore there is a correlation between the three-body and four-body ground state energies. Close to the unitary limit the few-body clusters show universal behavior and, using potential models, this can be described using for example a soft gaussian potential constructed with a two- and a three-body term as:

$$V = \sum_{ij} V_0 e^{-r_{ij}^2/r_0^2} + \sum_{ijk} W_0 e^{-2\rho_{ijk}^2/\rho_0^2} \tag{1}$$

where r_{ij} is the interparticle distance and $\rho_{ijk}^2 = (2/3)(r_{ij}^2 + r_{jk}^2 + r_{ki}^2)$. For different values of the range parameters, r_0 and ρ_0, the strength V_0 is fixed to describe the (large) two-body scattering length and the strength W_0 is fixed to describe the trimer ground-state energy. This is an effective description that, for small number of particles, gives a reasonable description [1, 2].

In the present presentation we will analyze the capability of the soft potential to describe saturations properties as the number of bosons $N \to \infty$. A nice example is given by helium drops, from one hand the two-body potential has a strong repulsion at short distances. On the other hand, the extremely weak binding of the helium dimer locates this system very close to the unitary limit allowing for a description based on an effective theory [3]. Fixing the potential parameters in order to describe specific observables in the few-body sector as the two-body scattering length and the dimer, trimer and tetramer binding energies, we will show that the above potential describes with a good accuracy the energy per particle E_N/N and rms radius as $N \to \infty$. In this way we make a connection between few-body low-energy observables and many-body properties. Preliminary results for fermionic systems will be also presented.

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Testing the Born-Oppenheimer approximation and universality in a one-dimensional three-body system

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The Born-Oppenheimer (BO) approach [1] relies on separating the dynamics of the light particles from that of the heavy ones which makes it suitable for systems with large mass-imbalance. On the other hand, the integral equation of Skorniakov and Ter-Martirosian (STM) [2] provides in principle an exact description of a three-body system for any mass ratio.

In this poster we analyze a three-body system consisting of a light particle and two identical heavy particles. The system is confined to one dimension and the heavy-light interaction is modeled by delta-functions. First, we compare both methods in terms of the bound state spectrum and put it into context of results in the literature [3, 4]. Moreover, we test the separation ansatz used in the BO method by comparing the corresponding wave functions.

In order to investigate the universal behavior with respect to the form of the potential, we also match the results of the STM approach against those obtained from spectral methods for nonzero-range heavy-light interactions (e.g. Gaussian or Lorentzian shape).

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Scattering using real-time path integrals*

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Path integrals are a powerful tool for solving problems in quantum theory that are not amenable to a treatment by perturbation theory. Most path integral computations use an analytic continuation to imaginary time. While imaginary-time treatments of scattering are possible, imaginary time is not a natural framework for treating scattering problems.

The purpose of this work is to test a recently introduced method [1] for performing direct calculations of scattering observables using real-time path integrals.

The computations are based on a new rigorous interpretation [2][3][4] of the path integral as the expectation value of a potential functional on a space of continuous paths with respect to a complex probability distribution [4]. The method has the advantage that it can be applied to arbitrary short range potentials.

The method is tested by applying it to calculate half-shell sharp-momentum transition matrix elements for one-dimensional potential scattering. The calculations for half-shell transition operator matrix elements are in agreement with a numerical solution of the Lippmann-Schwinger equation. The computational method has a straightforward generalization to more complicated few-body systems.

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Combining structure and reactions : construction of microscopic optical potentials.*

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The strong coupling to decay/reaction channels is an essential feature of nuclei in the vicinity of the driplines and requires new theoretical developments for the study of these systems far from stability. In reaction models, one usually reduces the many-body picture to a few-body one, where only the most relevant degrees of freedom are retained. In such approaches one introduces effective interactions, the so-called optical potentials, between the clusters considered. Traditionally one uses parametrized interactions constrained by data on stable isotopes. The application of these phenomenological potentials to exotic regions of the nuclear chart is unreliable and it is therefore critical for progress in the field of reactions that these effective interactions be connected to the underlying microscopic theory. During this talk, I will show results towards our goal of constructing nucleon-nucleus microscopic potentials using recent chiral-EFT Hamiltonians within the Coupled Cluster approach [1, 2].

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QED IN THE CLOTHED-PARTICLE REPRESENTATION

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We will present a field-theoretical method to construct in a consistent way relativistic (Hamiltonian) interactions in QED. In particular, the interaction operators for processes of the type $e^-e^- \to e^-e^-$, $e^-e^+ \to e^-e^+$, $e^-e^+ \longleftrightarrow 2\gamma$, $\gamma e^- \to \gamma e^-$ are derived on one and the same physical footing. The method is based on the unitary clothing approach [1,2] (cf. [3]) which introduces a new representation of the primary total Hamiltonian in terms of the operators for creation and destruction of the so-called clothed particles, viz., those particles that can be observed. Within the approach all interactions constructed are responsible for physical (not virtual) processes in a given system of interacting fields. Such interactions are Hermitian and energy independent including the off-energy-shell and recoil effects (the latter in all orders of the v^2/c^2 - expansion). The persistent clouds of virtual particles are no longer explicitly contained in the representation, and their effects are included in the properties of the clothed particles and in the interactions between them. Special attention is paid to a distinct feature of the first unitary clothing transformation, which leads to some cancellation (full for the energy-shell elements of the H-matrix) of the noncovariant Coulomb contribution in the CPR Hamiltonian. A possible way in describing the positronium properties is discussed.

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A FRESH LOOK AT TREATMENT OF RADIATIVE CAPTURE IN NUCLEAR REACTIONS: APPLICATIONS TO THE $\alpha - \alpha$ BREMSSTRAHLUNG

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Our departure point in describing electromagnetic (EM) interactions with nuclei (in general, bound systems of charged particles) is to use the Fock-Weyl criterion and a generalization of the Siegert theorem (see [1] where this approach is compared with that by Friar and Fallieros [2]). It has been shown how one can meet the gauge invariance principle (GIP) in all orders in the charge and construct the corresponding EM interaction operators in case of nuclear forces arbitrarily dependent on velocity (see paper [1] and refs. therein). Along the guideline we have derived the conserved current density operator for a dicluster system (more precisely, the system of two finite-size clusters with many-body interaction effects included). Being expressed through electric and magnetic field strengths and matrix elements of the generalized electric and magnetic dipole moments of a system the single-photon transition amplitudes attain a manifestly gauge-independent (GI) form. Special attention is paid to the cluster structure of the T-matrix for radiative process $A + B \to \gamma + C$, in which a target-nucleus A captures a projectile-nucleus B that is followed by the single-photon emission and formation of a system $C = A + B$ in a bound or continuum state , e.g., as in case of $\alpha + \alpha \to \alpha + \alpha + \gamma$ bremsstrahlung. We show how the decomposition of T into separate contributions responsible for the photon emission stems from the time-space current components and depends on the interactions between colliding nuclei (clusters) . The latter may be nonlocal. Evidently, if we switch off the $\alpha + \alpha$ interaction in entrance and exit channels, such a process will be impossible. Keeping this in mind, it is easily to see (at least, within potential models of the $\alpha + \alpha$ scattering) that the relevant Coulomb-like integrals with distorted waves can be calculated in terms of the half-off-energy-shell $\alpha + \alpha$ scattering amplitudes. In this connection, we would like to show with a separate poster our by-product calculations of such amplitudes for a few popular $\alpha + \alpha$ potentials. When calculating these quantities we show a constructive way for taking into account the interplay between the Coulomb repulsion and strong interaction of colliding nuclei. At the same time, one should note that the bremsstrahlung amplitudes in question are expressed through the cluster form factors. Calculations are compared with data. We are addressing to some advances in evaluating the so-called Nordsieck integrals for scattering problems (see, e.g., [4, 5]).

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Resonance production of two pions in the reaction $pd \to pd\pi\pi$ at 1-2 GeV

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Search for dibaryon resonances in two-nucleon systems has a long history (for review see [1]). The resonance behaviour of the single pion production reaction $pp \to (^1S_0)\{pp\}\pi^0$ in the isovector channel was observed by ANKE@COSY [2] at proton beam energy 0.5-0.8 GeV. Theoretical analysis [3] shows that in contrast to the $pp \to d\pi^+$ reaction, an ordinary mechanism with the Δ-isobar excitation is not sufficient to explain a full set of this data. At present as one of the most realistic candidate to dibaryon is considered the resonance $D_{IJ} = D_{03}$ observed by WASA@COSY [4] in the total cross section of the reaction of two-pion production $pn \to d\pi^0\pi^0$, here I is the isospin and J is the total angular momentum of this resonance. The mass of the resonance is 2.380 GeV is close to the $\Delta\Delta$-threshold, but its width $\Gamma = 70$ MeV is twice lower as compared to the width of the free Δ-isobar. This narrow width is considered as the most serious indication to a non-hadronic, but most likely, quark content of the observed resonance state. The spin-parity of this resonance $J^P = 3^+$ were established by polarized measurements [5], however information about its production (decay) channels is non-complete. One possible mechanism of the reaction $pn \to d\pi^0\pi^0$ suggested in paper [7] involves sequential excitation and decay of two dibaryon resonances, $D_{03}(2380)$ and $D_{12}(2150)$.

Very similar resonance structure was observed by ANKE@COSY in the differential cross section of the two-pion production reaction $pd \to pd\pi\pi$ at beam energies 0.8-2.0 GeV with high transferred momentum to the deuteron at small scattering angles of the final proton and deuteron [6]. This kinematic conditions strongly differ from the quasi-free reaction studied in Ref.[4]. In the distribution over the invariant mass $M_{d\pi\pi}$ of the final $d\pi\pi$ system the resonance peaks were observed at $M_{d\pi\pi} \approx 2.380$ GeV [6] that is the mass of the isoscalar two-baryon resonance $D_{IJ} = D_{03}$ [4]. However the widths of these peaks are by factor of ~ 1.5 larger than for the D_{03}. In order to explain the observed resonance behaviour of the reaction $pd \to pd\pi\pi$ we apply the two-resonance model [7] and modify it by inclusion of the σ-meson exchange between the proton and deuteron. Since not all required partial width were determined in [7], we use here the results of the quark model [8], where some of these width were calculated. When doing so and neglecting the contribution of the isovector state of the final $\pi\pi$ pair, we show that the calculated within this model absolute value of the peaks is consistent with the ANKE@COSY date [6] whereas the widths are narrower.

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Exotic Quantum States for Charmed Baryons at Finite Temperature

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Abstract

The significantly screened heavy-quark potential in hot medium provides the possibility to study exotic quantum states of three-heavy-quark systems. By solving the Schroedinger equation for a three-charm-quark system at finite temperature, we found that, there exist Borromean states which might be realized in high energy nuclear collisions, and the binding energies of the system satisfy precisely the scaling law for Efimov states in the resonance limit.

Reference

Jiaxing Zhao and Pengfei Zhuang, Physics Letters B775(2017), 84–88.

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