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Book of Abstracts

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Plenary Session 1 Monday / 147

Observation of Efimov states in ultracold atoms

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Efimov states form in a three-body system when the pair-wide interactions are resonantly enhanced. Predicted by Vitaly Efimov in 1970, first Efimov state was observed in 2006 in ultracold cesium atoms near a Feshbach resonance. Since then, dozens of Efimov states have been identified in cold alkali and helium atoms.

In this talk, I will describe the intriguing history of the observation of the first Efimov state, unexpected Efimov universality, confirmation of Efimov geometric scaling, and various extensions of Efimov physics to complex systems.

Plenary Session 1 Monday / 31

Exotic structures in exotic nuclei

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The advent of new generation radioactive beam facilities has provided for a rather complete mapping of the nuclear landscape up to mass number 30. Among all the so-called exotic nuclei (not found on Earth), some very neutron-rich ones exhibit properties that are in fact exotic: extended matter distributions, few-body resonances, extreme neutron to proton ratios… In this talk we will illustrate some of these examples with recent results obtained at the Radioactive Isotope Beam Factory (RIBF) of the RIKEN Nishina Center in Japan.

Plenary Session 1 Monday / 14

Constraining Hyperon-Nucleon and Hyperon-Hyperon interactions with femtoscopy in ALICE

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Pioneering studies by the ALICE Collaboration demonstrated the potential of employing femtoscopy to investigate and constrain hyperon-nucleon and hyperon-hyperon interactions with unprecedented precision. This kind of interaction is particularly interesting since it is closely connected to the physics of neutron stars. In particular, one of the plausible hypotheses about the content of neutron stars is that, in addition to neutrons, hyperons might be contained in the core. To obtain a better understanding of the composition of these objects, a detailed knowledge of the interactions between the constituents becomes mandatory. Such femtoscopic analyses are complementary to previous attempts to study the interaction with scattering experiments, which are difficult to perform due to the unstable nature of hyperon beams.

In this contribution, we present measurements from the ALICE Collaboration in pp collisions at $\sqrt{s}$ = 7 and 13 TeV and p–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV. The small size of the particle-emitting source in these collision systems is particularly well suited to study short-ranged strong potentials. The data samples collected by the ALICE experiment enable studies of the p-p, p-Λ and Λ-Λ correlations, and additionally make it possible to probe the interaction of more exotic pairs such as p-K, p-Ξ, p-Σ^0 and p-Ω. Newly developed analysis tools allow for a comparison of the measured correlation function between the particle pairs of interest to theory predictions using either potentials or wave functions as an input. This enables us to verify chiral and lattice calculations of the interaction and to constrain the corresponding scattering parameters.

Plenary Session 2 Monday / 18

Ultra cold chemistry using the R-matrix method

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A quiet revolution is occurring at the border between atomic physics and experimental quantum chemistry. Techniques for producing cold and ultracold molecules are enabling the study of chemical reactions and heavy-particle scattering at the quantum scattering limit with only a few partial waves contributing to the incident channel leading to the observation and even full control of state-to-state collisions in this regime.

We have developed a new R-matrix-based formalism for tackling problems involving low- and ultra-low energy collisions between heavy particles. This
formalism is completely general and could prove transformative in its scope. It is particularly appropriate for slow collisions occurring over deep potential energy wells which support many bound ro-vibrational states. These systems also support many quasibound or resonance states which make them hard to treat theoretically but offer the best prospects for novel physics.

The R-matrix method involves dividing space into an inner and outer region. In our method, the inner region exploits codes for performing high-accuracy variational nuclear-motion calculations of molecular spectra which have bee developed over many years in my group. The codes have already be used to compute wavefunctions up to and above dissociation. These variational nuclear motion methods are used to provide wavefunctions (both bound and continuum) for the whole system at short internuclear distances only. These collision-energy-independent, inner-region wavefunctions are then used to construct collision-energy-dependent R-matrices which can then be propagated to asymptotia.

Progress on the project will be described including results of test
calculations on ultra-low energy Ar − Ar and O − He collisions, as well as studies of polyatomic collision systems.

Plenary Session 2 Monday / 32

Solutions of the Faddeev-Yakubovsky equations for five-nucleon systems

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Rigorous solution of the few-particle scattering problem is one of the most complex and important problems of Quantum Mechanics. 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. This formalism has been generalized by Yakubovsky [2] to any number of particles. Regardless presence of the formal theory – progress in solution of Faddeev-Yakubovsky equations (FYe's) is slow and only very recently rigorous numerical solution of a five-body problem has been achieved by this formalism [3].

In this presentation I will shortly describe the numerical tools employed to solve FYe's in configuration space. Then some recent applications will be presented. In particular, related to low energy neutron scattering on ^{4}He by involving hadronic parity violation. As well possible existence of the resonant states in ^{5}H nucleus will be studied. Modern realistic nuclear Hamiltonians are employed in describing these five-nucleon systems.

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Plenary Session 2 Monday / 10

The molecular nature of some exotic hadrons

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The exciting discovery by LHCb of the $P_c(4380)$ and $P_c(4450)$ pentaquarks, or the suggestion of a tetraquark nature for the $Z_c(3900)$ state seen at BESIII and Belle, have triggered a lot of activity in the hadron physics field, with new experiments planned for searching other exotic mesons and baryons, and many theoretical developments trying to disentangle the true multiquark nature from their possible molecular origin. After a brief review of the present status of these searches, in this talk I will present a theoretical model that points towards the possible interpretation of some of the Ω_c states recently seen at LHCb as being hadron molecules. The model also predicts the existence of quasibound meson-baryon Ξ_{cc} states, which would be excited states of the recently observed ground-state double-charmed baryon, with a mass of 3261 MeV, by LHCb. Predictions of the model for the bottom sector will also be discussed.

Parallel Session Monday: Atoms and Molecules / 131

Three-body systems in novel two-dimensional materials

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Studies related to the formation and calculations of the properties of positively (ehh) and negatively (eeh) charged trions in two-dimensional (2D) materials, which includes transition metal dichalcogenides (TMDC) [1], silicene, germanene, and stanene (Xenes) [2], and phosphorene are presented. We provide the current status of the theoretical and experimental research and recent calculations.

It is demonstrated that the reduction of dimensionality itself necessitates a change to the formalism, and requires the modification of the bare Coulomb potential to account for non-local screening effects. The screening effects, resulting from the host lattice, make the Coulomb force between charge carriers much weaker than in atomic systems. Results of calculations of the binding energy of trions in these materials by using the Rytova-Keldysh (RK) potential [3] are presented.

We study the binding energies of trions in suspended two dimensional monolayers of TMDC in the framework of the effective-mass model by employing the method of hyperspherical harmonics in configuration space [1,4]. The trion fine structure, based on formation of intravalley trions in spin singlet and intervalley trions in triplet states and their stability is addressed. We study the binding energies of trions in Xenes by solving the Schr\"{o}dinger equation with the RK potential and field-dependent charge carrier masses and demonstrate that an external electric field can be used to tune the eigenenergies of trions by changing the effective mass of charge carriers. To understand the importance of dielectric screening on the formation of trions, we perform calculations of the binding energy for trions in 2D materials placed in three different dielectric environments: suspended in vacuum, supported on different substrates, and encapsulated by dielectric. The analysis and comparison of our results for the binding energies of trions with experimental data and those calculated via different theoretical methods are presented.

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Parallel Session Monday: Short-range Correlations in Nuclei / 111

Short-range nucleon correlations studied with electron and photon probes.

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The Glasgow Nuclear Physics research group has maintained a long interest in few-body physics, studying two- and three-body nucleon-nucleon interactions using real and virtual photons at the Mainz 1.6 MeV Microtron (A1, A2 collaborations) and at the Jefferson Laboratory 12 GeV accelerator (CLAS collaboration). Initial work at Mainz looked at the role of neutron-proton correlations in a range of light nuclei to investigate experimentally observed reduced nucleon occupancies compared to shell model predictions. The observed pair-momentum distributions were found to be sensitive to short-range nucleon–nucleon (SRC) interactions. Experiments with polarised photons provided a sensitive method to study SRC and indicated correlations were also present in the much weaker proton-proton pair emission channel. The role of three-body forces was studied using electron scattering measurements on 3He and by looking at three-nucleon emission reactions. More recent work at Jefferson Lab has focussed on SRC at higher energies in heavier nuclei. This work has investigated the isospin dependence of SRC and suggested a connection between SRC and the EMC effect, in which the structure function F2(xB,Q2) observed in Deep Inelastic Scattering (DIS) on nucleons bound in heavy nuclei is reduced at high xB, and high Q2, compared to the same structure function on unbound nucleons.

Parallel Session Monday: Few-Nucleon Systems / 27

Investigations of the Few-Nucleon Systems \newline within the LENPIC Project

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Results presented in this contribution are obtained within the Low Energy Nuclear Physics International Collaboration (LENPIC). In the project manifesto [1]. it has been stated that LENPIC aims to develop chiral effective field theory nucleon-nucleon and many-nucleon interactions complete through at least fourth order in the chiral expansion (N3LO). Using these interactions, LENPIC's intent is to solve the structure and reactions of light and medium-mass nuclei including electroweak observables with consistent treatment of the corresponding exchange currents. Further plans include high precision calculations of heavier nuclei and infinite nuclear matter with various versions of nuclear interactions derived from chiral effective field theory.

In the contribution the current status of the chiral nuclear forces [2-4] and current operators [5-6] will be briefly discussed. A special emphasis will be put on recent calculations of the elastic nucleon-deuteron scattering and nucleon-induced deuteron breakup processes [7]. Fully consistent results for ground and low-lying excited states of light nuclei ($A \leq 16$) at next-to-next-to-leading order in chiral effective field theory using semilocal coordinate-space regularized two- and three-nucleon forces [8,9] will also be presented.
Finally, calculations performed with various chiral potentials for selected electroweak processes [10] will be reported.

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Parallel Session Monday: Short-range Correlations in Nuclei / 88

Measurement of the ratio of the nucleon structure functions, F2n/F2p, from electron deep inelastic scattering off the A=3 mirror nuclei.

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Preliminary results from a Jefferson Lab (JLab) experiment on electron deep inelastic scattering (DIS) from the 3H and 3He mirror nuclei will be presented. The experiment (MARATHON, "MeAsurement of the F2n/ F2p, d/u RAtios and A=3 EMC Effect in Deep Inelastic Electron Scattering Off the Tritium and Helium MirrOr Nuclei") took data for 70 days in the period January-April 2018 in the Hall A Facility of JLab, using an 11 GeV electron beam, two High Resolution Spectrometers, and a high-pressure 2H/3H/3He target system. The experiment has measured DIS cross section ratios for 2H,

3H and 3He. It will determine, using a new novel method, free of theoretical uncertainties present in previous SLAC measurements, the ratio of the F2n/F2p structure functions of the neutron and proton, and extract the d/u ratio of the up and down quark probability distributions in the proton. The results from the experiment are expected to test predictions of the quark model of the nucleon and of perturbative quantum chromodynamics, and to constrain the nucleon's parton distribution function parametrizations needed for the interpretation of high energy collider data. The experiment will also determine precisely the EMC effect of the two A=3 mirror nuclei. The results are considered essential for the explanation of the EMC effect, which describes the modification of the nucleon structure functions in the nuclear medium.
(Work supported by the United States National Science Foundation Grant PHY-1714809)

Parallel Session Monday: Atoms and Molecules / 55

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

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We study a three-body system confined to one space dimension, consisting of two identical, non-interacting, heavy particles and a light particle with arbitrary mass ratio interacting with the two heavy particles. In this talk we focus on a contact heavy-light interaction, and therefore apply the exact integral equations of Skorniakov and Ter-Martirosian, in order to obtain the three-body energy spectrum together with the corresponding wave functions. The accuracy of the Born-Oppenheimer approximation is then studied by comparing both spectrum and wave functions to the exact results. In addition, we present a proof showing that the results of the contact interaction are universal, if the underlying two-body system is tuned on resonance.

Parallel Session Monday: Few-Nucleon Systems / 89

Tracing a few-fermion system inside the unitary window

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We analyse the behaviour of few-fermion systems having 1/2 spin-isospin symmetryclose to the unitary limit, the limit in which the scattering length takes values much bigger than the typical length of the system. In the case of nucleons, the large values of the singlet and triplet scattering lengths locate the system naturally close to the unitary limit. Using a potential model with variable strength, set to give controlled values to the singlet and triplet scattering lengths and the triton binding energy, we study the spectrum of $A = 2, 3, 4, 6$ nuclei in the region between the unitary limit and their physical values. In particular we analyse how the values of the binding energies emerge from the unitary limit forming the observed levels. To this end we consider the system with and without the Coulomb interaction and with a without a three-body force paying particular attention to the four-fermion excited state.

Parallel Session Monday: Short-range Correlations in Nuclei / 33

Latest results concerning short range correlations obtained in the dp elastic and dp breakup processes at Nuclotron, JINR.

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Deuteron spin structure program is aimed on extraction of two and three nucleon forces information, including their spin dependent parts, from dp elastic and dp breakup processes investigated at intermediate energies. The dp elastic data were obtained at Internal Target Station of Nuclotron (JINR) in the energy range of 400-1800 MeV using polarized deuteron beam. Angular dependencies of the vector Ay and tensor Axx and Ayy analyzing powers below deuteron energy of 1000 MeV at large scattering angles are presented. Strong sensitivity to the short range spin structure of the isoscalar nucleon-nucleon correlations is observed in deuteron analyzing powers. Preliminary results of the cross section for the dp breakup reaction have been obtained in the energy range from 300 - 500 MeV of the incoming deuteron. Results are obtained for various detector configurations, in which the sensitivity to the three nucleon correlations and relativistic effects are assumed.

Parallel Session Monday: Atoms and Molecules / 60

Universal Short Range Correlations in Bosonic Helium Clusters

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Short-range correlations in bosonic Helium clusters, composed of ^{4}He atoms, are studied utilizing the generalized contact formalism. The emergence of universal n-body short-range correlations, associated with the repulsive $1/r^{12}$ part of the Lennard-Jones potential, is formulated and demonstrated numerically via Monte Carlo simulations. The values of the n-particle contacts are evaluated for $n \leq 5$. In the thermodynamic limit, the two-body contact is extracted from available experimental measurements of the static structure factor of liquid ^{4}He at high momenta, and found in a good agreement with the value extracted from our calculations.

Parallel Session Monday: Few-Nucleon Systems / 91

Four-nucleon continuum: from near-threshold resonances to intermediate-energy collisions

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Recent developments in four-nucleon scattering calculations will be presented. They are based on the Faddeev-Yakubovsky-type equations for transition operators that are solved in the momentum-space partial-wave representation. Their solution is complicated due to the presence of kernel singularities corresponding to open many-cluster channels. This difficulty becomes most evident if two-cluster channels are absent, as in 4n system, and at intermediate energies where breakup channels dominate. These cases will be discussed in detail.

Parallel Session Monday: Short-range Correlations in Nuclei / 72

Theoretical study of Deeply Virtual Compton Scattering off 4He

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In recent times, it has become clear that inclusive Deep Inelastic Scattering does not allow to fully understand few fundamental issues about the nuclear partonic structure, such as the origin of the EMC effect. These difficulties can be overcome considering a new generation of experiments at high energy and high luminosity [1] involving exclusive scattering processes. Among them, deeply Virtual Compton Scattering (DVCS) is a very promising direction for unveiling the 3 dimensional nuclear structure. The first experimental DVCS data considering an ^{4}He target have become recently available at the Jefferson Laboratory (JLab) where, for the first time, the coherent [2] and incoherent channels of the process have been successfully disentangled .
The accuracy of the present and expected data is such to require sophisticated studies to properly evaluate conventional nuclear physics effects, using the state-of-the-art wave functions accounting for realistic nucleon-nucleon potential including three-body forces. Since the ^{4}He nucleus is the lightest system showing the dynamical features of a typical atomic nucleus and realistic calculations, although challenging, are possible, this nucleus is a paradigmatic system. For both DVCS channels, we studied the handbag contribution to the process in impulse approximation. Within this scenario, for the coherent DVCS contribution [3], a convolution formula for the only leading twist Generalized Parton Distribution (GPD) describing the ^{4}He partonic structure is derived in terms of the non-diagonal nuclear spectral function of ^{4}He and on the GPD of the struck nucleon. A model for the off-diagonal spectral function, based on the momentum distribution corresponding to the Av18 potential [4], is used in the actual calculation together with a well known model as far as concerns the nucleonic GPD [5] . Then, the numerical results of this approach are compared with the experimental data published by the EG6 experiment at Jlab [2], showing an overall good agreement. The results obtained allow to conclude that the description of the present data does not require exotic arguments, such as dynamical off-shellness or non-nucleonic degrees of freedom.

Calculations of the relevant observables for the incoherent DVCS channel, starting from the DVCS cross section for an initially moving nucleon embedded in the ^{4}He target, will be addressed. Finally, more refined nuclear calculations, with a view to the next generation of experiments at the JLab12 and at the future electron-ion collider, will be described.

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Parallel Session Monday: Atoms and Molecules / 11

Link between the complex rotation resonances and scattering matrix resonances

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We consider a multichannel Schroedinger operator with binary channels and a three-body Hamitonian with pairwise interactions. Being written in the momentum representation, both of these operators are subject to the complex deformation, a kind of inhomogeneous complex rotation/scaling. Isolated non-real eigenvalues of the complexly deformed Hamiltonians are called the complex rotation resonances. For a class of rapidly decreasing and momentum-space analytic interactions, we prove that the complex rotation resonances do correspond to the scattering matrix resonances, that is, to the poles of the scattering matrix analytically continued to the respective unphysical sheet. Our proofs employ the explicit representations [1,2] (see also [3,4]) that express the T- and S-matrices on unphysical energy sheets through the values of those same matrices only taken in the physical sheet. We think the proofs we give are more transparent than the ones found in the literature (see [5] and references therein). To make the presentation even more illustrative, we first give the proofs in the simplest possible case — for the Friedrichs-Faddeev model [6].

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Parallel Session Monday: Few-Nucleon Systems / 70

Derivation of relativistic Yakubovsky equations under Poincare invariance

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Recently, higher chiral-order nucleon-nucleon potentials have been developed with the chiral effective fields theory [1]. The three-body Faddeev equation had been extended by involving three-body forces [2]. The four-body Yakubovsky equations have also been extended as well [3]. In order to increase the accuracy of not only its two-body forces but also three-body forces, it is indispensable to study not only three-body systems but also four-nucleon systems using ab initio calculation.

Moreover, it is not ignorable that the effect of relativity in high energy region. We have been studying that in the proton-deuteron scattering the effect reveals at the backward of the scattering angle for the elastic process and three-body breakup [4]. It is, of course, expected that such a relativistic effect also appears in case of four-nucleon system.

I would like briefly to present my oral that I explain the Faddeev-Yakubovsky four-body equations including the three-body force [3]. Furthermore, these equations are extended in the framework of relativity. As the result we have the following coupled equations with three-body force W,
$\alpha = -G_0TPP_{34}\alpha + G_0TP\beta + (G_0 + G_0T)(G_0 + G_0t^\alpha)W(-P_{34}P + \tilde{P})(\alpha - P_{34}\alpha + \beta)$,
$\beta = G_0\tilde{T}\tilde{P}G_0(1 - P_{34})\alpha$,
where α and β are Yakubovsky components for 1+3 and 2+2 partitions, respectively, G_0 is Green's function, T, $\tilde{T}$ are transition matrices for 1+3 and 2+2 partitions, respectively. $P(\equiv P_{12}P_{23} + P_{13}P_{23})$, $\tilde{P}(\equiv P_{13}P_{24})$ and P_{34} are permutation operators. Detail is written in [3]. In particular, these transition matrices are the solutions of the following equations,
$T = \tau + \tau G_0 T$,
$\tau \equiv t^\alpha P + (1 + t^\alpha G_0)W(1 + P)$,
$\tilde{T} = t^\beta + \tilde{T}\tilde{P}G_0t^\beta$,
where t^α and t^β are 2-body transition matrix which are relativistically boosted depending on the partition sub-systems in the four-body system.

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Parallel Session Monday: Hadrons and particles / 140

Mesons with charm and bottom quarks in a covariant quark model

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We calculated bound states of quark-antiquark systems in which at least one of the constituents is a charm or bottom quark. We use a Minkowski-space formalism known as the Covariant Spectator Theory (CST), which, for example, has been successfully applied in exact relativistic calculations of two- and three-nucleon systems based on one-boson-exchange dynamics. It is also used quite extensively in phenomenological quark-diquark descriptions of baryons. The basic idea of the CST is to approximate the integration over the energy-component of the loop four-momentum in the Bethe-Salpeter equation by neglecting residues of poles in the kernel and keeping only those of the constituent particle propagators. This approximation can be shown to converge to the solution of the Bethe-Salpeter equation with the complete kernel (with all ladder and crossed-ladder diagrams) when one of the two particles becomes infinitely heavy. It should therefore be particularly well suited for the case of heavy and heavy-light mesons.

We use a covariant interaction kernel that consists of a Lorentz vector one-gluon exchange and a covariant generalization of a linear confining interaction with a mixed Lorentz structure, containing an equal-weight scalar+pseudoscalar term, and a vector term, whose relative weights can be changed through an adjustable parameter. In principle, scalar and pseudoscalar interactions break chiral symmetry, but in our formalism it is possible to include such interactions and still satisfy the constraints of chiral symmetry.

By fitting various sets of experimental masses of the heavy and heavy-light meson spectrum, we found that very good agreement can be achieved by adjusting a small number of global model parameters. It turned out that the relative weight of scalar+pseudoscalar versus vector confinement is not much constrained by the mass spectrum. In addition to the masses, we also calculated the corresponding relativistic wave functions, which are then used to calculate meson decay constants, some of which have been measured with high precision. We also investigated how much our results change when a fixed strong coupling constant α_s is replaced by a running coupling $\alpha_s(Q^2)$, and how much they depend on details of our regularization scheme.

Parallel Session Monday: Clustering in Nuclei / 35

Description of continuum structures in a discrete basis: Three-body resonances and two-nucleon decays

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Recent advances in radioactive ion beam physics and detection techniques have triggered the exploration of the exotic properties and decay modes of light nuclear systems at the limit of stability and beyond the driplines. Large experimental and theoretical efforts have been devoted to understanding the structure and reaction dynamics of loosely bound systems, such as halo nuclei, where continuum effects are of utmost relevance [1]. Of particular interest is the case of two-neutron halo nuclei, e.g., ^{6}He, ^{11}Li or ^{14}Be. These are Borromean systems, or three-body systems in which all binary subsystems cannot form bound states. While the correlations between the valence neutrons are known to play a fundamental role in shaping the properties of two-neutron halo nuclei [2], a proper understanding of their structure requires also solid constrains on the unbound binary subsystems ^{5}He, ^{10}Li or ^{13}Be [3]. The evolution of these correlations beyond the driplines gives rise to two-neutron emitters, e.g., ^{16}Be or ^{26}O [4]. A similar situation can be found for proton-rich nuclei. For instance, the Borromean ^{17}Ne nucleus, characterized by the properties of its unbound subsystem ^{16}F, has been proposed to exhibit a two-proton halo, while other exotic systems, such as ^{6}Be and ^{11}O (the mirror nuclei of ^{6}He and ^{11}Li), are two-proton emitters. Since they have a marked core+N+N character, three-body models are a natural choice to describe their structure and processes involving them [5]. The description of the continuum in three-body nuclei, however, is not an easy task. We have recently proposed a method to characterize few-body resonances by studying the time dependence of the lowest eigenstates of a resonant operator [6], with the aim of studying the population of resonances in two-nucleon emitters. The method has been applied to the two-neutron unbound system ^{16}Be, obtaining a remarkable agreement with calculations of the true three-body continuum [7] for the 0^+ ground-state resonance. An excited 2^+ state, recently observed experimentally [8], is also predicted. A summary of this work will be presented. The extension to study the corresponding relative-energy distributions, as well as its application to other unbound three-body systems, will be also discussed.

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Parallel Session Monday: Few-Nucleon Systems / 83

Measurement of Spin Correlation Coefficients in p–^{3}He Scattering at 65 MeV

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Few-nucleon scattering offers good opportunities to investigate dynamical aspects of the three-nucleon forces (3NFs), such as momentum, spin, and iso-spin dependencies. The nucleon-deuteron scattering at intermediate energies ($E/A \sim 100$ MeV) has provided a solid basis to nail down detailed properties of 3NFs [1.], however, the total isospin channel of the 3NFs is limited to $T = 1/2$. Recently importance of the iso-spin dependence of 3NFs has also been pronounced for understanding of nuclear system with larger-isospin asymmetry, e.g. neutron-rich nuclei [2.] and neutron matter [3.]. The p–^{3}He scattering is an attractive probe since this system is the simplest one in which the 3NFs in the channels of total isospin $T = 3/2$ can be studied. In order to explore the properties of three-nucleon forces via p–^{3}He scattering, we have performed the measurements of spin observables at 65 MeV by using the newly developed polarized ^{3}He target and the polarized proton beam.

The experiment was performed at RCNP, Osaka University. Polarized proton beams were accelerated up to 65 MeV by the AVF cyclotron, and bombarded the polarized ^{3}He target. The typical beam polarization was $p_y^{\uparrow} \sim 50\%$, $p_y^{\downarrow} \sim 20\%$. The scattered protons were detected by $E - dE$ detectors which consisted of NaI(Tl) and plastic scintillators. The measured angles were 47, 89, and 133 degrees in the center of mass system.

The results of the spin correlation coefficient $C_{y,y}$ are shown in Fig.1. The statistical errors are shown only. The data are compared with the rigorous numerical calculation of the four-nucleon scattering based on the modern nucleon-nucleon potential [4.]. Here the INOY04 potential [5.] is taken into account. Clear differences are found around 90 degree.

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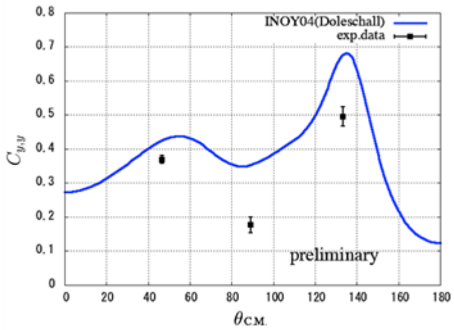

Figure 1: The results of the spin correlation coefficient.

Parallel Session Monday: Hadrons and particles / 110

The charged Z_c and Z_b structures in a constituent quark model approach

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The nature of the recently discovered Z_c and Z_b structures is intriguing. On the one hand, in the charm sector, the $Z_c(3900)^{\pm}$ and $Z_c(4020)^{\pm}$ were discovered in the $\pi J/\psi$ and $D^*\bar{D}^{(*)} + h.c.$ invariant mass spectra. Their nature is puzzling due to their charge, which forces its minimal quark content to be $c\bar{c}u\bar{d}$ ($c\bar{c}d\bar{u}$). Additionally, their strong coupling to channels such as $\pi J/\psi$ and the closeness of their mass to $D^*\bar{D}^{(*)}$-thresholds stimulates both a molecular interpretation or a coupled-channels threshold effect. On the other hand, in the bottom sector, the well-established $Z_b(10610)$ and $Z_b(10650)$ states couple to $B^{(*)}B^*$-channels and are heavy enough to assume that they should contain a constituent $b\bar{b}$-pair. Moreover, they are charged and hence they must also have another constituent light quark-antiquark pair, namely $u\bar{d}$ (Z_b^+). Their minimal structure would be then $b\bar{b}u\bar{d}$, which automatically qualifies them as an (exotic) bottomonium-like meson. Thus, in all cases, it is necessary to explore four-quark systems in order to understand their inner structure.

In this work we perform a coupled-channels calculation of the $I^G(J^{PC}) = 1^+(1^{+-})$ charm and bottom sectors in the framework of a constituent quark model [1,2] which satisfactorily describes a wide range of properties of (non-)conventional hadrons containing heavy quarks [3]. All the relevant channels are included for each sector: The $D^{(*)}\bar{D}^* + h.c.$, $\pi J/\psi$ and $\rho\eta_c$ channels for the Z_c [4] and $B^{(*)}B^*$ and $\Upsilon(nS)\pi$ ($n = 1, 2, 3$) channels for the Z_b analysis. Results will be discussed.

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Parallel Session Monday: Few-Nucleon Systems / 87

Studies of the star configurations at intermediate energies with the use of the BINA detector

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The Space Star Anomaly (SSA) 1 is a long-lasting discrepancy between differential cross-section measured for deuteron-proton breakup at 13 MeV and the theoretical predictions. The Space Star denotes a specific configuration where momenta of the reaction products form an equilateral triangle perpendicular to the beam momentum in the centre-of-momentum frame. The analyses for the other star configurations differing from the Space Star by the inclination angle of the triangle showed that the discrepancy disappears as a function of absolute difference of the inclination angle from the perpendicular case.

So far, there is no systematic studies of SSA at intermediate energies. The single measurement at 65 MeV suggests no anomaly and increased sensitivity to relativistic effects [2]. A scan over beam energies performed for a wide set of star configurations including the Space Star can shed light on the SSA problem and also on the role of relativistic effects in description of the breakup reaction. It is interesting to see, whether the effect persists at energies of the order of 100 MeV.

The data on deuteron-proton breakup measured with the BINA experimental setup are well-suited for such an analysis. In the first stage the data collected at the deuteron beam energy of 160 MeV were analysed. The star configurations at different inclination angles in the centre-of-momentum frame were identified and simulated in order to find the feasibility of the analysis. Then, cross-sections were calculated for star configurations. The angular resolution of the central and backward part of the BINA detector is limited by the granularity of the scintillator. Therefore, simulations were performed to study the averaging of kinematic configurations over the detector elements. Finally, the cross-sections were compared with the theoretical description given by the state-of-the-art calculations and they quality of agreement will be discussed in this contribution.

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Parallel Session Monday: Clustering in Nuclei / 115

19B isotope as a 17B-n-n three-body system in the unitary limit

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Motivated by the recent experimental observation of an extremely large scattering length for the n-17B system 1, we present a model describing the n-17B virtual state and the 19B bound isotope in terms of a 17B-n-n 3-body system, in which the two 2-body unbound subsystems 17B-n and n-n are close to the unitary limit. A n-17B local interaction is parametrized in order to reproduce the near-threshold virtual state observed in 1 as a function of the scattering length, and results are explored within the range as<-50 fm allowed by experiment. The binding energy of the 19B ground state is found to be in agreement with the experimental value [2] using only two-body potentials. The possible existence of resonant states is also discussed, as well as the eventual relation with Efimov physics and the extension of this work to heavier B isotopes [3].

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Parallel Session Monday: Hadrons and particles / 23

Generalized parton distribution functions of ρ meson

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Both unpolarized and polarized generalized parton distribution functions (GPDs) of the ρ meson are clculated with the help of a light-front quark model [1-2]. The contributions to the form factors and generalized parton distributions from the valence and nonvalence regimes are discussed and analyzed. Comparing to the available experimental data and Lattice calculation, we find that the present phenomenological model is reasonable to describe the general properties of ρ meson.
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Parallel Session Monday: Few-Nucleon Systems / 92

Dynamical effects in deuteron-proton reaction at 100 MeV

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Experimental studies of the deuteron-proton system at medium beam energies expose various dynamical ingredients, like three-nucleon force (3NF) and Coulomb force, which play an important role in correct description of observables (e.g. cross section). The experimentally determined differential cross sections for elastic scattering and breakup constitute the basis for testing various theoretical approaches [1 - 4] to model the interaction in three-nucleon systems. Moreover, studies of the dp breakup reaction at low energy are very crucial for testing The Chiral Perturbation Theory [5] (as soon as calculations for the nucleon-deuteron breakup reaction at low energies became available).
During presentation the differential cross sections for two main reaction channels (elastic scattering and breakup) of deuteron-proton system at beam energy of 100 MeV will be presented. The experiment has performed at KVI in Groningen, with the use of the forward part of the BINA detector

[6]. The data will be compared to theoretical calculations with including the 3NF and Coulomb force effects.

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Parallel Session Monday: Clustering in Nuclei / 49

Beryllium-9 in Cluster Effective Field Theory

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In our work we have studied ^{9}Be ground state with non-local αn and $\alpha\alpha$ potentials derived from Cluster Effective Field Theory. The Borromean system provided by the nucleus of ^{9}Be shows, at low energy ($< 20\,$MeV), a separation of scales and the dynamics describing the cluster configuration is insensitive to internal dynamics of the α particle. Therefore to describe such cluster nuclei we can use an Effective Field Theory where the degrees of freedom are represented by neutrons and α particles. We study the interaction among alpha and valence neutrons using non-local contact interactions. The potentials extracted from the theory are regularized by a Gaussian cutoff which regulates the short-distance dependence of the interaction. We choose the cutoff regularization, because of its ability to reproduce known features, such as parameters in the effective range expansion, including the scattering length and the effective range. Then, the potential parameters are fitted to reproduce these scattering parameters in the calculated scattering T-matrix. We implemented such non-local potential models in a Non-Symmetrized Hyperspherical Harmonics (NSHH) code in momentum space. The final goal of this project is to use these potentials in the calculation of the photodisintegration of ^{9}Be, a reaction of astrophysical relevance. Work is in progress to insert an effective $\alpha\alpha n$ interaction in the theory, then the prediction of the photodisintegration will be realized with the LIT method.

Parallel Session Monday: Clustering in Nuclei / 67

Deuteron-Alpha Scattering in a Three-Body Approach

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Single particle transfer reactions (d,p) involving rare isotopes continue to be an important tool for extracting nuclear structure information such as asymptotic normalizations coefficients, and contribute to the understanding of the dynamics of the reactions. The (d,p) reaction may be viewed as a three-body n+p+A problem in which the deuteron and the nucleus A act as participants in the reaction. It is advantageous to consider this reaction within a momentum space Faddeev framework, which allows treating all channels on the same footing, independent if the nucleus is heavy or light. As first application we concentrate on the deuteron-alpha system, for which we calculate d+alpha elastic scattering below and above the three-body breakup threshold, as well as exclusive break-up cross section in several configurations. The interactions in the respective two-body subsystems are given by multi-rank separable representations of realistic interactions based on the Ernst-Shakin-Thaler formulation, which have also been successfully applied in calculating the ground state of Lithium-6 as three-body system. We benchmark the calculations employing separable representations of the forces in the subsystems against calculations in which those forces are used directly and find excellent agreement for relatively moderate basis sizes in the separable expansion.

Parallel Session Monday: Hadrons and particles / 104

$Y(4260)$ as a $q\bar{q}c\bar{c}$ exotic vector meson by a quark-hadron hybrid model

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Recent BESIII experiments on the $e^+e^- \to \pi^+\pi^- J/\psi$ process have shown that the Y(4260) peak has rather complicated structure 1. It was reported that there are two peaks at the energy of 4220.0±3.1±1.4 MeV and 4320.0±10.4±7.0 MeV with a width of 44.1±4.3±2.0 MeV and 101.4$^{+25.3}_{-19.7}$± 10.2 MeV, respectively.
In the previous work, we found that there is a $J^{PC} = 1^{--}$ resonance around the $\bar{D}D_1$ threshold, 4293 MeV, when we consider the short range part of the two-meson states to be four quarks, $q\bar{q}c\bar{c}$, and introduce the color magnetic interaction among the quarks [2]. The attraction comes mainly from the color-magnetic interaction in the color-octet component of the two light quarks. Such a configuration can be expressed by a superposition of several $\bar{D}D$ states. In order to introduce the effect fully it is necessary to solve the systems with many two-meson channels coupled. Though the resonance obtained in this way is close to the threshold and its width is narrow, the attraction may contribute to form the observed Y(4260) resonance.
In the present work, we introduce the meson exchange between the two mesons to investigate how this coherent-channel resonance changes in a more realistic model, and discuss whether the model explains the observed complicated structure.
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Parallel Session Monday: Few-Nucleon Systems / 74

Differential Cross Section for Proton Induced Deuteron Breakup at 108 MeV

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Studies of few-nucleon system dynamics is the basis for understanding of nuclear interactions and properties of nuclei.
The very accurate theoretical calculations for three nucleon systems should be confronted with a rich set of systematic experimental data. For this purpose a series of measurements of deuteron breakup in collision with proton was conducted in KVI Groningen and FZ-Julich. These studies confirmed the important role of the Three-Nucleon Force (3NF) and huge influence of Coulomb interaction between protons [1-3]. However, some discrepancies persist, indicating that our present understanding of the problem is not yet perfect [4-6].
The origin of the discrepancies is not known. At intermediate energies, they can be possibly attributed to deficiencies of current 3NF models or to lack of fully relativistic calculations. Continuation of the studies in a wide range of energies, at the regions of the maximum visibility of the certain effects, are necessary. For this purpose, the BINA (Big Instrument for Nuclear-polarization Analysis) detection system has been installed at CCB (Cyclotron Center Bronowice).
The BINA setup is designed to study the elastic and breakup reactions at intermediate energies. It consist of the liquid target facility and the low threshold detector covering nearly 4π solid angle, enabling studies of almost full phase space of these reactions [4,7].
The data analysis and results of the first experimental run of proton-induced deuteron breakup at beam energy of 108 MeV performed at Cyclotron Center Bronowice PAS in Cracow will be presented. Differential cross section determined for a set of kinematic configurations will be compared to state of the art theoretical calculations.

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Parallel Session Monday: Few-Nucleon Systems / 143

Studies of Few-Nucleon Systems via $^2H(dn)p$ Deuteron Breakup Reaction.

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Few-nucleon systems are the basic laboratories for studying the mechanisms of interactions between nucleons. 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.
Experiments devoted to studies of 3NF were carried out at the KVI in Groningen in the Netherlands. The BINA detector system collected a set of high precision data of the deuteron breakup reaction with the use of 160 MeV deuteron beam. The detector has been designed to detect charged reaction products, mainly protons and deuterons. A number of techniques have now been developed to

allow direct registration of neutron. Using the time-of-flight method and signal asymmetry in the scintillators, we were able to reconstruct the neutron momentum from the collected data. Using this information, the new reaction channel $^2H(dn)p$ were measured. Having determine the differential cross-section for this reaction one can compare it with analyzed $^2H(dp)n$ channel [1, 2] at the same kinematic conditions and direct study the coulomb effect and possible charge symmetry breaking, like it was suggested in [3].
The results covering sample distributions of differential cross section of $^2H(dn)p$ reaction as well as important steps in neutron detection methods will be presented.

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Plenary Session 1 Tuesday / 12

Skyrmions and clustering in light nuclei

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It is almost 60 years since Skyrme introduced his model of nuclei as topological solitons (Skyrmions) in a nonlinear pion theory. I shall review the Skyrme model and discuss some of the successes and failures of Skyrmions. In particular, I will describe some recent work that yields improved results for binding energies and clustering in light nuclei, by extending the standard theory of Skyrmions to include the next lightest subatomic meson particles traditionally neglected. Related Skyrmions in magnetic materials will also be briefly discussed.

Plenary Session 1 Tuesday / 15

Lattice simulations for nuclei, ultracold atoms, and ions

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I give a brief tour of recent applications of lattice simulations using the framework of effective field theory. The topics to be covered are first principles calculations of nuclear structure and reactions, ultracold atoms in the unitarity limit, and discrete scale invariance in trapped ion quantum simulators.

Plenary Session 1 Tuesday / 45

Nucleon structure from Lattice QCD and future prospects

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We present recent results on the structure of the nucleon using simulations carried out within the framework of lattice QCD. These simulations are performed with physical values of the quark masses yielding results that can be directly compared with experimental results. A complete calculation of the contributions of quarks and gluons to the spin of the nucleon explains the so-called spin puzzle of the proton. First results on the direct determination of nucleon parton distribution functions hold to the promise for an ab initial computation of these important quantities.

Special Session: in memoriam of Roy Glauber / 134

Roy Glauber and asymptotic diffraction theory

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I shall present a review of Glauber's asymptotic diffraction theory, in which diffractive scattering is described in terms of interference between semiclassical amplitudes, resulting from a stationary-phase approximation to the integration over impact parameters. Typically two such amplitudes are sufficient to accurately describe elastic scattering, but the stationary points are located at complex values of the impact parameter. Their separation controls the interference pattern, and their offset from the real axis determine the overall fall-off with momentum transfer. Asymptotically, at large momentum transfers, the stationary points move towards singularities of the profile function. I shall also present some reminiscences from my collaboration with Roy.

Special Session: in memoriam of Roy Glauber / 108

The eikonal model of reactions involving exotic nuclei; Roy Glauber's legacy in today's nuclear physics

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In the late 1950s, Roy Glauber introduced the eikonal approximation within quantum-collision theory 1. Since then, it has been applied to a wide variety of cases, ranging from atomic physics to particle physics. In nuclear physics, the interest in this model of reactions has been revived by the development of Radioactive-Ion Beam (RIB) facilities, where nuclear structure can be probed far from stability. In such facilities, the structure of radioactive nuclei is mostly studied through reactions. An accurate model of reactions is thus needed to reliably infer nuclear-structure information from reaction measurements. The eikonal model introduced by Roy Glauber has been widely used to study the single-particle structure of exotic nuclei through knockout reactions at high energy [2]. It also provides a very reliable model of reactions involving halo nuclei at intermediate and high energy [3,4].
In this contribution, after a brief presentation of the eikonal approximation, I will review its use in modern nuclear physics and the exciting results this model of reactions has enabled today's nuclear physicists to obtain far from stability. In addition, I will discuss the various improvements that have been introduced to extend its range of validity, e.g., to include the dynamics of the projectile within the model of the reaction [3,4,5], to use it al low beam energy [6,7,8], or to include relativistic effects

at high energy [9,10].
This series of examples illustrates the impact the eikonal approximation introduced by Roy Glauber sixty years ago has had, and certainly will continue to have, in the exciting and developing field of nuclear-reaction theory.

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Parallel Session Tuesday: Few-Nucleon Systems / 37

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 explored in the medium energy region [1-3]. The interpretation of the experimental data is possible due to rigorous calculations of three nucleon (3N) observables 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 development of exact numerical calculations for four-nucleon breakup are still distant in time given complexity of the problem. 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]. Moreover, the experimental data for four-body breakup are very scarce [8,9,10], especially for exclusive measurements. In this talk a set of data for differential cross section of the 2H(d, dp)n breakup [8], d-d elastic scattering and 2H(d, 3He)n transfer [9] reactions measured with the BINA@KVI setup at 160 MeV will be presented. The breakup data will be compared with the recent SSA calculations [7]. In addition, the scheme of analysis of the exclusive d-d three-body and four-body breakup data collected with the WASA@COSY detector at 350 MeV will be outlined.
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Parallel Session Tuesday: Atoms and Molecules / 137

Donor impurities in silicon as a platform for few-body problems: donor excitation and donor-donor interactions

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Shallow donor impurities in silicon, once frozen out at low temperature, share many properties in common with free hydrogen atoms, with a single electron orbiting a singly positively charged ion core. Phosphorus donors in silicon show extremely long spin relaxation lifetimes making them very attractive for encoding quantum information, and the orbitals are very large, suggesting good prospects for precise control over interactions between neighbours. We have demonstrated temporal coherent control of orbital superpositions, using photon echoes, Ramsey interference and donor-donor interactions etc. Since silicon doped with phosphorus (Si:P) is an industry standard dopant, the technology for electrical contacting for initialization, gating and readout is pretty well established. Si:P can now be placed in a device, with a precision approaching the bond length, using a scanning-probe-based lithography technique. At Surrey we have been developing a complementary nanometer-scale implantation facility with much greater flexibility in species (at the price of trade-off with precision), and are now beginning to be able to produce spatial control required for few-body experiments. I will describe the donor-donor interaction experiments performed so far (on randomly arranged donors) and progress on deterministic placement.

Parallel Session Tuesday: Short-Range Correlations in Nuclei / 133

Study Nucleon-Nucleon Interaction with Short Range Correlation

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Electron scattering experiments demonstrate that about 20% of the nucleons in nuclei have momentum greater than the nuclear Fermi momentum. This is predominantly due to close-proximity neutron-proton pairs, which interact via a strong short-range force. I will discuss these close-nucleon in few body systems and their importance to the study of nucleon-nucleon interaction, neutron stars, and the modification of the internal structure of nucleons bound in nuclei.

Parallel Session Tuesday: Few-Nucleon Systems / 105

Quasi-free limit in the deuteron-deuteron three-body break-up process

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Detailed measurements of five-fold differential cross sections and a rich set of vector and tensor analyzing powers of the 2H(~d, dp)n break-up scattering process are presented. The data were obtained using a polarized deuteron-beam with an energy of 65 MeV/nucleon impinging on a liquid-deuterium target. The experiment was conducted at the AGOR facility at KVI using the BINA 4π-detection system. The main focus of this contribution is to determine the quasi-free limit in dd scattering which corresponds to the elastic deuteron-proton scattering process. To achieve this, events for which the final-state deuteron and proton are coplanar have been analyzed and the data have been sorted for various reconstructed momenta of the missing neutron. In the limit of vanishing neutron momentum and at small deuteron-proton momentum transfer, the data match very well with measured and predicted spin observables of the elastic deuteron-proton scattering process. The agreement deteriorates rapidly with increasing neutron momentum and deuteron-proton momentum transfer.

Parallel Session Tuesday: Atoms and Molecules / 76

Energy spectrum of excitons in semiconductor quantum wells

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The electron-hole bound states (excitons) in the semiconductor quantum wells (QW) are remarkable examples of Coulomb systems, in which the external potential of the heterostructure plays a role of the third particle, thus 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 an 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 Schroedinger equation for the exciton in a QW and analysing the spectrum of the Schroedinger operator. 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 [10]. 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.

Financial support from the Russian Science Foundation (grant No. 19-72-20039) is acknowledged. The calculations were carried out using the facilities of the Computational Center of SPbU.

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Parallel Session Tuesday: Short-Range Correlations in Nuclei / 66

Towards Renormalization Invariant Equation of State of Nuclear Matter

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The current paradigm to describe the nuclear interaction is within the frame of Chiral Effective Field Theory (χEFT) which organizes contributions to nuclear observables in a series of decreasing importance. Within this framework the leading contribution already requires to solve exactly the many-body Schrödinger equation with a particular Hamiltonian. Nevertheless, such calculations are numerically intractable for A-body observables whenever $A \gg 10$.

Consequently, following the EFT program to describe infinite nuclear matter, and in particular its Equation of State (EoS), appears to be challenging. In this talk I will focus in particular on Many-body Perturbation Theory (MBPT) and more generally on many-body approximations that can be expressed as a sum of perturbation diagrams. Such additional approximations depart from the original EFT program. The goal of this talk is thus to emphasize the impact of many-body approximation on the renormalization invariance of many-body observables. I will also present new formal developments that pave the way to a systematic approach for renormalization-invariant many-body calculations. In practice, these developments could lead, in the near future, to a reduction of systematic theoretical uncertainties of nuclear many-body observables.

Parallel Session Tuesday: Few-Nucleon Systems / 79

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

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One of the most important topics of nuclear physics is to describe various nuclear phenomena based on the nucleon-nucleon interactions combined with three-nucleon forces ($3N$Fs). $3N$Fs are key elements to understand various nuclear phenomena, e.g. binding energies of light mass nuclei 1 and the equation of state of nuclear matter [2]. In the last decades, the study of $3N$Fs effects has been extensively performed in deuteron–proton (dp) scattering at intermediate energies (E/A 60 MeV). Rigorous numerical Faddeev calculations of the $3N$ scattering by using NN potentials as well as $3N$Fs models have made it possible to compare the data to the theoretical calculations. Consequently, the first evidence of $3N$Fs effects has been found in the dp scattering system [3]. As an extension of $3N$Fs study, it should be interesting to see how $3N$Fs act in p–^{3}He scattering system. In this system, one could study $3N$Fs effects in $4N$ scattering. Also one could approach to $3N$Fs with the channels of the total iso-spin $T = 3/2$.
In order to study $3N$Fs effects in p–^{3}He elastic scattering, we performed the measurement of the cross section and the proton analyzing power A_y at 65 MeV with a polarized proton beam at Research Center for Nuclear Physics (RCNP), Osaka University. The gaseous ^{3}He target was bombarded 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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Parallel Session Tuesday: Atoms and Molecules / 96

Theory of three and four body quantum dots in Monolayer Transition Metal Dichalcogenides

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In latest years, there have been a promptly increasing number of experimental and theoretical publications focusing on transition metal dichalcogenides (TMD) crystals. Quantum dots TMD have the potential to combine the essential features of both optically active and electrically defined quantum dots. Strong electron–hole binding in TMDs suggests that it would be possible to obtain a discrete spectrum due to trapping of trions and biexcitons in strong electric or magnetic fields. The properties of the charged excitons and biexcitons in a parabolic quantum dot in an external magnetic field are studied using an effective-mass Hamiltonian. The Hamiltonian is written in terms of the center of mass and relative coordinates. The Schrödinger equation for electron – hole systems in a quantum dot in a magnetic field was solved in the framework of the hyperspherical functions method. We assume that electrons and holes are interacted via Ritova- Keldysh potential 1. It is shown that the ground state properties are approximately determined by that part of the total Hamiltonian that depends only on relative coordinates.
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Parallel Session Tuesday: Short-Range Correlations in Nuclei / 65

Bogoliubov Many-Body Perturbation Theory

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The last few decades in nuclear structure theory have seen a rapid expansion of ab initio theories, aiming at describing the properties of nuclei starting from the inter-nucleonic interaction. Limited for a long time to very light nuclei, they are now able to access nuclei with up to A ~ 100 particles. Such an expansion relied both on the tremendous growth of computing power and novel formal developments, with methods scaling polynomially with the number of particles.
The recently proposed Bogoliubov Many-Body Perturbation Theory 1 makes use of a particle-number-breaking reference state to tackle singly open-shell nuclei and capture pairing correlations, while dynamical correlations are accounted for perturbatively through quasiparticle excitations truncated in a systematic way. While BMBPT is presently used as a stand-alone approach, it eventually provides the first step towards the implementation of the particle-number projected BMBPT (PNP-BMBPT) which exactly restores good particle number at any truncation order.
As the number of contributions to be considered grows very rapidly with the perturbative order, the development of the present diagrammatic formalism has been associated to the production of an open-source software [2] generating and evaluating contributions at arbitrary truncation orders, with implications possibly extending to quantum chemistry and condensed matter communities.
Systematic ground-state energies along complete isotopic chains from oxygen up to tin have been computed using a standard chiral effective field theory Hamiltonian. Low-order BMBPT calculations performed on the basis of a soft interaction were found to agree at the 2% level with state-of-the-art non-perturbative many-body methods at a small fraction of the computational cost [3]. They establish BMBPT as a method of interest for large-scale computations of isotopic or isotonic chains in the mid-mass sector of the nuclear chart, be it for the systematic pre- or post-diction of nuclear properties or the test of newly developed Hamiltonians.
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Parallel Session Tuesday: Few-Nucleon Systems / 78

Measurement of ^{3}He analyzing power for $p-^3$He scattering using the polarized ^{3}He target

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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]. The isospin $T = 3/2$ components of the 3NF also play an important role in many-nucleon systems especially for neutron-rich nuclei as well as neutron matter properties. The $p-^3$He scattering is one of the simplest prove for studying the $T = 3/2$ components of the 3NF. With the aim of exploring the properties of the 3NF we are planning the measurement of ^{3}He analyzing power for $p-^3$He scattering with the polarized ^{3}He target at intermediate energies ($E/A \geq 65$ MeV). Polarized ^{3}He was produced by the alkali-hybrid spin-exchange optical pumping method. To measure the ^{3}He polarization and control ^{3}He spin directions, we used the adiabatic fast passage-NMR method. We obtained the absolute value of the ^{3}He polarization and calibrated the NMR signal by the electron spin resonance measurement of Rb. The maximum ^{3}He polarization was ~ 50 % in our system.

Using the polarized ^{3}He target, we performed the measurement of ^{3}He analyzing power at CYRIC ($E_p = 70$ MeV) and RCNP ($E_p = 100$ MeV) in Japan. Measured angles were $\theta_{\mathrm{lab.}} = 35^\circ - 125^\circ$ ($\theta_{\mathrm{c.m.}} = 46^\circ - 141^\circ$) at CYRIC and $\theta_{\mathrm{lab.}} = 35^\circ - 135^\circ$ ($\theta_{\mathrm{c.m.}} = 47^\circ - 149^\circ$) at RCNP respectively. 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. 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 report recently results of the experimental data.

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Parallel Session Tuesday: Atoms and Molecules / 126

Dipolar condensed atomic mixtures and miscibility under rotation

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By considering symmetric and asymmetric dipolar coupled mixtures (with dysprosium, erbium and rubidium isotopes), we reporta study on relevant anisotropic effects, related to spatial separation and miscibility, due to dipole-dipole interactions (DDI) in rotating binary dipolar mixtures Bose-Einstein condensates 1.
The binary mixtures are kept in strong pancake-shaped trap, with repulsive two-body interactions modeled by an effective two-dimensional coupled Gross-Pitaevskii equation. The DDI are tuned from repulsive to attractive by varying the dipole polarization angle. A clear spatial separation is verified in the densities for attractive DDI, being angular for symmetric mixtures and radial for asymmetric ones. Another relevant outcome is the observed mass-imbalance sensibility verified by the vortex-pattern binary distributions in symmetric and asymmetric-dipolar mixtures, which requires the use of a relation for nonhomogeneous mixtures to estimate the miscibility of two components.

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Parallel Session Tuesday: Short-Range Correlations in Nuclei / 152

Nuclear short range correlations and universality

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Few years ago it was suggested by S. Tan that the properties of cold and dilute quantum gases depend on a new characteristic quantity, the contact", that describes the probability of two particles coming close to each other. Generalizing this concept to nuclear physics interesting relations between e.g. the 1-body, 2-body momentum distributions, and the 2-body density can be derived. In my talk I will present Tan'scontact" and its generalization to nuclear and molecular systems. I will introduce the various nuclear contacts, and their applications to analyse electron scattering experiments.

Parallel Session Tuesday: Hyperon interactions and hypernuclei / 53

Exploring the Unknown Λn Inteaction

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No published data for Λn scattering exist. A relativistic heavy-ion experiment 1 has suggested that a Λnn bound state has been seen. If that were the case, our knowledge of the nn interaction would permit one to use that Λnn bound state energy to generate strong constraints on the Λn interaction. JLab would be an ideal facility to obtain such data using the ^{3}H(e,e'K$^+$)$^3_\Lambda$n reaction. However, at least four theoretical analyses based on a pairwise nn and Λn interaction hypothesis have cast serious doubt on the bound-state assertion [2-5]. However, there could exist a three-body Λnn resonance. Such a resonance could be used to constrain the Λn interaction.

We discuss calculations for the Λnn system using pairwise interactions of rank-one, separable form that fit effective range parameters of the nn system and those hypothesized for the as yet unobserved Λn system based upon two different Nijmegen one-boson exchange potentials [6,7], a J\"{u}lich one-boson exchange potential [8] and a chiral ΛN potential [9], each of which is fit the known Λp scattering data. The use of rank-one separable potentials allows us to analytically continue the Λnn Faddeev equations into the second complex energy plane in search of resonance poles, by examining the eigenvalue spectrum of the kernel of the Faddeev equations.

Although none of the potential models utilized (each based upon the nominal Λp scattering length and effective range) predict a physical resonance pole, scaling of the Λn interaction by as little as $\sim$5\% (well within the Λp scattering data uncertainties), does produce a resonance in the Λnn system. This suggests that one may use photo (electro) production of the Λnn system as a tool to examine the strength of the Λn interaction. In particular, an experiment using K$^+$ electro production from tritium at Jefferson Lab has been performed in an effort to explore the Λnn final state (physical resonance or sub-threshold resonance); modeling the position and width of the spectrum would provide significant constraints on the scattering length and effective range of the heretofore unmeasured Λn interaction.

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Parallel Session Tuesday: Atoms and Molecules / 52

Revealing missing charges in few-body cold-atom systems with generalised quantum fluctuation relations

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The out-of-equilibrium dynamics of quantum systems is one of the most fascinating problems in physics, with outstanding open questions on issues such as relaxation to equilibrium. An area of particular interest concerns few-body systems, where quantum and thermal fluctuations are expected to be more relevant and play an important role in the efficient design of novel quantum nano-devices.

In this talk, I will present a new set of exact relations between out-of-equilibrium fluctuations and equilibrium properties of a quantum system. Then, I will illustrate its application to reveal the conserved quantities (or 'charges') constraining the out-of-equilibrium dynamics of a few-body system implementing the Dicke model with a state-of-the-art cold-atom system [2,3].

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Parallel Session Tuesday: Light Nuclei / 71

Influence of the Pauli principle on two-cluster potential energy

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We study properties of an interaction between two clusters within the resonating group method. Due to the Pauli principle, a cluster-cluster interaction is a nonlocal potential within the standard version of the resonating group method. We employed the algebraic version of the method, which involves a complete basis of oscillator functions to expand a two-cluster wave function. In the framework of the latter method, a nonlocal cluster-cluster interaction is represented as a matrix. Our main aim is to study properties of matrix of the potential energy operator generated by a nucleon-nucleon and Coulomb potentials. We construct the matrix with the full antisymmetrization and without antisymmetrization (folding potential). These two matrixes allow us to reveal explicitly the influence of the Pauli principle on the shape of the cluster-cluster interaction.

Eigenvalues and eigenfunctions of the folding cluster-cluster potential have been compared with those of the non-local cluster-cluster potential for the lightest nuclei of the p-shell: ^{5}He, ^{5}Li, ^{6}Li, ^{7}Li, ^{7}Be and ^{8}Be. All these nuclei are considered as two-cluster systems composed of an alpha particle and a nucleus of the s-shell. We employ the Minnesota potential, the modified Hasegawa-Nagata potential and Volkov N2 potential to investigate the dependence of cluster-cluster interaction on the shape of the potential.

It is demonstrated that eigenvalues of the folding two-cluster potential coincide with the potential energy in coordinate space at some specific discrete points. It is also shown that the eigenfunctions of the folding potential energy matrix are the expansion coefficients of the spherical Bessel functions in a harmonic oscillator basis.

In general, the eigenvalues of the folding and exact cluster-cluster potential do not diverge considerably. However, the dependence of the exact cluster-cluster potential on the number of the invoked functions reveals a number of resonance states which are absent in the case of folding potential. The structure of the resonance states is much different from the eigenfunctions of the folding potential. Such resonance states are mainly localized in the region of small number of quanta in discrete space and, consequently, in the region of small distances between clusters in coordinate space.

Parallel Session Tuesday: Hyperon interactions and hypernuclei / 86

Light single- and double-lambda hypernuclei in pionless effective field theory

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We present the first comprehensive study of pionless effective field theory to A$\leq$6 single and double Λ hypernuclei.
The theory, which is fitted entirely from available experimental data, solves the longstanding overbinding problem of the $^{5}_{\Lambda}$He hypernucleus and allows to predict the existence of bound states in single- and double-Λ neutral Hypernuclei still under debate.
The renormalizability of the theory is also analyzed and the difficulties that this introduces in the computational calculations are discussed together with the possible extensions of the method.

With a limited amount of experimental data available, the extension of nuclear physics to the strange sector can be hardly done using the same techniques employed for standard nuclei.
Pionless effective field theory revealed to be a very successful approach due to the small number of parameters to be determined and the good theoretical accuracy (of the order of 10% of binding energies), which is enhanced by the large breaking scale and the small momentum of the lambda particles.

Parallel Session Tuesday: Light Nuclei / 50

Electric-dipole transitions in 6Li with a fully microscopic six-body calculation

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Nuclear cluster structure often appears in the spectrum of light nuclei. The role of the nuclear clustering in the electric-dipole (E1) transitions is of great interest since they are closely related to important astrophysical reactions. Recently, an interesting speculation on the E1 excitation mechanism was made in the measurement of the photoabsorption cross section of 6Li that implied the coexistence of typical and cluster E1 excitation modes 1. To understand the excitation mechanism of 6Li, we perform a fully microscopic six-body calculation with the correlated Gaussian method [2,3], which the formation and distortion of the nuclear clusters are naturally taken into account.

We calculate the E1 transition strengths and their transition densities and discuss how 6Li is excited by the E1 field as a function of the excitation energy. We find the out-of-phase transitions due to valence nucleon around the alpha cluster dominate in the low-lying energy regions below the alpha breaking threshold indicating "soft" Goldhaber-Teller(GT [4]) dipole excitation, which is very unique in 6Li, whereas the typical GT mode appears in the higher-lying energy regions. We show the various cluster components in the six-body wave function and discuss the role of the nuclear clustering in the E1 excitations of 6Li [5].

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Parallel Session Tuesday: Atoms and Molecules / 39

A coherent superposition of Feshbach dimers and Efimov trimers.

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We show a powerful experimental technique to study Efimov physics at positive scattering lengths in a gas of ultracold atoms. We use the Feshbach dimers as a local reference for Efimov trimers by creating a coherent superposition of both states. Measurement of its coherent evolution provides information on the binding energy of the trimers with unprecedented precision and yields access to previously inaccessible parameters of the system such as the Efimov trimers' lifetime and the elastic processes between atoms and the constituents of the superposition state.

Parallel Session Tuesday: Hyperon interactions and hypernuclei / 21

Lambda-nucleon potentials and Gel'fand-Levitan-Marchenko theory

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In the strangeness sector, baryon-baryon interactions play a very important role in our understanding of the strong force. Their significance lie in the extra quantum number that the hyperons (lambda, sigma, etc.) bring into nuclear systems. The lambda-nucleon interaction is the most studied interaction in the strangeness sector. Currently used lambda-nucleon potentials have their roots in meson theory and quark theories. These potentials have been subjected to testing by computing the binding energy and lifetime of the lambda hypertriton, as well as the lambda separation energy of mirror-image hypernuclei. Significant differences were observed between some of these computations and experimental observations, implying that much effort is still needed in understanding the lambda-nucleon force. Two aspects of the hyperon-nucleon force still remain poorly understood: charge symmetry breaking and lambda-sigma conversion. The aim of this project is to propose new spin-dependent potentials for the lambda-nucleon interaction, using Gel'fand-Levitan-Marchenko inversion theory. In this theory, the lambda-nucleon potential is recovered from spectral data. Due to experimental difficulties arising from the short lifetimes of hyperons, the available experimental spectral data has poor statistics. Theoretical data is therefore used as input in our inversion scheme. By using rational-function approximations for this spectral data, so as to ensure well-posedness of the inverse problem, new lambda-proton and lambda-neutron potentials are constructed. These new potentials retain all the main features of a baryon-baryon interaction, in addition to certain distinctive features whose effects may show up in Schrödinger calculations. In test calculations for the hypertriton, the binding energy computed was -2.46 MeV.

Parallel Session Tuesday: Light Nuclei / 129

From three- to six-body systems within a properly symmetrized hyperspherical harmonics approach

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We develop a new numerical method to construct an orthonormal basis of properly symmetrized hyperspherical harmonic functions 1. Refined algorithms for calculating the transformation coefficients between hyperspherical harmonics based on different sets of Jacobi coordinates are described. A method to extract a maximal set of linearly independent hyperspherical states from a highly redundant set of symmetric ones (in case of bosonic systems) or antisymmetric ones (in case of few-nucleon systems) is also presented. Based on these properly symmetrized hyperspherical harmonics basis, the spectra of helium clusters with up to six atoms are studied variationally using soft-core potentials. The obtained results are compared with literature ones [2]. Preliminary results on few-nucleon systems are also presented.

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Parallel Session Tuesday: Atoms and Molecules / 136

Phase Transitions of an Ultracold Gas in a Quasicrystalline Potential

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The recent experimental advancement to realise ultracold gases scattering off a quasicrystalline optical potential [Phys. Rev. Lett. 122, 110404 (2019)] heralds the beginning of a new technique to study the properties of quasicrystal structures. Quasicrystals possess long-range order but are not periodic, and are still little studied in comparison to their periodic counterparts. Ultracold atoms are well described by Bose-Hubbard models when loaded into an optical lattice. Here, we consider an ultracold bosonic gas loaded into an eight-fold symmetric optical lattice. We study the ground state phases of the system, with particular interest in the local nature of the phases. We observe the usual Mott-insulator, superfluid, density wave, and supersolid phases of the standard and extended Bose-Hubbard model. For non-zero long-range interactions we observe density waves that have spontaneously broken the quasicrystal symmetry, and can even possess no rotational symmetry. We find the local variation in the number of nearest neighbours to play a vital role in the phase transitions, local structure, and global symmetries of the ground states. This variation in the number of nearest neighbours is not a unique property of the considered eight-fold optical lattice, and we expect our results to be generalisable to any quasicrystalline potential where there are only small variations in on-site energy.

Parallel Session Tuesday: Hyperon interactions and hypernuclei / 75

Study of the Hyperon-nucleon interaction using the CLAS detector

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Obtaining a detailed understanding of the physics of hyperons allow us to improve our basic understanding of the strong force, which is currently based on nucleons, and allow a deeper understanding of matter in neutron stars. The difficulty in obtaining a high-quality data set of hyperon-nucleon scattering lies with experimental difficulties in obtaining hyperon beams or targets. Here I will present our novel approach that allows us to access the Hyperon- Nucleon interaction by producing a hyperon beam electromagnetically within a few-body nuclear system, and studying final-state interactions. The CLAS detectors housed in Hall-B of the Thomas Jefferson laboratory provides a large kinematic coverage, and in combination with the exceptionally high quality of the experimental data from experiment E06-103, we are able identify and select final-state interactions events in the reaction $\gamma d \rightarrow K^+ \Lambda n$ and to establish their kinematical dependencies. A polarised photon beam allows the determination of a large set of observables that provides stringent constraints on modern Hyperon-Nucleon potentials.

Parallel Session Tuesday: Light Nuclei / 107

Study of 3- and 4-neutron systems using the hyperspherical method

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The low energy collision of three- and four-neutrons is studied using the adiabatic hyperspherical representation, aimed at understanding whether low energy resonances might exist. This study is motivated by the recent experimental claim of an observation of a four neutron resonance [Kisamori et al., 2016]. From the theoretical side, several studies haven been reported, however, the conclusions reached are in conflict. We study directly the three- and four-neutrons scattering process by means of the adiabatic formalism, and using modern microscopic nucleon-nucleon and three-nucleon interactions. We have found that a resonance-like feature arises in the time-delay spectrum for four neutrons, which according to criteria utilized to classify features in atomic physics, would indeed be designated as an observable resonance, at an energy around 0.7 MeV. A similar structure is also observed for three neutrons, although much less evident, at an energy very close to zero.

Parallel Session Tuesday: Atoms and Molecules / 94

The nodal structure of wave functions with non-local potentials

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The nodes theorem provides a relation between the quantum number of a given bound state and the number of nodes of its wave function. We describe here a family of non-local potentials, with analytical known solutions, whose spectra can be modified at will. For these potentials, there is no relation between the quantum number of a state and its number of nodes. The existence of these potentials suggests that the nodes theorem is not valid when non-local interactions are considered.

Public Lecture / 149

The day without a yesterday

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The greatest discovery in the history of science is that there was a day without a yesterday. The Universe has not existed forever. It was born. 13.82 billion years ago, it erupted into being in a titanic fireball called the big bang. Marcus Chown explains how the man who first guessed that the Universe had arisen in a hot big bang believed (incorrectly) that it was the furnace which had forged the atoms in our bodies, and therefore got the right answer for the wrong reason! Marcus

also discusses the outstanding questions such as: What was the big bang? What drove the big bang? And what happened before the big bang? The latter is the stickiest question of all, and why most scientists had to be dragged kicking and screaming to the idea of the big bang.

Plenary Session 1 Wednesday / 13

Hyperons - a strange key to the strong interaction

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The Standard Model has been successful in describing the elementary particles and their interactions. However, a missing piece is a coherent description of the strong interaction in the confinement domain. This puzzle manifests itself in the non-perturbative properties of the proton: neither its mass, its spin nor its radius are straight-forward to understand from first principles. Furthermore, our Universe consists of matter (e.g. nucleons), not anti-matter (e.g. anti-nucleons). What is the origin of this asymmetry?

One approach to shed light on a system one does not understand is to replace one of its building blocks and see how the system reacts. This leads to the central question in hyperon physics: what happens if we replace one of the light quarks in a proton, with a heavier one? Hyperons have an advantage with respect to nucleons: thanks to the weak, self-analysing decay of the hyperons, their spin is traceable. This provides a unique opportunity to study the role of spin in non-perturbative strong interactions. Experiments with various probes in different energy regimes show that hyperons often are produced polarised, even when the initial state is unpolarised.

In this talk, I will discuss the hyperon as a diagnostic tool for some of the most challenging questions in contemporary physics. The focus is on the strong interaction, in particular hyperon structure where non-perturbative effects are quantified by electromagnetic form factors. Recent results from modern detector facilities like BaBar, CLEO-c, Belle and BESIII, will be presented. I will also outline how hyperon decays can give clues to the matter-antimatter asymmetry of the Universe. Results from dedicated studies within the BESIII experiment will be reviewed. Finally, I will discuss the hyperon physics prospects at the future PANDA experiment at FAIR.

Plenary Session 1 Wednesday / 5

Nuclear structure corrections in light muonic atoms

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The measurement of the Lamb shift in muonic hydrogen and the subsequent emergence of the proton radius puzzle have motivated an experimental campaign devoted to other light muonic atoms, such as muonic deuterium and helium. For these systems, nuclear structure corrections are the largest source of uncertainty and constitute the bottle-neck for exploiting the experimental precision to extract precise nuclear radii. Nuclear theory can contribute by simulating the dynamics of few nucleons interacting with the muon and by assessing related uncertainties. Utilizing techniques and methods developed in few-body physics, we have been able to provide the so far most precise determination of nuclear structure corrections in light muonic atoms.
I will review our recent calculations and present an outlook for the future.

Plenary Session 1 Wednesday / 8

Energy-dependent 3-body loss in 1D Bose gases

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We study 3-body loss in bundles of quasi-1D gases using ultracold Cs atoms in 2D optical lattices. We take the atoms out of equilibrium using the quantum Newton's cradle method, varying the average energy deposited and the strength of confinement in the tubes. Taking advantage of the system's near integrability, we can infer the center of mass energy of all 3-body inelastic collisions that occur. In contrast to such collisions in 3D, and in accord with strictly 1D theory adapted to quasi-1D, we experimentally find that the 3-body inelastic collision rate strongly depends on the collision energy.

Plenary Session 2 Wednesday / 17

Exploring Three-Nucleon Forces in Three- and Four Nucleon Scattering

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Nucleon-deuteron (Nd) scattering, the three-nucleon ($3N$) scattering system, offers a good opportunity to study dynamical aspects of 3NFs, which are momentum,
spin and isospin dependent, since it provides not only cross sections but also a variety of spin observables at different incident nucleon energies. Direct comparison between the experimental data and the rigorous numerical calculations in term of Faddeev theory based on the realistic bare nuclear potentials provides information on 3NFs. Indeed the last two decades have witnessed the extensive experimental and theoretical investigations of the Nd scattering performed in a wide range of incoming nucleon energies up to $E \sim 300$ MeV/nucleon.

The four-nucleon ($4N$) systems could also play an important role for the study of 3NFs. 3NF effects are expected to be sizable in the $4N$ system. In addition, while the Nd scattering is essentially a pure isospin $T = 1/2$ state, tests of the $T = 3/2$ channel in any 3NFs can be performed in a $4N$ system such as proton-^{3}He scattering. In recent years, there has been a large progress in solving $4N$ scattering problem with realistic Hamiltonian even above four-nucleon breakup threshold energies [4], which opens up new possibilities to approaching to properties of 3NFs.

With the aim of exploring the 3NFs experimental programs of deuteron–proton scattering as well as proton-^{3}He scattering using the polarized beam and target systems are in progress at RIKEN, RCNP, and CYRIC in Japan.

In the conference we introduce recently conducted experiments and present the
results of comparison between the experimental data and the theoretical
predictions based on the realistic bare nuclear potentials. Parts of the results are published in Ref. [5].

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Plenary Session 2 Wednesday / 3

d^* (2380) hexaquark: from Photoproduction to Neutron Stars

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A resonance like structure observed in double-pionic fusion to the deuteron, at M=2.38 GeV with Γ=70 MeV and I(J^P)=0(3^+) has been consistently observed in a wealth of reaction channels, supporting the existence of a resonant hexaquark state - the d^* (2380). It was recently indicated that this new particle may set a limit on achievable neutron star masses, play a key role in the dynamics of neutron star merger events (including resultant gravitational wave emission) and has the potential to be an important intermediate step in the nuclear to quark-gluon plasma transition.

The talk will present the first results on d*photoproduction, obtained with the Crystal Ball at MAMI. The new analysis indicated that the d*(2380) is likely to be excited predominantly through an *M3* transition rather than an *E2* transition, which is consistent with its proposed compact nature. The d*(2380) is likely be the first genuine hexaquark. Further possible astrophysical implications will also be outlined.

Plenary Session 2 Wednesday / 24

Dibaryon resonances and NN interaction

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The idea of an important role of dibaryon (six-quark) states in NN interaction was suggested some time ago 1. A new interest to this idea has risen recently due to the reliable detection of the dibaryon resonances [2]. Later on, it has been shown that the mechanism with excitations of intermediate diproton resonances in isovector pp channels gives a leading contribution into polarization observables of the one-pion production in pp collisions at intermediate energies [3]. Here we examine this mechanism in elastic and inelastic NN scattering at intermediate and small energies, where an effective energy-dependent NN potential is introduced. It is shown that in the particular NN channels, where dibaryons have been found experimentally, this approach allows to reproduce real and imaginary partial NN phase shifts up to energies about 600 MeV which are far above the inelastic threshold. An effect of such type interaction on short-range NN correlations and 3N scattering is also studied.

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Plenary Session 1 Thursday / 122

Few-body strangeness nuclei and their puzzles

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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. The first HypHI experiment at GSI has demonstrated the feasibility of the method by reconstructing invariant masses and decay vertexes with 6Li beams at 2 A GeV bombarding a graphite target, and formation and mesonic weak-decay of light hypernuclei have been successfully observed. The results have revealed a significantly short lifetime of hypertriton. Furthermore, it has also revealed indications of signals in the d+pi- and t+pi- invariant mass distributions, that may indicate a possibility of a weakly bound state with a Lambda-hyperon together with two neutrons (n-n-Lambda). These observations are recently under debate. For the n-n-Lambda state, recent theoretical calculations have shown that such a state is unlikely bound.

The accuracy and the statistics of the developed method for the hypernuclear spectroscopy with heavy ion beams should yet be improved. The method also has to be further developed with different detection techniques and beams at higher energies. A new experimental project to study hypernuclei has been proposed at GSI, and it will introduce the WASA central detector, which has recently been transferred from COSY in Juelich to GSI, for pion measurement combined with the high resolution fragment separator, FRS, for measuring decay residues. The project has already been approved, and experiments with WASA+FRS will be performed in coming years. The project will be continued with the Super-FRS at FAIR. Another new development at higher energies is in progress for the future heavy ion accelerator facility in China, High Intensity heavy ion Accelerator Facility, HIAF. Both projects at FAIR and HIAF will open new possibilities to study double-strangeness hypernuclei with heavy ion beams and fixed targets as well as to measure directly magnetic moments of hypernuclei. The current situations to study the lifetime of hypernuclei and n-n-Lambda as well as these new projects will be discussed in the talk.

Plenary Session 1 Thursday / 127

Ab Initio Calculations of Light Hypernuclei

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While atomic nuclei are believed to be understood in terms of dynamics between pions and nucleons, it is unclear whether these constituents are the only relevant degrees of freedom in the ground state of baryonic matter. At higher densities, realized perhaps in the cores of neutron stars, hadrons with non-zero strangeness such as hyperons are expected to appear. Strangeness nuclear physics and the study of hypernuclei are in the center of the scientific endeavor to address such questions. Hypernuclei provide important information on hyperon-nucleon interaction and, at the same time, serve as laboratories to test fundamental symmetries of nature.

Over the past decade, first-principles description of nuclear structure has seen a remarkable progress driven by advances in computational techniques to solve the nuclear many-body problem and developments of realistic Hamiltonians derived from effective field theories. As a result, accurate calculations are now possible for a wide range of hypernuclei and observables. In this contribution I will present recent developments in ab initio no-core shell model calculations of of light hypernuclei [1,2] and report on their selected applications as for example to study charge-symmetry breaking in mirror hypernuclei [3] and pi-mesonic decay of the hypertriton. Moreover, I will discuss our very recent quantification of theoretical uncertainties of hypernuclear observables resulting from the remaining freedom in the construction of nuclear interactions.

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Plenary Session 1 Thursday / 113

Weakly bound nuclei: A unified description of intrinsic and relative degrees of freedom

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In this talk we present a recently developed method where cluster correlations co-exist with an underlying mean-field described core-structure. The method will be applied to nuclei close to the driplines, which are assumed to clusterize into a well-defined core and two valence nucleons. The variation of an antisymmetrized product of cluster and core wave functions and a given nuclear interaction, gives rise to a set of self-consistent equations of motion, which split into a set of standard Hartree-Fock equations, but distorted by the presence of the valence nucleons, and a three-body equation where the core-nucleon interaction is dictated by the core mean field.

The technique is first tested on the neutron dripline nucleus 26O, considered as 24O surrounded by two neutrons, for which experimental data are available. We choose Skyrme effective interactions between all pairs of nucleons, and the hyperspherical adiabatic expansion method to solve the three-body problem. On the proton dripline sector, we show results for 70Kr, described as 68Se plus two protons, which is a prominent waiting point for the astrophysical rp-process. We calculate radiative capture rates and discuss the capture mechanism. Finally, results for different Ca isotopes are also shown. In particular, we investigate the appearance of the halo structure in the case of 72Ca, as well as the possibility of appearance of Efimov states.

Young Researcher's Award Session / 120

The Hoyle Family: precision break-up measurements to explore nuclear α-condensates

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The 0^+ excited state of ^{12}C at 7.65 MeV is named after Sir Fred Hoyle, who proposed its existence in order to account for stellar abundances of carbon [1,2]. Aside from this astrophysical significance, it is thought to possess a curious α-cluster structure. However, many questions still remain. To what extent can this state be described as three interacting α-particles, and if so, what geometric configuration do they take — a linear chain, equilateral triangle or something in-between? Is it that the bosonic nature of the α-particle dominates the dynamics of this nucleus meaning that it could be the nuclear analogue of a Bose Einstein Condensate?

Since its discovery [3], measurements of the Hoyle state excitations and radius have provided indirect insights into its structure [4]. However, another way to examine its structure could be to examine the energy distributions of the α-particles emitted during its rare three-body direct break-up [5]. Their relative energies in the final state could reflect the initial structure. Previous studies have set an upper limit on the branching ratio for the direct break-up process at 0.2\% [6].

We present a recent high statistics, low background measurement of the 3α decay of the Hoyle state \cite{Seven}. The ^{12}C(α,α)3α reaction at 40 MeV beam energy was measured using the Birmingham MC40 cyclotron. The particles were detected in complete kinematics and the upper limit on the direct break-up branching ratio was lowered by almost an order of magnitude compared with previous measurements. This places it below what is predicted by a number of theoretical models, opening new intriguing questions about the structure of this important state.

I will finally discuss the Optical Readout Time Projection Chamber (O-TPC) at HIγS [8] and the previous determination of the direct 3α decay branching ratio of the Hoyle state 2^+ excitation [9]. This has allowed us to extrapolate down in energy and calculate a theoretical upper limit for the direct 3α branching ratio of the Hoyle state.

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Young Researcher's Award Session / 116

Few nucleons and other stories

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Universality connects few-nucleon systems to seemingly very different areas of physics, ranging from cold atoms to hadronic molecules. An important principle that guides the description of all these systems is the existence of a separation of scales. The key insight is that it is possible to built a theory where all forces are of short range, while the universal physics of interest is governed by the long-range tails of wavefunctions. Not only is such a scale separation the physical principle that enables the construction of effective field theories (EFTs), a framework that has revolutionized nuclear physics and contributed significantly also to the other areas mentioned at the outset, it moreover leads to powerful relations which enable the extraction of physical observables from simulations performed at finite volume. In this talk I will give overview of recent developments along these lines, covering both fundamental questions regarding the construction of nuclear forces, as well as finite-volume calculations for few-body bound states and resonances.

Parallel Session Thursday: Hadrons and Particles / 124

Heavy-Baryon Spectroscopy

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We present excitation spectra for heavy baryons - containing c and b flavors - calculated from a universal relativistic constituent-quark model valid for all baryons. The three-quark system is solved along modified Faddeev equations adapted to treat long-range interactions, here in particular the confinement. The hyperfine interaction is furnished by Goldstone-boson exchange. The full interaction is represented by a Poincaré-invariant mass operator.
Most prominently we focus on the spectra of charm and beauty baryons, which have recently become amenable to new measurements especially at LHCb. Beyond the ground states of corresponding Λ, Σ, Ξ, and Ω baryons we also predict their first few excitations, which are expected to be manifested by future experiments.

Parallel Session Thursday: Atoms and Molecules / 106

Fully Differential Study of Ionization of H2 by p Impact Near Velocity Matching

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We have measured fully momentum-analyzed scattered projectiles and recoil ions, produced in ionization of H2 by 75 keV p impact, in coincidence. The ejected electron momentum was deduced from momentum conservation. From the data we extracted fully differential cross sections for fixed projectile energy losses of 50,53,57, and 60 eV, for various fixed scattering angles theta_p, and for electrons ejected into the scattering plane as a function of the emission angle. Here, an energy loss of 57 eV corresponds to an electron speed equal to the projectile speed. The data were compared to two conceptually very similar distorted wave calculations.
In the FDCS two separate peak structures can be seen, one near the direction of the momentum transfer q and one in the direction of the initial projectile beam direction. The former, known as the binary peak, is a signature of a first-order mechanism. The latter, to which we refer as the forward peak, is a result of a higher-order mechanism, known as post-collision interaction PCI, involving at least 2 interactions between the projectile and the active electron. The first interaction lifts the electron to the continuum and in the second interaction the electron and the scattered projectile attract each other towards the initial beam axis. As expected, the forward to binary peak intensity ratio maximizes at the matching velocity (energy loss of 57 eV).
The data were compared to continuum distorted wave – eikonal initial state (CDW-EIS) and 3-body distorted wave (3DW) calculations, respectively. While at theta_p = 0.1 mrad both calculations are in reasonable agreement with experiment, increasing discrepancies and differences between both models are observed with increasing theta_p. At the largest theta_p there is not even qualitative agreement. There, PCI effects are most pronounced in the ex-perimental data and much stronger in the 3DW model compared to the CDW-EIS calculations. Considering that both theoretical approaches are conceptually very similar these surprisingly large differences demonstrate the high sensitivity of the FDCS to the details of the few-body dynamics in this kinematic regime.

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Parallel Session Thursday: Few-Nucleon Systems / 121

Electroweak processes in few-nucleon systems

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In this talk, I will present results of the application of the recently derived axial currents (with and without delta excitations) to selected electroweak nuclear processes in few-nucleon systems. In particular I will focus on the Gamow-Teller matrix element of tritium β-decay. Finally I will discuss a recently proposed quantum algorithm that could be useful to study binding energies of light nuclei.

Parallel Session Thursday: Hadrons and Particles / 103

Hadronic molecules of heavy hadrons with tensor force

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Exotic hadrons close to the hadron-hadron threshold have been one of the interesting topics in the hadron and nuclear physics. Especially, in the heavy quark sector, some of the quarkonium-like states called XYZ and the hidden-charm pentaquark Pc near the thresholds have been discussed as a hadronic molecule. The hadronic molecules is realized as a loosely bound state of a hadron composite system. In the formation of such molecules, the one-pion exchange potential (OPEP) working as a long range force is considered to have an important role. The tensor force of the OPEP is well-known as the driving force of atomic nuclei, and is emphasized in the heavy quark sector thanks to the heavy quark spin symmetry.
In this talk, we study the hadronic molecules of heavy meson and heavy baryon, which can be compared with the pentaquark Pc reported by LHCb. The coupled channel Schrodinger equations of the heavy meson and heavy baryon are solved. Due to the heavy quark symemtry, various meson-baryon channels are mixed in the systems. The full coupled channel analysis including channels with large orbital angular momenta are performed, because the tensor force of the OPEP yields an attraction in the mixing of those channels. We investigate the formation mechanism of the hadronic molecules in the heavy quark sector estimate and the role of the tensor force.

Parallel Session Thursday: Atoms and Molecules / 56

Hyperfine state-to-state ultracold atom-dimer reaction in a magnetic field

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In the ultracold region, the quantum mechanics principle governs a collision reaction process. The investigation of the ultracold state-to-state collision reaction will provide a deeper understanding of both quantum mechanics and chemical reaction. We present a multichannel finite-range three-body scattering theoretical model used for investigating the magnetically tuned atom-dimer collision reaction on the level of hyperfine state-to-state resolution. We take the Li-Li2 system as an example to calculate the atom-dimer scattering length and dimer relaxation rate steered by a magnetic field. We find that the two-body p-wave interaction has a significant influence on the atom-dimer collision reaction in the three hyperfine channels and a new universality in the atom-dimer collision reaction, i.e., the universality of deep dimer product.

Parallel Session Thursday: Few-Nucleon Systems / 36

Response functions and cross sections for inclusive neutrino scattering off ^{2}H, ^{3}H and ^{3}He

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Neutrino scattering on nuclei has been investigated for several decades. It played an important role in establishing fundamentals of the theory of weak interactions and electroweak unification. Later it became a tool to study the much more subtle properties of neutrinos, such as masses and oscillations.

Most of the calculations for neutrino scattering on light nuclei were performed in coordinate space, see important Refs. (1-4). In a recent paper (5) we presented momentum-space based results for several (anti)neutrino induced reactions on light nuclei: $\nu(\bar\nu) + {}^2\mathrm{H} \to \nu(\bar\nu) + p + n\,,$
$\bar\nu + {}^2\mathrm{H} \to e^+ + n + n\,,$
$\nu(\bar\nu) + {}^3\mathrm{He} \to \nu(\bar\nu) + p + {}^2\mathrm{H}\,,$
$\nu(\bar\nu) + {}^3\mathrm{He} \to \nu(\bar\nu) + p + p + n\,,$
$\nu(\bar\nu) + {}^3\mathrm{H} \to \nu(\bar\nu) + p + {}^2\mathrm{H}\,,$
$\nu(\bar\nu) + {}^3\mathrm{H} \to \nu(\bar\nu) + n + n + p\,,$
$\nu + {}^3\mathrm{He} \to e^+ + n + {}^2\mathrm{H}\,,$
$\nu + {}^3\mathrm{He} \to e^+ + n + n + p\,,$
$\nu + {}^3\mathrm{H} \to e^+ + n + n + n\,. We restricted ourselves to neutrino energies up to 300 MeV and pointed out to problems arising from$
at many incoming neutrino energies. The essential building block for the total cross section at a given (anti)neutrino energy E is the threefold differential cross section $d^3\sigma/d\Omega'\,dE'$, which depends on E, on the (anti)neutrino scattering angle θ' and on its final energy E'.

Namely, the total cross section is most easily calculated as $\sigma_{tot}(E) = \int d\Omega' \int dE' \frac{d^3\sigma}{d\Omega'\,dE'} = 2\pi \int d\theta' \sin\theta' \int dE' \frac{d^3\sigma}{d\Omega'\,dE'}\,. The cross section$ $\mathrm{d}^3\sigma/d\Omega'\,dE'$ can be expressed in terms of the so-called response functions R_{jk} (5), which depend on two parameters only: on the internal energy of the nuclear system E_{CM} and on the magnitude of the three-momentum transfer Q: $\mathrm{d}^3\sigma \frac{}{d\Omega'\,dE' = \sum_{jk} v_{jk}(E,\theta',E')\,R_{jk}(E_{CM},Q)\,.} Si$
functions, stemming from the lepton matrix element, are analytically known, it is thus much more efficient to calculate just the response functions on a sufficiently dense two dimensional grid in the

(E_{CM}, Q) plane and use interpolations to obtain these values of the response functions which are needed to compute $\sigma_{tot}(E)$ at a required energy E. Note also that in the case of the neutral current driven reactions, exactly the same response functions can be used to obtain cross sections with neutrinos and antineutrinos. This approach has been already successfully tested for the (anti)neutrino reactions on the deuteron and one example of the response function for the $\nu(\bar{\nu})+{}^2\mathrm{H} \rightarrow \nu(\bar{\nu})+p+n$ reaction is shown in Fig. 1. The corresponding work for several reactions with the three-nucleon systems is in progress and will be reported at the conference. As in Ref. (5), also in the present calculations the single nucleon current from Ref. (6) and the AV18 two-nucleon potential (7) is employed.

!Fig.1 [The R_{00} response function (see Ref. (1) for the definition and more details) for the neutral-current driven process $\nu(\bar{\nu}) + {}^2\mathrm{H} \rightarrow \nu(\bar{\nu}) + p + n$]1

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Parallel Session Thursday: Hadrons and Particles / 139

Properties of heavy mesons at finite temperature

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Heavy hadrons at finite temperature are nowadays attracting much attention in the field of hadron physics in view of the extremely high temperatures reached in the on-going and upcoming heavy-ion collision experiments and the new level of accuracy of the numerical simulations of QCD on the lattice. Along these lines, we go beyond the state-of-the art to study the properties of heavy mesons using a unitarized approach in a hot pionic medium, based on an effective hadronic theory. The interaction between the heavy mesons and pseudoscalar Goldstone bosons is described by a chiral Lagrangian at next-to-leading order in the chiral expansion and leading order in the heavy-quark mass expansion so as to satisfy heavy-quark spin symmetry. The meson-meson scattering problem in coupled channels with finite-temperature corrections is solved in a self-consistent manner. In this talk I will show the in-medium unitarized amplitudes in a pionic environment at finite temperature for heavy-mesons and their spectral funcions. The aim is to test our results against Lattice QCD calculations in the near future.

Parallel Session Thursday: Atoms and Molecules / 47

Weakly bound He_2 Li molecules in framework of Faddeev equations

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The Efimov effect is a remarkable phenomenon, which is an excellent illustration of the variety of possibilities arising when we transit from the two-body to the three-body problem. In 1970 V.Efimov 1 proposed that three-body systems with short range interaction can have an infinite number of bound states when none of the two-particle subsystems has bound states but at least two of them have infinite scattering lengths. In such a case the scattering length is much larger than the range of the interaction.

One of the best theoretically predicted three-body system with an excited state of the Efimov type is a naturally existing molecule of the helium trimer $^4He_3$ (see, [2] and refs. therein). The interaction between two helium atoms is quite weak and supports only one bound state with the energy about 1mK and a rather large scattering length about 100 A. Only recently the long predicted weakly-bound excited state of the helium trimer was observed for the first time using a combination of Coulomb explosion imaging and cluster mass selection by matter wave diffraction [3].

There is a growing interest in the investigation of He_2 - alkali-atom van-der-Waals systems, that are expected to be of Efimov nature. In addition to the Helium dimer, the He - alkali-atom interactions are even shallower and also support weakly bound states. In triatomic $^4He_2$-alkali-atom systems presence of Efimov levels can be expected. Three-body recombination and atom-molecular collision in Helium-Helium-alkali-metal systems at ultracold temperatures have been studied using adiabatic hyperspherical representation in [4]. Here we use the Faddeev equations in total angular momentum representation to calculate the $^4He_2$ $^{6;7}Li$ binding energies and a scattering length, which has not been studied before.

Our results for $^4He_2{}^7Li$ and $^4He_2{}^6Li$ trimers binding energies show that different potential models support two bound states in both trimers. The energy of the excited state is very close to the energy of the lowest two-body threshold. In case of the $He_2{}^6Li$ system the lowest threshold is different for different potentials but the relative energy with respect to the lowest two-body threshold is practically the same.

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Parallel Session Thursday: Few-Nucleon Systems / 101

Isospin-breaking nucleon-nucleon interaction up to fifth order in chiral EFT

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Chiral EFT in the nucleon-nucleon (NN) sector has finally entered the precision era with a $\chi^2/\mathrm{datum} \sim 1$ description of NN scattering data for recent fifth order potentials. However, none of these potentials include a complete treatment of isospin-breaking effects. I present new NN potentials from chiral EFT with a complete inclusion of isospin-breaking effects up to fifth order, whose adjustable parameters have been fitted to the 2013 Granada database of NN scattering data. I give an overview of the parameter-free and adjustable IB contributions to the potential and discuss their impact on the two-nucleon system. The long-standing question regarding the charge-dependence of the one-pion exchange coupling constant will also be considered.

Parallel Session Thursday: Hadrons and Particles / 98

Strange pentaquark resonances with a heavy quark-antiquark pair

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Recently LHCb has reported that a narrow pentaquark state and a double peak resonance were found in the Λ_b decay, which are considered to be $q^3c\bar{c}$ systems 1.
A previous work by the authors have shown that a quark cluster model, or a hadron model which includes the five-quark mode, gives narrow resonances or cusps in the NJ/ψ-$\Lambda_c\bar{D}$-$\Sigma_c\bar{D}$ baryon meson scattering [2,3]. Such structures appear because the three light quarks in the system can take a color-octet configuration in which the color-magnetic interaction is attractive.
Here we discuss the strange pentaquark systems with the hidden heavy quark pair. The three light quarks now can also form a color-octet flavor-singlet spin-1/2 configuration. There, the color magnetic interaction is attractive and causes resonances in the strange-baryon meson systems. We argue that strange pentaquarks with a heavy quark-antiquark pair can be candidates of the exotic baryons.
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Parallel Session Thursday: Atoms and Molecules / 64

A few-body integrodifferential equation with exact boundary conditions

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The integrodifferential equation for few- and many-body systems is modified by introducing explicit boundary conditions in the problem domain boundaries. The resulting two-variable integrodifferential equation has the same form, while the corresponding two-body amplitudes have the same boundary conditions, as the three-body Faddeev equations in configuration space. Test calculations, with systems of up to ten bosons, show that the new few-body integrodifferential equation can be solved directly and as efficiently with any numerical method applicable to the three-body Faddeev integrodifferential equations.

Parallel Session Thursday: Few-Nucleon Systems / 43

Application of the JISP16 potential to the nucleon induced deuteron breakupprocess at E=13 MeV and E=65 MeV.

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The JISP16 nucleon-nucleon force 1 arise from the Inverse Scattering Methods and was proposed as an alternative to the standard models of two-nucleon interactions. It provides a sufficient convergence of the no-core shell model [2] calculations enabling accurate predictions for nuclear binding energies and spectra of excited nuclear states with established extrapolation techniques [3–5] and the ability to perform calculations of nuclear matter properties [6]. The description of the properties of light nuclei by JISP16 is also quite satisfactory [7,8]. However, the recent application of the JISP16 force to the nucleon-deuteron elastic scattering [9] revealed some drawbacks of this force, especially regarding P-waves components of the JISP16 potential. It occurs that the bound and excited states energies, used to fix free parameters of the JISP16 model are not enough sensitive to the P-waves contributions. In order to improve the JISP16 model additional fitting, preferably taking into account nucleon-deuteron scattering observables, should be performed. In this contribution we check if the nucleon induced deuteron breakup reaction can be useful in this context.
We applied the JISP16 potential 1 to investigate the nucleon induced deuteron breakup reaction at energies E=13 and 65 MeV. The formalism of Faddeev equation [10] was used. Our study reveals that the JISP16 interaction delivers, in general, qualitatively a similar description of the exclusive cross section and the nucleon analyzing power for the studied reaction to the one based on the standard realistic nucleon-nucleon AV18 interaction [11]. However, in some regions of the phase space the differential cross section based on the JISP16 and on the AV18 forces differs by more than 100% and 50% at E=13 and E=65 MeV, respectively. In the case of analyzing power – this difference also exceeds 100% at E=65 MeV. Such specific parts of the phase space can be used to fine-tune the JISP16 potential parameters.

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Parallel Session Thursday: Kaonic Atoms and Clusters / 151

Kaonic atoms experiments at the DAFNE collider

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I shall present a series of frontier experiments searching for X rays coming from exotic atoms produced at the DAFNE collider of LNF-INFN (Italy). I shall introduce the physics and studies of kaonic atoms in the framework of the SIDDHARTA collaboration at the DAFNE Collider at the LNF-INFN, Frascati (Roma) laboratory. Combining the excellent quality kaon beam delivered by the DAFNE collider with new experimental techniques, as fast and very precise X ray detectors, like the Silicon Drift Detectors, we have performed unprecedented measurements on kaonic hydrogen and helium. Presently, a major upgrade of the setup, SIDDHARTA-2 is being realized to perform in the coming year the first ever measurement of kaonic deuterium. Kaonic atoms studies represent an opportunity to unlock the secrets of the strong interaction in the strangeness sector and understand the role of strangeness in the Universe, from nuclei to the stars.

Parallel Session Thursday: Clustering in Nuclei / 62

Few-body reactions investigated via the Trojan Horse Method

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A review of the main applications of the Trojan Horse Method (THM) will be presented, focusing on reactions involving few-body systems. This indirect method exploits nuclei clustering properties to measure cross sections otherwise very difficult to get.
The THM has been applied to the sub-Coulomb proton-proton elastic scattering to investigate the suppression of the Coulomb field effects and to the deuteron-deuteron fusion channels, where interesting results for astrophysics and energy fusion power plants have been obtained.
Other results will be shown, such as those involving light nuclei Li, Be and B, and some preliminary results for the ^{3}He(n,p)^{3}H reaction.
Finally, new perspectives and research lines with the THM will be mentioned.

Parallel Session Thursday: Few-Body Techniques / 84

Removing the Wigner bound in non-perturbative EFT

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The Wigner bound is examined at different non-perturbative pionless effective field theory ($slashed\pi EFT$) orders. Using cutoff regulator we show that the Wigner bound loosens when going from the next-to-leading-order (NLO) to the next-to-next-to-leading-order (N^{2}LO), and up to N^{6}LO. We conjecture an analytic formula for the general dependence of the Wigner bound on the theory's order. It follows that the bound vanishes in limit of infinite order. Surprisingly, we find that the functional behaviour of the Wigner bound is regulator dependent. We demonstrate that the above surmise still holds after renormalization at finite cutoff. Furthermore, for the non-perturbative approach, we find that there exist multiple renormalization choices, only one of which is physical. A method to pick the physical solution is suggested.

Parallel Session Thursday: Few-Body Techniques / 82

On the determination of response functions obtained from their Lorentz integral transforms

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The accuracy of reconstructing a response function from its Lorentz integral transform is studied for an exactly solvable case. The model considered here is the dipole photodisintegration of the bound state of three particles interacting via a hypercentral potential. The inversion procedure is discussed

in detail and its optimal version is presented. Unlike results in the literature pertaining to the same model, the response function is reconstructed from its Lorentz integral transform with rather high accuracy.

Parallel Session Thursday: Kaonic Atoms and Clusters / 130

Isospinless Model for ppK^- Kaoinc Cluster

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The recent and old experiential data indicate that kaonic cluster $NN\bar{K}$ has deep quasi-bound state 1. However, the theoretical models based on phenomenological $N\bar{K}$ potentials do not confirm it. Loosely bound state has been predicted by theoretical analysis of the JPARC
E15 experiment [2] using chiral potentials in the fixed center approximation.
In the framework of the Faddeev equations in configuration space the quasi-bound state of the kaonic system $NN\bar{K}$ is considered using both the isospin and ‘’isospinless" particle representations.

Within the isospin formalism, the ‘’ppK^- cluster" is determined as $NN\bar{K}(s_{NN}=0)$ system.
We present the Faddeev equations in the "given charge" isospin basis, which allow us to show relation to the particle representation.
The alternative consideration of the kaonic clusters has been proposed by isospinless ‘’particle representation" [3]. In our approach the system is described
as superposition of ppK^- and pnK^0 states, which are possible due to a particle transition. We consider the equivalence of isospin and particle representations and show that the equivalence is possible only under condition that the probabilities to find the system in the ppK^- or pnK^0 states are equal (strong coupling of the channels). Numerical calculations using phenomenological potentials will be presented. The relation of the isospinless model to the theory of two-level systems is addressed and discussed taking into account the possibilities of deep and shallow $NN\bar{K}(s_{NN}=0)$ quasi-bound states.

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Parallel Session Thursday: Clustering in Nuclei / 117

Clustering in ^{18}O – absolute determination of branching ratios via high-resolution particle spectroscopy

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Nuclear clustering is of great interest to the nuclear physics community as it allows complicated systems of many nucleons to be reduced to a few-body system, enabling the modelling of nuclei beyond where a traditional description of a nucleus would prove computationally challenging, as well as providing a good test of theoretical models. An experiment utilising the ^{12}C(^{7}Li, p)^{18}O*reaction was performed at Maier-Leibnitz Laboratory (MLL) in Munich by von Oertzen*et al. *1 which discovered 30 new states in ^{18}O. Using these in conjunction with previously determined states, rotational bands were proposed. Some of these bands were suggested to have cluster structures previously suggested by both theoretical and experimental work, such as ^{14}C ⊠ and ^{12}C ⊠ 2n ⊠ [2-5]. In order to determine the validity of these assertions an experiment was performed, again at MLL with the ^{12}C(^{7}Li, p)^{18}O* reaction. This time, the Q3D magnetic spectrograph was used in conjunction with the Birmingham DSSD array to enable the high-resolution reconstruction of decay fragments from ^{18}O* to determine absolute branching ratios of each high-energy excited state. The study also enabled a comparison of their α reduced widths to the Wigner limit to ascertain both the tendency towards α-clustering and consistency across the proposed rotational bands. This presentation will detail the final results of the analysis.

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Parallel Session Thursday: Few-Body Techniques / 102

Extrapolation of bound state energies obtained in the oscillator basis

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An extrapolation of *ab initio* results to get more accurate observables became a trend in nuclear physics [1-4]. We consider calculations of binding energies in oscillator basis, which depend on two basis parameters, the oscillator frequency, $\hbar\Omega$, and the oscillator quanta, N. We study general convergence patterns of these calculations. We use the SS-HORSE (single-state harmonic-oscillator representation of scattering equations) approach [5], extended to the case of bound states. Within this method, we extract the S-matrix from the results obtained in oscillator basis, and locate S-matrix poles associated with bound states. The respective binding energies improve the variational results obtained by the pure diagonalization in oscillator basis [6]. In this way we can extrapolate binding energies to the infinite basis and eliminate the dependence on basis parameters. By calculating the S-matrix pole, we can also calculate the asymptotic normalization constant. Till now we use a two-particle model problem with known exact solution to verify our method with an idea to apply it later to many-body shell-model afterwards. We compare also our method with approaches of Ref. [1-3].

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Parallel Session Thursday: Kaonic Atoms and Clusters / 28

Four-body Faddeev-type calculation of the $\bar{K}NNN$ system

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The attractive nature of $\bar{K}N$ interaction has stimulated theoretical and experimental searches for K^- bound states in different systems. In particular, many theoretical calculations devoted to the lightest possible system $\bar{K}NN$ have been performed using different methods: Faddeev equations with coupled channels, variational methods, and some others. 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, but the measured binding energies and decay widths of such state differ from each other and are far from all theoretical predictions.

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 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, but more accurate calculations within Faddeev-type equations are needed. The reason is that only these dynamically exact equations written in momentum representation can treat energy dependent $\bar{K}N$ potentials, necessary for the this system, exactly.

We are solving four-body Faddeev equations in AGS form in order to search for the quasi-bound state in the $\bar{K}NNN$ system. We are using our experience with the three-body AGS calculations, and our two-body potentials, constructed for them. Namely, three models of the $\bar{K}N$ interaction are being used: two phenomenological potentials and a chirally motivated one. All 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.

A reliable calculation of a four-body problem is much harder task than a three body one, that is why we are using some approximations. In contrast to our three body calculations, where the coupling between the $\bar{K}N$ and $\pi\Sigma$ channels was taken into account explicitly, here we are using the exact optical (and due to this energy-dependent) $\bar{K}N$ potentials, corresponding to our antikaon-nucleon potentials with coupled channels. We shown 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 as well. In addition we are using 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. The first peliminary results of the calculations are expected to be ready.

Parallel Session Thursday: Clustering in Nuclei / 97

How to determine the shape of nuclear molecules with polarized gamma-rays

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A method has been recently proposed on Phys.Rev. C 99 (2019) 031302 to establish the geometry of the alpha-cluster arrangement in 12C making use of polarized gamma-rays. The ratio of intensities of scattered radiation at 90 degree along and perpendicular to the initial direction of the electric field vector, called depolarization ratio, is a key quantity that allows to underpin the nature of totally symmetric modes of vibrations. This allows to connect with the underlying point-group structure and therefore to the geometric shape of the nuclear molecule.
This method is reviewed for 12C and extended to other configurations, such as three unequal clusters and four identical clusters (e.g. 16O).

Parallel Session Thursday: Few-Body Techniques / 112

Effective field theory in finite volume

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We utilize a baryonic effective field theory (EFT) to analyze recent Lattice QCD (LQCD) few-body calculations. To this end we have developed a finite volume few-body code based on the Stochastic Variational Method (SVM) including 2 and 3-body interactions. This new tool enable us to study the LQCD spectra directly without the need of infinite volume extrapolation. Furthermore, it can be used to study the evolution of the few-body spectra with the volume size down to small volumes, where the asymptotic Luscher theory breaks down. In this talk we present our results, analyzing LQCD results for two, three and four-nucleon systems.

Parallel Session Thursday: Kaonic Atoms and Clusters / 109

Hyperspherical Harmonics Method with Particle Transition Degrees of Freedom

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Some of the interactions in nuclear systems envisage the possibility that the constituents change in intermediate states. An example is the $\Lambda - \Sigma$ coupling in hyperon-nucleon potentials or the $N - \Delta$ coupling in nucleon-nucleon potentials. The fact that the constituents change in particular their masses represent a problem for the Hyperspherical Harmonics (HH) method, since hyperspherical coordinates are generally based on mass weighted Jacobi coordinates, and in presence of those transitions the masses are no longer fixed.

We present our recent developments of the HH formalism applied to systems with particle excitations degrees of freedom.
The transformations W among sets of internal coordinates with different weights are presented in

detail. The representation in the HH basis of such transformations is defined in terms of an elementary set of coefficients, the $\mathcal{W}$-coefficients, representing 1-d scaling transformations in real space. Exchange operators involving different particles can also be defined in terms of such coefficients. The generator of the W transformations is derived analytically and the selection rules in terms of angular and grand-angular quantum numbers are shown.
As 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 1. We also calculate the triton binding energy and wave function by considering the explicit Δ(1232) isobar degrees of freedom and including all the NN, NΔ and $\Delta\Delta$ 2-body channels. In this last case we adopt the Argonne v28 potential [2].

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Parallel Session Thursday: Clustering in Nuclei / 54

Impact of uncertainties of unbound ^{10}Li on the ground state of two-neutron halo ^{11}Li

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Since the discovery of the neutron halos, they have gained extensive attention of the nuclear physics community. Particularly two-neutron halo systems, consisting of a core and two weakly bound valence neutrons, demand a three-body description with proper treatment of continuum. The stability of such three-body $(\mathrm{core} + \mathrm{n} + \mathrm{n})$ system is linked to the continuum spectrum of the two-body $(\mathrm{core} + \mathrm{n})$ subsystem. Although ^{11}Li is the first observed two-neutron halo four decades ago. Since then a lot of experimental and theoretical studies have been reported on structure of the ^{11}Li. Recently role of ^{10}Li resonances is investigated in the halo structure of ^{11}Li via ^{11}Li$(p,d)^{10}$Li transfer reaction at TRIUMF 1 and at same facility the first conclusive evidence of a dipole resonance in ^{11}Li having isoscalar character has been reported [2, 3]. These new measurements and the sensitivity of core+n potential with structure of three-body system, are the motivation for selecting ^{11}Li for the present study.

For this study we use our recently implemented three-body structure model for the ground and continuum states of the Borromean nuclei [4, 5]. Within this framework, we start from the solution of the unbound subsystem and the two-particle basis is constructed by explicit coupling of the two single-particle continuum wave functions. We will present the results on the ground-state properties and two-neutron correlations in ^{11}Li with different choices of the ^{9}Li +n potential. We compare our findings with the more recent experimental works and the theoretical work that has been done in the past. We also present the ^{9}Li +n potential dependence on the configuration mixing in the ground state of 11Li.

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Parallel Session Thursday: Clustering in Nuclei / 22

Study of relativistic dissociation the 12C and 16O nuclei with nuclear track emulsion

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Relativistic dissociation of light nuclei observed in the nuclear track emulsion (NTE) contains holistic information on the nuclear clustering [1,2]. The unstable nuc-lei ^{8}Be and ^{9}B produced in the dissociation can be identified by the invariant mass Q_2 and Q_{2p} defined by products of 4-momenta of relativistic fragments He and H $P_{i,k}$, in turn, determined in approximation of conservation the projectile momentum per nucleon [2]. In such an approach the contribution of the decays ^{9}B → ^{8}Bep → 2αp in dissociation ^{10}B and ^{10,11}C is revealed and, then, an indication to the resonance ^{10}C → ^{9}Bp (around 4 MeV) found [2]. This experience gave confidence to search for the Hoyle state (HS) in the relativistic dissociation ^{12}C → ^{8}Be + α (Q_3) [3]. Recent analysis of angular measurements of 3α-events in NTE layers exposed to ^{12}C nuclei at 420 A MeV and 3.65 A GeV allowed one to identify the HS contribution of (13 ± 2)%. Besides, distribution Q_3 of all 3α combinations of 641 "white" stars ^{16}O → 4α pro-duced at 3.65 A GeV is revealed clear peak in the region Q_3 < 700 keV having average value $\langle Q_3 \rangle$ = (349 ± 14) keV and RMS 174 keV as expected for HS. The contri-bution of HS decays to coherent dissociation of ^{16}O → 4α is estimated at (22 ± 2)%. The current status of the evolving analysis on the topics noted will be presented.

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Poster Session / 26

Semiclassical description of chiral partner bands in odd-odd triaxial nuclei

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A triaxial rotor Hamiltonian with two rigidly aligned high-j quasiparticles is treated within a time-dependent variational principle, using angular momentum coherent states. A stereographic parametrization of the coherent state gives the dependence of the associated classical energy function on azimuth angle and a canonical conjugate coordinate related to the polar angle. The rotational dynamics of the considered system is then investigated by extracting the evolution on total angular momentum of the canonical variables as well as spherical angles corresponding to distinct minima in the constant energy surface. At a certain critical angular momentum, the clasical energy surface is found to exhibit two minima associated with distinct chiral geometries of the involved spin vectors. This is attributed to the breaking of the chiral symmetry. The discrete energy levels are obtained through a quantization procedure applied to the classical energy function. The method is employed for the description of the chiral doublet bands in the odd-odd nucleus 134Pr.

Poster Session / 38

Breakup of halo nuclei

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The breakups of 8B and 11Be nuclei is investigated in order to further investigate the effect of breakup dynamics on fusion process. It is obtained that projectile continuum-continuum couplings delay the breakup process, especially for heavy targets. This is observed by keeping both real and imaginary parts of the nuclear interaction between the projectile and target in the center of mass motion.

Poster Session / 40

Methods of Hyperspherical Functions with Application of Neutron Rich Isotopes in Heavy Ion Reactions

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The effect of projectile shape on cross sections and momentum distributions of fragments from heavy ion reactions is studied. We propose a new approach that implements the underlying symmetries of each isotope with a few parameters directly in the density. Various densities and their nuclear structure are then analyzed in the reactions of 12C and 11Li, 11Be, and 11 C on a carbon target.

Poster Session / 42

Solution of the four-body Coulomb problem by the modified Faddeev-Yakubovsky equations

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Inspired by the Faddeev-Merkuriev approach 1 we have modified the four-body Faddeev-Yakubovsky [2] equations, writing them in a form suitable to solve the four-body Coulomb problem. The newly developed formalism has been applied to study bound and some resonant states in $(\mathrm{Ps})_2$ and $\overline{H}$-Ps compounds. The first successful attempt to describe low energy Ps-Ps and $\overline{H}$-Ps scattering has been also realized. The aforementioned systems represent great interest for the experiments with antimatter (like AEGIS, ALPHA or GBAR) carried out at CERN .

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QED in the Clothed-Particle Representation (CPR): a fresh look at positronium bound states description

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We have extended our previous applications of the method of unitary clothing transformations (UCTs) in mesodynamics 1 to quantum electrodynamics (QED) [2,3]. Starting from the primary canonical interaction between electromagnetic and electron-positron fields, the QED Hamiltonian has been expressed through a new family of the Hermitean and energy independent interaction operators built up in the e^2-order for the clothed electrons and positrons. The problem of describing the bound states in QED in case of the positronium has been considered by using the new interaction. At the beginning, we have evaluated the first correction to positronium ground state energy by using the perturbation theory recipe. It is proved that its value surprisingly coincides with those estimations given in [4] (see formula (1.1) therein). In order to verify such a coincidence beyond the perturbation theory, we are addressing to the partial wave decomposition of the positronium eigenvectors that has been successful when finding the u and w components of the deuteron wave function (WF) [5]. In this context, we derive the partial eigenvalue equation for the para-positronium WFs that belong to the total angular momentum J, viz.,

$$2\mathrm{p}_0\Psi^J(p) + \int_0^\infty \frac{p'^2dp'}{p_0p'_0}\Psi^J(p')\bar{V}^J(p,p') = m_{\text{p-Ps}}\Psi^J(p).$$

Here $\bar{V}^J(p,p')$ is the partial electron-positron quasipotential derived in the momentum representation from the new e^-e^+-interaction operator, $m_{\text{p-Ps}} = m_{e^-} + m_{e^+} + \varepsilon_{\text{p-Ps}}$ the para-positronium mass and $\varepsilon_{\text{p-Ps}}$ its binding energy. In turn, we have

$$^J(p,p') = \bar{v}^J(\text{Feynman-like}) + \bar{v}^J(\text{off-energy-shell}).$$

Such a separation implies that only the Feynman-like part survives on the energy shell, where $p'_0 = \sqrt{p'^2+m^2} = p_0 = \sqrt{p^2+m^2}$. Our next step will be to solve the eigenvalue equation to obtain the corresponding positronium states in the CPR (see Appendix C in [6]). Finally, our aim is to evaluate the positronium decay rates.

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Modelling incomplete fusion of complex nuclei at Coulomb energies: Superheavy element formation

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Superheavy elements (SHE) have an atomic number Z ≥ 104, and their existence was predicted almost 50 years ago due to quantum shell effects that influence their stability and decay 1. SHE production is very challenging (due to very small cross sections in the range of a few picobarns or less), with complete fusion of heavy ions being one of the most successful ways of producing SHEs. The complete fusion mechanism produces neutron-deficient SHEs, making investigation into new methods of production crucial for further progress in SHE research.

The aim of the project is to investigate the incomplete fusion of neutron-rich projectiles with heavy stable targets, following the multi-fragmentation of a projectile at Coulomb energies. This mechanism has not been thoroughly explored yet, and could prove to be an effective way of producing neutron-rich SHE isotopes with low excitation energies [2].

To this aim, a semi-classical dynamical model is being developed by combining a classical trajectory model with stochastic breakup, as implemented in the PLATYPUS code [3], with a dynamical fragmentation theory [4] treatment of two-body clusterisation and decay of a projectile. A finite-difference method solution to the time-independent Schrödinger equation in the charge asymmetry coordinate is being employed by way of diagonalising a tridiagonal matrix with periodic boundary conditions.

Currently, this new model is being tested against existing experimental data [2] and after refinement will ultimately be used to make predictions for producing new SHE isotopes in future experiments planned at the Joint Institute for Nuclear Research in Dubna, Russia, and elsewhere [5].

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Search for 7H at ACCULINNA-2

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The 7H isotope is the Golden Fleece to be searched by the RIB holders. Until the present moment only upper limits of its lifetime and ground state energy were estimated. Such unbound complicated five-body nuclear system, which has extremely large mass-to-charge ratio, lies far beyond the drip-line and has not been detected yet.
An experimental search for the 7H resonance was performed with the 2H(8He,3He)7H reaction. Beam of the 8He with energy of ~26AMeV provided by ACCULINNA-2 fragment separator interacted with the gaseous cryogenic deuterium target (6 mm thick at 27K and at 1 atm). The detector system was consisted of Si and CsI telescope detectors intended for detection of the recoil 3He and 3H emitted from 7H decay. Compared with the previous works dedicated to 7H the main advantage and novelty of the used setup was the possibility to measure the angle and energy of the emitted tritium.
Events with a coincidence of detected 3He and 3H was considered as candidates for 7H event. The number of coincidences of the decay products allowed us to estimate the reaction cross-section. Measuring the spectra of 3He under the small angles allows to reconstruct the 7H missing-mass spectrum. The obtained angles and energies of 3He and 3H in coincidence gave a lot of informative angular correlations.
In the report we will present preliminary 7H missing-mass spectrum together with estimation of detection efficiency of the 7H and various angular correlations of reaction products (e.g. missing-mass spectrum with the angle of the emitted tritons). Simulations needed for data analysis has been performed within the ExpertRoot framework 1.

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1 http://er.jinr.ru/

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How to interpret a noisy dimer-trimer interferometer signal.

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The best strategy to precisely determine the energy difference between two adjacent energy levels is to perform an interferometric measurement. If the signal-to-noise ratio (SNR) is not favorable, either due to large unavoidable noise or a naturally small signal, but the signal is many oscillations long, the standard analysis takes advantage of a fast Fourier transform (FFT). What if the signal, due to inherent decay of the coherent oscillations, is not long though?

Such a short, low frequency and low SNR signal was recently obtained in a novel experimental approach to probe the energy level as well as lifetime and collision properties of Efimov trimers in ultra-cold atoms 1. Here we demonstrate that the correct analysis to this kind of signal is based on a three-parameter (amplitude, frequency and phase) sinusoidal fit applied in the vicinity of various initial parameter values. This allows precise determination of the global minimum in parameter space. By means of randomly generated data with an SNR as low as unity, we show that a dozen or so oscillations suffice to determine the largest frequency contribution with high statistical significance. Unlike FFT, this method is hardly affected by parasite frequencies arising from the large noise.

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An Accurate Allowance for Initial and Final State Interections in The Treatment of The alpha-alpha Bremsstrahlung

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One of motivations in studying the $\alpha + \alpha \to \alpha + \alpha + \gamma$ bremsstrahlung is to get a supplementary information on a strong part of the $\alpha - \alpha$ interaction 1. We find some correlation function, in which one of the outgoing alphas is detected in coincidence with the emitted photon, depends consid-erably on the strong interaction in the entrance and exit channels (see Fig.1 for $d^5\sigma/dE_\gamma d\Omega_i d\Omega_f$ in the lab. frame and coplanar momenta disposal, where the photon momentum is directed along the Z-axis and the rest lie in the XZ-plane, viz., $\hat{k}_{1i} = (\theta_{1i}, 0)$, $\hat{k}_{1f} = (\theta_{1f}, \pi)$ at energies of the incident α-particle $E_i = 10$ MeV and photon $E_\gamma = 1$ MeV). As before, our depar-ture point in describing electromagnetic (EM) interactions with nuclei is to use the Fock-Weyl cri-terion (see [2] and refs. therein). According to [3], the cross section can be expressed through the charge form factor of α-particle $F_{CH}(q)$ depending on the stretched photon momentum $q = \lambda k_\gamma$ ($0 \leq \lambda \leq 1$) and the overlap integral $I = \langle \chi_{k'}^{(-)} | e^{iq\rho} | \chi_k^{(+)} \rangle$, where the ingoing $\chi_k^{(+)}$ and out-going $\chi_{k'}^{(-)}$ solutions for the $\alpha - \alpha$ scattering induced with interaction $V = V_C + V_S$ that consists of the repulsive Coulomb potential V_C and its strong counterpart V_S. The Nordsieck-type integral I_C in the partition $I = I_C + I_{CS}$, which determines the purely Coulomb mechanism of the bremsstrah-lung, is given by (10) in [6] while the radial integrals in fast-convergent series of the mix integral I_{CS} in partial waves have been calculated via the contour integration method [7]. When collision energy increasing the cross sections become more sensitive to distinctions between the two phase-equivalent $\alpha - \alpha$ potentials.

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Three-Nucleon Force Effects in the FSI configuration of the $d(n, nn)p$ Breakup

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We investigated three-nucleon force (3NF) effects in the Final State Interaction (FSI) configuration of the $d(n,nn)p$ breakup reaction. Solutions of the 3N Faddeev equations [1] with the CDBonn nucleon-nucleon potential [2] and the Tucson-Melbourne 3NF [3] give access not only to the elastic scattering observables but also to the three-body breakup ones. In this contribution we focus on an integrated breakup cross section around the final state interaction condition for two neutrons:

$$\frac{d^2\sigma}{d\Omega_1 d\Omega_2} \equiv \int_{S_0-\Delta S}^{S_0+\Delta S} \frac{d^3\sigma}{d\Omega_1 d\Omega_2 dS} dS \Big|_{\Omega_1=\Omega_2} \qquad (n+d \to p+(nn)) \qquad (1)$$

Here Ω_1 and Ω_2 represent the directions of the momenta of outgoing neutrons 1 and 2, respectively. For fixed Ω_1 and Ω_2, the arc-length variable S defines uniquely the three-nucleon kinematics, yielding a specific (E_1, E_2) point on the allowed kinematical curve in the (E_1, E_2) plane, where E_1 and E_2 are the kinetic energies of neutron 1 and 2, respectively. Choosing an appropriate starting point where $S = 0$, S is calculated as a distance taken along the curve from its starting point:

$$S = \int dS = \int \sqrt{(dE_1)^2 + (dE_2)^2} \qquad (2)$$

where E_1 and E_2 are the kinetic energies of neutron 1 and 2, respectively. The FSI occurs at the condition $E_1 = E_2$ at the parameter $S = S_0$.

Fig.1 shows the integrated breakup cross section of Eq.(1) at the incident neutron laboratory energy E_{lab}=200 MeV with the averaging width parameter ΔS= 20 MeV. The angle θ_{lab} is the laboratory scattering angle of nucleons 1 and 2, for which the FSI condition is realized.

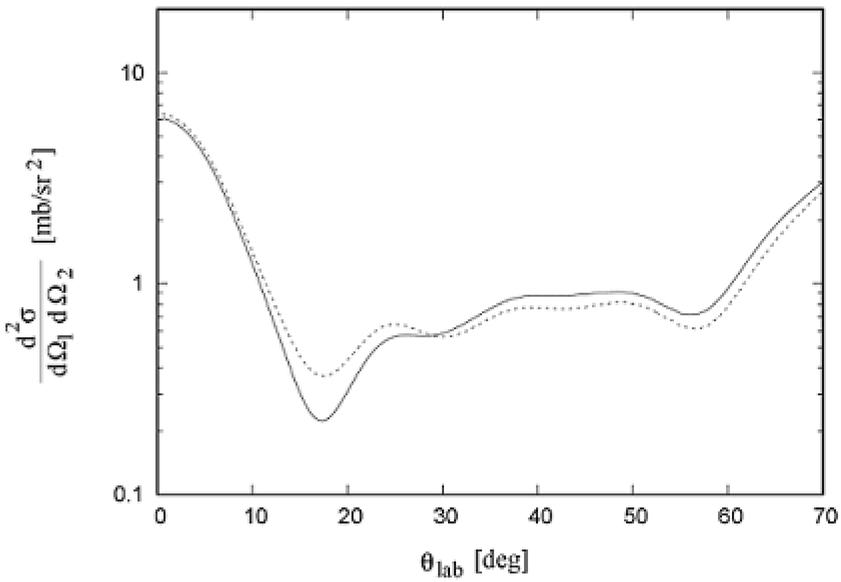

Figure 2: Integrated final state interaction configuration breakup cross section for the incident neutron laboratory kinetic energy 200 MeV. The theoretical predictions based solely on a two-nucleon interaction (here the the CDBonn potential [2]) are represented by the dotted line, while the results obtained with the two-nucleon potential augmented by the the Tucson-Melbourne 3NF [3] are shown with the solid line.

We found a large deviation between the theoretical predictions including or not including 3NF. Although the 3NF effects for the elastic scattering cross section are located predominantly in the region starting from middle up to backward scattering angles,the 3NF effects for the integrated FSI configuration breakup cross section are found also at forward scattering angles.

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Poster Session / 123

Identifying α-cluster states in ^{14}O, using the thick target inverse kinematics method to measure α strength via resonance scattering.

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Since the origin of nuclear physics, cluster structures have been observed in the excited states of many light nuclei.[1] It is noted that α particles are strong cluster candidates due to their significant binding energy and energy of their first excited state. Evidence for this clustering lies within the energy levels of the compound nucleus formed in scattering reactions, which correspond to resonances in the reaction cross section.

In a commissioning experiment in collaboration with Texas A&M University, the thick target inverse kinematics (TTIK) method has been used to perform continuous measurement of the elastic scattering excitation function of the ^{14}O nucleus. Excited states above the α threshold have been populated using the $^{4}\mathrm{He}(^{10}\mathrm{C}, \alpha)^{10}\mathrm{C}$ reaction with a radioactive ^{10}C beam. A Micromegas gaseous parallel plate detector was used to facilitate high resolution track reconstruction, and silicon strip detector (SSD) arrays employed to reconstruct the energies of the scattered particles.

The current state of the analysis will be presented, starting from track identification via an iterative implementation of the Hough Transformation.

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Poster Session / 128

Calculation of asymptotic normalization coefficients in the complex-range Gaussian basis

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Complex-range Gaussian basis (CRGB) has been demonstrated to give a convenient representation for bound-state 1 and scattering [2] calculations. The basis functions are constructed from the conventional real-valued Gaussians with additional oscillating factors which makes them suitable for approximation of wave functions of highly excited bound states and continuum states as well. Recently, this basis has been successfully applied for calculation of scattering amplitudes of charged

particles within the Coulomb wave-packet formalism [2]. Here we examine the CRGB in evaluation of asymptotic normalization coefficients (ANCs) which represent an important information for a description of nuclear reactions, e.g. for calculation of the radiative capture cross-sections in nuclear astrophysics. It is shown that a diagonalisation procedure for the total Hamiltonian matrix in the CRGB results in approximation for a radial part of the bound state wave function from the origin up to the far asymptotic distances, which allows to extract ANCs rather accurately. The values of the ANC found by this way for test local potentials are in full agreement with the results of the conventional methods. The method will be illustrated by calculations of single-particle ANCs for nuclei bound states in cases of non-local nucleon-nucleus interactions, in particular, phenomenological global potentials with the Perey-Buck's non-locality (see e.g. [3]) and microscopic non-local potentials provided by the Dispersive Optical Model [4].

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Poster Session / 132

Effect of Isospin Averaging for ppK^- Kaonic Cluster

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The kaonic cluster $NN\bar{K}(s_{NN}=0)$ is modeled based on the configuration space Faddeev equations. The $N\bar{K}$ interaction is given by isospin-dependent potentials having significant difference between singlet and triplet components. We show that the relation $|E_3(V_{AA}=0)| < 2|E_2|$ is satisfied, where E_2 is the binding energy of the $N\bar{K}$ subsystem and $E_3(V_{AA}=0)$ is the three-body binding energy, when interaction between identical particles is omitted, V_{NN}=0.*Takingintoaccountweakattractionof*NN*in*
2|E_2|.*The"isospinlessmodel"forthekaonicclustersbasedontheisospinaveraged*N{\bar K}*potential*[1, 2, 3]*demo*
E_{3}(V_{AA}=0)\right\vert~>~2\left\vert E_{2}\right\vert.*Theisospinaveragingleadstolooselybound*NN{\bar
K}$ system due to reduction of two-body threshold. Numerical calculations using phenomenological potentials will be presented.

This work is supported by the National Science Foundation grant HRD-1345219 and NASA grant NNX09AV07A.

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Poster Session / 135

Hyperspherical harmonics expansion on Lagrange meshes for bosonic systems in one dimension

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A one-dimensional system of bosons interacting with contact and single-Gaussian forces is studied with an expansion in hyperspherical harmonics. The hyperradial potentials are calculated using the link between the hyperspherical harmonics with single-particle harmonic oscillator basis and the coupled hyperradial equations are solved with the Lagrange-mesh method. Extensions of this method are proposed to reach a good convergence with small numbers of mesh points for any truncation on hypermomentum. The convergence on hypermomentum strongly depends on the range of the two-body forces: it is very good for large ranges but deteriorates with their decrease, being the worst for the contact interaction. In all cases the lowest order energy is within 4.5% of exact solution and shows the correct cubic asymptotic behaviour at large boson numbers. Details of convergence studies are presented for 3, 5, 20 and 100 bosons and a special treatment for three bosons was found to be necessary. For gaussian interaction, the convergence rate improves with increasing boson numbers, similar to three-dimensional systems of bosons.

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Continuum-Discretized Coupled Channel description of (d,p) reactions with nonlocal optical potentials

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Treating deuteron breakup in (d,p) reaction requires solving three-body Schrodinger equation with nucleon optical potentials. According to a general theory of optical potentials they should be nonlocal. We present two approximate methods to account for this nonlocality within the Continuum-Discretized Coupled Channel (CDCC) method:
(1) we derive a leading-order local-equivalent CDCC model
(2) we solve the CDCC equations with velocity-dependent optical potentials that represent nonlocal optical potential in the next-to-leading order.
Examples of numerical calculations will be given.

Poster Session / 144

Universality in few-body physics around the unitary limit

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The first evidence for universality in three-body systems was the discovery by Vitally Efimov of the Efimov effect **1**, a remarkable feature of the three-body spectrum for identical bosons with resonant short-range interactions. Nowadays it has been realized that the striking features of the Efimov effect are not restricted to three-body systems, but propagate by increasing the number of particles. The Helium atomic system stands very close to the resonant region, thus we propose a simplified description of the few-body Helium system based on Gaussian two-body interactions. Accordingly, we solved the few-body problem within the lowest hyperspherical harmonic channel, and using constraints on the energy spectrum we estimated the energies of the atomic Helium system for up to N=40 atoms at the unitary limit. For N=3 and N=4 Helium atoms these estimates are compared with the results in **[2]** obtained by driving the realistic LM2M2 He-He potential towards the unitary

limit. To the best of our knowledge, there are no energy calculations at the unitary limit for atomic Helium systems with more that four particles, thus our work provides first estimates for them.

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Poster Session / 145

Muonic Lithium atoms: nuclear structure corrections to the Lamb-shift

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The CREMA collaboration plans to measure the Lamb shift in muonic Lithium atoms,
with the goal to extract the charge radius and confront it to electron scattering data.
For this experiment to be successful, theoretical information on the nuclear structure
corrections to the Lamb shift are needed.
Recently, few-body methods were used to tackle this problem and the most precise
estimate of two-photon exchange corrections were provided for a series of light
muonic atoms with nuclear mass number ranging from 2 to 4 **1**. With respect to previous estimates, uncertainties were reduced by up to a factor of 5 in certain cases. For the muonic 6Li and 7Li atoms, there exist only rough estimates based on old experimental data, that suffer from very large uncertainty of about 20%.

We will present the first attempt to compute these quantity using the few-body hyper-spherical harmonics technique with a simple nuclear potential **[2]**.

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Poster Session / 146

Time-dependent exploration of 3-alpha states in ^{12}C

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We use nuclear time-dependent Hartree-Fock (TDHF) to simulate the reaction of three alpha particles at low energy by first fusing two alpha to from ^{8}Be* followed by a third alpha impinging during the lifetime of the beryllium resonance. Depending on the energies and impact parameters of the reacting nuclei different outcomes are obtained with some fusion events showing short-lived alpha chain or bent-arm configurations which oscillate with characteristic frequencies in the range 6-15 MeV.

The method assumes a Skyrme-type effective interaction, and intial alpha particles made of antisymmetrised nucleons which are free to develop as single particles. The alpha structures seem to survive during the resonant capture process, following which a more compact final state is reached.

We discuss various typical trajectories showing the range of resonance behaviours observed depending on initial conditions, and comment on perspective for further work, such as a requantisation of the dynamics.

Plenary Session 1 Friday / 61

Study of light nuclei by polarization observables in electron scattering

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Electron-induced proton, neutron and deuteron knock-out remains the most versatile probe of the electro-magnetic properties and spin structure of light nuclei. The advent of highly polarized beams and targets and improvements in recoil polarization methods, as well as analysis and simulation techniques, have enabled us to study the statical and dynamical properties of few-body systems with unprecedented precision. Recent experiments at Jefferson Lab (TJNAF) and MAMI will be presented and put into perspective of state-of-the art Faddeev calculations, with focus on the 3He nucleus.

Plenary Session 1 Friday / 20

Universal few-body clusters in cold atoms

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Few-body systems can show universal cluster states when their inter-particle scattering length is much larger than range of the interactions. Prime examples are three-body bound states called the Efimov states, which have been argued to appear in various physical systems such as halo nuclei and Hoyle states of 12C, and recently clearly observed in experiments with atoms. Those observations motivated theoretical and experimental attempts to extend the paradaigm of Efimov physics and related universal few-body phenomena towards systems with more than three particles or with higher angular momentum. We will give overview of these studies, together with some of our recent theoretical work with cold atoms toward these directions.

Plenary Session 1 Friday / 19

Giving a twist to Halo states: Helium Dimer and Trimer in Rotation

Authors: Maksim Kunitski[None] ; Stefan Zeller[1] ; Lothar Schmidt[None] ; Till Jahnke[None] ; Markus Schoeffler[None] ; Qingze Guan[None] ; Doerte Blume[None] ; Reinhard Doerner[1]

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We will review how to make Helium Dimers, Trimers and the Efimov State of He3 and show how the wavefunction of theses species can be imaged. We then show how quantum dynamics in theses systems can be induced and show movies of the time evolution of a kicked dimer.

Parallel Session Friday: Atoms and Molecules / 114

Spin-orbit-coupled Bose-Einstein Condensate as playground to explore quantum collision and chemistry

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Abstract: In this talk I will describe our recent experiments studying spin-dependent quantum transport/collision as well as chemical reactions in a Bose-Einstein condensate (BEC) of ultracold (87Rb) atoms subject to optically-generated "synthetic" spin-orbit coupling (SOC). By performing a "quantum quench" (suddenly reducing the optical Raman coupling that generates the synthetic SOC and gauge fields), we induce head-on collisions between two (dressed) spinor BECs (so called "spin dipole mode") and study how such spin transport is affected by SOC, revealing rich interplay between quantum interference, many-body interactions, and (im)miscibility between (dressed) spinor condensates 1. We also demonstrate a new approach of quantum control of (photo) chemical reactions (photoassociation of molecules from atoms) — a "quantum chemistry interferometry" — by preparing reactants in (spin) quantum superposition states and interfering multiple reaction pathways [2]. Time permitting, I may briefly discuss our recent realization of a BEC on a "synthetic" cylinder (by cyclicly couple spin states based "synthetic dimensions") with a synthetic radial magnetic flux, giving rise to a symmetry protected topological band crossings and quantum transport mimicking motion on a Mobius strip in momentum space [3]. Our experimental system can be a rich playground to study physics of interests to AMO physics, quantum chemistry, condensed matter physics, and even high energy/nuclear physics.

1 C. Li et al."Spin Current Generation and Relaxation in a Quenched Spin-Orbit Coupled Bose-Einstein Condensate", Nature Comm. 10, 375 (2019)
[2] D.Blasing et al. "Observation of Quantum Interference and Coherent Control in a Photo-Chemical Reaction", PRL 121, 073202 (2018)
[3] C.Li et al., "A Bose-Einstein Condensate on a Synthetic Hall Cylinder", arXiv:1809.02122

Parallel Session Friday: Nuclear Reactions / 29

Effects of an induced three-body force in the incident channel of (d,p) reactions

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Effects of an induced three-body force in the incident channel of (d,p) reactions

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A widely accepted practice for treating deuteron breakup in A(d,p)B reactions relies on solving a three-body A+n+p Schrodinger equation with pairwise A-n, A-p and n-p interactions. However, it was shown in 1 that projection of the many-body A+2 wave function into the three-body A+n+p channel results in a complicated three-body operator that cannot be reduced to a sum of pairwise potentials. It contains explicit contributions from terms that include interactions between the neutron and proton via excitation of the target A. Such terms are normally neglected. We estimate the first order contribution of these induced three-body terms and show that applying the adiabatic approximation to solving the A+n+p model results in a simple modification of the two-body nucleon optical potentials. We illustrate the role of these terms for the case of 40Ca(d,p)41Ca transfer reactions at incident deuteron energies of 11.8, 20 and 56 MeV, using several parameterisations of nonlocal optical potentials.

1 R.C. Johnson and N.K. Timofeyuk, Phys. Rev. C 89, 024605 (2014).

Parallel Session Friday: Nuclear Reactions / 119

Analysis of breakup of halo nuclei using configuration space Faddeev-Yakubovsky formalism

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Experimentally and theoretically, the study of the structure of the halo bound nuclei is nowadays an active research topic of interest. One of the reasons of this huge interest is that, being loosely bound, the halo nuclei, when used as projectiles in nuclear reactions, they can easily breakup. This immediately brings the question of which of the interactions between nuclear and Coulomb, plays a prominent role in the breakup. Thus, the nuclear-Coulomb interferences are of importance. Moreover, the easy breakup makes the breakup reactions a useful tool to study the structure and dynamics of the halo nuclei themselves. However, the full understanding of the dynamics of the breakup reactions, for example, the study of the breakup cross sections, is far from being established. Additionally, the influence of the breakup reactions on other reaction channels such as fusion (complete or incomplete) and elastic scattering breakup is yet to be fully understood. The latter point is underscored by the new data in Ref. 1, which cannot be understood in terms of fusion and transfer cross sections, where the projectile is treated as a two-body system, making its interaction with the target a three-body problem. In this work, we perform the four-body analysis of the breakup reactions involving halo projectiles. This is relatively a difficult problem, which needs innovative techniques in order to have numerical traction. We use the configuration space Faddeev-Yakubovsky equations for our formalism, and computationally we use the GPU-based calculations of our newly developed four-body numerical technique [2].

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2. K Chitakwa [Private Communication].

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Parallel Session Friday: Atoms and Molecules / 100

Four-Body Scale in Universal Few-Boson Systems

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We trace the perturbative refinement of the two-boson interaction − which augments an initial, unitary description by a finite effective range − up to the six-boson system. Hereby, we expose a significant dependence of the predicted ground-state energies of tetra-, penta-, and hexameres on details of the interaction which is resolved at distances much smaller than the effective range. We demonstrate how to remove this sensitivity from all ≤ 6-boson systems numerically and semi-analytically with a single four-body contact parameter.

Parallel Session Friday: Nuclear Reactions / 118

Multi-neutron transfer in the scattering of 8He at Coulomb barrier energies

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The study of neutron clusters in light nuclei has attracted considerable attention during recent years. Although the two-neutron system is unbound, there are evidences of its existence in exotic neutron rich nuclear systems like 6He and 8He [1, 2, 3]. The predominance of the dineutron configuration in the ground state of 6He has been well established both theoretically and experimentally, but the case of 8He is still an open question. The scattering of 8He by 208Pb has been investigated in a range of energies around the Coulomb barrier at the SPIRAL facility (GANIL, Caen, France), and the cross-sections for producing 6He and 4He have been measured in a large angular range (15 − 165 deg. lab) [4]. In order to reproduce the data we have carried out CRC calculations for one-neutron stripping and DWBA calculations for two- and four-neutron transfer mechanisms. The relative contributions of sequential and direct transfers are discussed and compared with the experimental results.

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Parallel Session Friday: Atoms and Molecules / 9

Elastic scattering of three ultracold bosons

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Elastic scattering of three bosons at low energy is a fundamental problem in the many-body description of ultracold Bose gases, entering via the three-body scattering hypervolume D. We study this

quantity for identical bosons that interact via a pairwise finite-range potential. Our calculations cover the regime from strongly repulsive potentials towards attractive potentials supporting multiple two-body bound states and are consistent with the few existing predictions for D. In particular, we present the first numerical confirmation of the universal predictions for D that are made in the strongly-interacting regime, where Efimov physics dominates, for a local nonzero-range potential. Our findings highlight how finite-range effects, such as d-wave interactions, become important as the interaction strength is reduced.

Parallel Session Friday: Nuclear Reactions / 142

Few-body results for 12C(p,pN) at high energies

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Nucleon knockout reactions have been used to extract single particle information from nuclei. The analysis of nucleon knockout from a stable projectile in the collision with a proton target and the comparison with the experimental data is a key test for the reaction and structure models used to evaluate the reaction observables.

Three-body Faddeev/Alt-Grassberger-Sandhas (Faddeev/AGS) equations for transition operators [1,2] have been solved for p- and n-knockout from 12C at 400 Mev/u, assuming that only the heavy fragment or core C (taken as inert), the knockout particle N, and the proton target p participate in the collision process [3].

We present calculated kinematically fully exclusive, semi-inclusive and inclusive cross sections and an analysis of the

(i) dominant kinematic conditions of the emitted particles;

(ii) isospin dependence (here p- and n- knockout) of the calculated reaction cross sections.

(iii) Final state interaction (FSI) to the calculated observables

A comparison with available data [4] is shown. Future developments are discussed.

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Parallel Session Friday: Atoms and Molecules / 90

An investigation for the appearance of long range nuclear potential on the ultra low energy nuclear synthesis

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On the three-body kinematics, the author proposed a $general\ particle\ transfer$ (GPT) potential which appears, not only at the three-body break-up threshold, but also at the quasi two-body threshold.The new potential represents a Yukawa-type potential for shorter range,but a $1/r^n$-type potential for longer range. The longer range part of the GPT potential for $n = 1$ indicates an attractive Coulomb-like or a gravitational potential. While, $n = 2$ includes the Efimov-like potential. The GPT-potential implies the existence of Efimov-like states in the hadron systems. In order to confirm the GPT potential, we investigate the possibility of lanthanum (La)-nucleus creation via the $ultralowenergyreaction$ Cs(2d,γ)La on the three-ion quasi-molecule
CsD_2 in the CsD_2Pd_{12}-cluster where D-Cs-D (d-Cs-d) three-body bound states and wave functions are calculated. The $wavefunctionoverlap$ value (WFO: $W_{n,m}$) between the La highest nuclear excited state with the quantum number $n = 5$, and the lowest CsD_2 quasi molecular modified states with the quantum number $m = 6$ is of critical importance for the existence of the electro-magnetic (EM) transition in the Cs(2d,γ)La reaction. We found that the $W_{5,6}$ value is very sensitive to the nuclear potential tail with a two- or three-body $1/r^2$-type long range hadron potential. It gives the ratio: $W^L_{5,6}/W^S_{5,6} \approx 10^7$, where $W^L_{5,6}$ is given by the nuclear force with the long range GPT potential, and $W^S_{5,6}$ is obtained by the usual short range nuclear potential. The ratio corresponds to the E2-transition ratio, where the E1-transition is forbidden in this reaction.This fact means that the quasi molecular state is stable only for the short range nuclear potential, but the nuclear synthesis occurs for the short range nuclear potential with the GPT long range potential. We can conclude that if the reaction occurs, then the GPT potential is confirmed.

Parallel Session Friday: Atoms and Molecules / 46

Low-dimensional few-body collisional processes in atom-ion traps

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In recent years, there has been a rapidly growing interest in ultracold hybrid atomic-ion systems. It is caused by the new opportunities opening here for modeling various quantum system and processes with controllable properties. Particularly, in the recent paper of Melezhik and Negretti1 the confinement-induced resonances (CIRs) in ultracold hybrid atom-ion systems were predicted, which can be used for controlling the effective atom-ion interaction.
In my talk I will present recent results of my group on the few-body atom-ion systems. It is quantitative description of collisional dynamics near atom-ion CIRs with including the effect of the irremovable ion "micromotion'' in the Paul trap. Another problem was to extend the fundamental result by Olshanii[2] - the prediction of the s-wave CIRs in one-center confined problem - to the two-center confined problem[3]. While recovering the usual result when the scattering centers coincide [2,4], the conditions of CIR appearance for the general two-center case were derived. Our results can

be potentially applicable in a number of hot problems in physics of cold atoms and ions: confined atomic scattering by fixed impurities, such as ions, Rydberg atoms or two-atomic molecules, with possible extension to N impurities.

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Parallel Session Friday: Few-Nucleon Systems / 25

Study of deuteron-proton backward elastic scattering at intermediate energies.

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We study deuteron- proton elastic scattering in the deuteron energy range between 500 MeV and 2 GeV at the cms scattering angle of 180^0. The simplest reaction mechanism is one-nucleon-exchange (ONE). But the ONE-predictions are in a disagreement with the experimental data both for the differential cross section and polarization observables.

In this report we consider deuteron- proton elastic scattering in the relativistic multiple scattering expansion framework [1-3]. 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.

The model is applied to describe the energy dependence of the differential cross section and polarisation observables such as tensor analyzing power T_{20} and polarization transfer from deuteron to proton
$varkappa$. Contributions of the different reaction mechanisms into the reaction amplitude are demonstrated in comparison with the existing experimental data.

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Parallel Session Friday: Few-Nucleon Systems / 68

Three-nucleon force effects in nucleon-deuteron scattering at backward angles

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The necessity of three-nucleon potentials (3NPs) in the nuclear Hamiltonian in addition to two-nucleon potentials (2NPs) is well recognized. A 3NP based on two-pion exchange process among three nucleons (2piE) is often used in few-nucleon calculations, where its strong attractive effect is suppressed by a form factor with a low value of the cutoff mass parameter (about 700 MeV).
In spite of various successful 2piE-3NP effects on 3N observables, there are still unsolved discrepancies between experimental data and calculations. A typical example is the differential cross sections at backward angles for intermediate energy elastic nucleon-deuteron (Nd) scattering.
In this work, Nd cross sections are studied using Hamiltonian models consisting of a two-nucleon potential and 2piE-3NPs with a large cutoff mass parameter by adding phenomenological repulsive 3NPs as a counterpart. The use of the large cutoff mass parameter brings an increase of the ND cross sections at backward angles, which tends to reduce the discrepancies between previous calculations and data. This indicates an importance of the pion-exchange process at medium range region in the 2piE-3NP. Furthermore, possible spin-dependence of phenomenological repulsive 3NPs will be discussed in comparing with ND polarization observables.

Parallel Session Friday: Atoms and Molecules / 59

Three-body correlations in mesonic-atom-like systems

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Mesonic atoms are the Coulomb bound systems of a nucleus and mesons. They interact with short-range strong interactions in addition to the long-range Coulomb potential. Studies of such kind of systems lead to the understanding of the short-range interactions such as meson-nucleon interactions. In Ref. [J.-M. Richard, C. Fayard, Phys. Lett. A 381, 3217-3221 (2017)], a system consisting of identical bosons that interact with schematic long- and short-range attractive potentials was studied as the simplest case. Importance of the three-body correlations was discussed by varying the strength of the short-range interaction. Extending that study, we employ more realistic three-body models. The one consists of identical bosons that interact with the long-range Coulomb and short-range potentials. The other consists of two identical bosons and one different boson that has half mass and opposite charge of the other bosons. We discuss the changes in the binding energy with respect to the strength of the short-range interaction and define the critical strength of the short-range interaction where the three-body correlations are not negligible.

Parallel Session Friday: Few-Nucleon Systems / 41

Correlation analysis and statistical uncertainty of three-nucleon scattering observables

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The ab-initio theoretical study of the three-nucleon (3N) observables for the nucleon elastic and inelastic scattering on the deuteron is possible using realistic models of nuclear forces. Such models contain a number of free parameters whose values are typically fixed using the two-nucleon data. In case of few models, as the One-Pion-Exchange-Gaussian (OPE-Gaussian) force 1 or the chiral force with the semilocal momentum-space regularization [2] derived by Bochum group even beyond the fifth order of chiral expansion (N4LO), in addition to the central values of parameters also their correlation matrix has been determined. The knowledge of the correlation matrix of the potential parameters opens new possibilities in studies of few-nucleon systems. In this presentation I will give two examples of such studies:

Firstly, we have applied the OPE-Gaussian force and the chiral N4LO potential with the semilocal momentum space regularization to study the propagation of uncertainties of two-nucleon interaction parameters to 3N scattering observables [3, 4] and have determined corresponding statistical uncertainty of these observables for the first time.

Secondly, we have investigated correlations between various two- and three-nucleon observables as well as between observables and specific potential parameters. While the complex structure of 3N scattering equations makes analytical studies of such correlations extremely difficult, the statistical approach can be here successfully applied. Knowledge of correlations between observables increases our understanding of 3N Hamiltonian. That piece of information is also necessary for a correct and precise performing the fitting procedure for many-body interactions. Our study indicates which of the 3N observables are particularly useful in this context.

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Parallel Session Friday: Atoms and Molecules / 48

Scattering phase shifts and mixing angles for an arbitrary number of coupled channels on the lattice

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We present a lattice method for determining scattering phase shifts and mixing angles for the case of an arbitrary number of coupled channels. Previous lattice studies were restricted to mixing of up to two partial waves for scattering of two spin-1/2 particles, which is insufficient for analyzing nucleon-nucleus or nucleus-nucleus scattering processes. In the proposed method, the phase shifts and mixing angles are extracted from the radial wave functions obtained by projecting the three-dimensional lattice Hamiltonian onto the partial wave basis. We use a spherical wall potential as a boundary condition along with a channel-mixing auxiliary potential to construct the full-rank S-matrix. Our method can be applied to any type of particles, but we focus here on scattering of two spin-1 bosons involving up to four coupled channels. For a considered test potential, the phase shifts and mixing angles extracted on the lattice are shown to agree with the ones calculated by solving the Schrödinger equation in the continuum.

Parallel Session Friday: Atoms and Molecules / 69

Solving the few-body problem with artificial neural networks

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Artificial Neural Networks (ANNs) have recently been used to solve a variety of quantum few- and many-body problems [1,2]. ANNs efficiently encapsulate information of the wavefunction and can be used to effectively solve variational problems [3]. I will discuss an implementation of these methods to solve a benchmark nuclear physics problem – the ground state of the deuteron [4]. I will describe the ANN architecture, training, and energy minimisation algorithm that is used in this first application to theoretical nuclear physics. I will then consider the extension to higher mass numbers, and identify challenges in the use of ANNs for nuclear theory applications.

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Parallel Session Friday: Few-Nucleon Systems / 81

The $D_{03}(2380)$ dibaryon resonance excitation in pd collision in the GeV region

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At present as one of the most realistic candidate to dibaryon resonance is considered the resonance $D_{IJ} = D_{03}$ observed by WASA@COSY \cite{WASA11} 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. 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 \cite{Cyrkov}. In the distribution over the invariant mass $M_{d\pi\pi}$ of the final $d\pi\pi$ system the resonance peaks were observed at $M_{d\pi\pi} \approx 2.38$~GeV \cite{Cyrkov} that is the mass of the isoscalar two-baryon resonance $D_{IJ} = D_{03}$, while the kinematic conditions differ considerably from that in Ref. \cite{WASA11}. This data we analyzed in Ref.\cite{UzikovTurs} assuming excitation of the D_{03} resonance via t-channel σ-meson exchange between the proton and deuteron and using the two-resonance mechanism of the D_{03} resonance decay \cite{PK2013}. The shapes of the distributions over the invariant masses of the final $d\pi\pi$ and $\pi\pi$ systems were explained qualitatively in \cite{UzikovTurs} assuming the lowest values of the orbital angular momenta in the vertices $\sigma d \to D_{03}$ ($L = 2$), $D_{03} \to D_{12} + \pi$ ($l_1 = 1$), $D_{12} \to d + \pi$ ($l_2 = 1$). In this work we study the role of higher orbital momenta in those vertices ($L = 2, 4,\ l_1 = 1, 3, 5,\ l_2 = 1, 3$). Furthermore, a contribution of the D_{03} excitation to the pd-backward elastic scattering is studied in the 1 GeV region.

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Final session / 7

Experiments and analyses aimed at understanding nuclear clustering

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The experimental programme at Birmingham in the the area of light nuclei focuses on nuclear cluster states. Recent investigations including a new limit on the direct decay of the carbon-12 Hoyle state, the use of machine learning to extract cluster signatures from resonant scattering data for medium-mass nuclei, and precision investigations into cluster and molecular candidate states in the oxygen isotopes. Additionally, resonances in the key X-ray-burst nucleus, neon-19, have been elucidated.
A selection of these highlights will be presented.

Final session / 150

Few-body physics: getting more effective

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Over the last twenty years, the language of universality, the renormalisation group, and effective field theory has become central to few-body physics. The original application of these ideas to strongly-interacting, nonrelativistic particles was to nuclear forces, where they have led to improved descriptions of few-nucleon systems and better understanding of the role of three-body forces. Since then they have been realised most dramatically in systems of ultracold atoms. In this talk, I discuss some recent developments in applications to nuclear forces, hadronic molecules, clustering in nuclei, and atomic systems. I also look at some of the questions that remain open, particularly in the context of nuclear reactions.