25th European Conference on Few-Body Problems in Physics

Sunday 30 July 2023 - Friday 4 August 2023

Alte Mensa

Book of Abstracts

Contents

Monday Plenary Session (AudiMax) / 19

Dynamics of weakly-bound molecules

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The helium dimer is extremely weakly bound. Specifically, two bosonic helium-4 atoms support a single bound state with binding energy of approximately 1.5mK; no rotationally excited states are supported. The mixed isotope dimer (one helium-4 atom and one helium-3 atom), in contrast, does not support a bound state at all. In the trimer sector, three helium-4 atoms support two bound states. The ground state is about 100 times more strongly bound than the dimer while the excited Efimov state has a binding energy that is comparable to that of the dimer. The excited trimer state disappears upon isotope substitution. The system consisting of two helium-4 atoms and one helium-3 atom supports only a single bound state. The extremely weakly bound nature of small helium molecules makes them intriguing candidates for dynamical studies. This talk will discuss the helium and trimer dimer dynamics that ensues in response to a short laser kick.

Monday Plenary Session (AudiMax) / 151

Few-body systems under confinement

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With the experimental realization of strongly confined atomic and molecular systems using, for example, optical lattices or tweezers the modification of the few-body physics due to tight confinement is of increasing importance, since the interaction and confinement lengths
can become comparable in these systems. The physics may fundamentally change, if the confinement leads to effectively reduced dimensionality. Open channels describing asymptotically free particles become formally closed leading to a modification of resonance positions. This effect is also relevant, if, e.g., a confining potential is artificially introduced in order to numerically treat nuclear systems adopting bound-state approaches.

Furthermore, new types of resonances, so called confinement-induced resonances (CIRs) can occur. These come in two flavours: elastic CIRs that occur for a unique ratio between scattering and confinement lenghts, and an in principle infinite series of inelastic CIRs. While the former are limited to (quasi) one- and two-dimensional geometries, the latter occur in all dimensions and have very recently also experimentally been observed under three-dimensional confinement. The occurrence of CIRs is not limited to ultracold atoms or molecules, but is also predicted for, e.g., electrons or excitons in quantum dots, the latter system allowing for on-demand single-photon sources.

Another interesting aspect of confined few-body systems arises, if the confining potential allows for tunneling. The study of the tunneling dynamics of (periodically) driven few-body systems like ultracold atoms in optical tweezers may even serve as a quantum simulator for simulating the behaviour of atoms and molecules in intense ultrashort laser pulses (”attosecond physics in slow motion”).

Monday Plenary Session (AudiMax) / 17

Cold Collisions of Ultracold Atoms in a Miniature Laser-based Accelerator

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I present results from experiments exploring two types of scattering resonances in the collision of ultracold clouds of atoms —shape resonances[1] and Feshbach resonances[2,3]. Using a laser-based accelerator that capitalizes on the energy resolution provided by the ultracold atomic setting, we unveil these resonance phenomena in their quintessential form by literarily photographing the halo of outgoing scattered atoms. Such images for example capture the quantum mechanical interference between partial waves and the interplay between S-matrix poles. In particular, the tunability of magnetic Feshbach resonances opens up a unique possibility to experimentally[4] record the imprint from a flow of S-matrix poles in the complex energy plane[5].

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Monday Plenary Session (AudiMax) / 114

Recent progress in hypernuclear physics

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One of important subject in hypernuclear physics is to obtain information on Baryon-Baryon interaction. Especially, it is hot topic to obtain information on ΞN interaction and predict energy spectra of light Ξ hypernuclei theoretically. In this conference, I report the recent progress of Ξ hypernuclei and ΞN interaction theoretically and experimentally.

Monday Plenary Session (AudiMax) / 50

Precision benchmarks for nuclear and atomic physics from laser spectroscopy of muonic atoms

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Laser spectroscopy of muonic atoms, hydrogen-like atoms formed by a negative muon and a nucleus, has recently provided the charge radii of the lightest nuclei (proton, deuteron, 3He and 4He) with unprecedented accuracy. In this talk we present laser spectroscopy of these exotic atoms and their contribution to nuclear physics. Emphasis will be given to the new results in 3He.

Moreover we will emphasise how these measurements are impacting the determination of fundamental constants leading to the best tests of atomic and molecular energy levels for few-body systems such as H, He, H2+ and H2 providing the best verification of Quantum Electrodynamics for bound systems.

Monday Plenary Session (AudiMax) / 139

Recent results on Proton Charge Radius and Polarizabilities

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Nucleons (protons and neutrons) are the building blocks of atomic nuclei and are responsible for more than 99% of the visible matter in the universe. Despite decades of efforts in studying the structure of the proton, the proton remains fascinating and even puzzling. Low-energy experiments play an important role in elucidating the structure of the nucleon and advance our understanding of the theory of strong interaction, quantum chromodynamics (QCD) in the non-perturbative region. In this talk I will discuss some recent results from electron scattering and Compton scattering experiments on the proton charge radius and nucleon polarizabilities. This work is supported in part by the U.S. Department of Energy under Contracts No. DE-FG02-03ER41231."

Monday Plenary Session (AudiMax) / 150

The Proton Radius and its Relatives A.D. 2023

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The size of the proton as measured with electromagnetic probes has been heavily debated in the last decade or so. Here I discuss the dispersion-theoretical framework which is based on elementary principles of quantum field theory like analyticity and unitarity.
It allows to analyse electron-proton scattering data for all values of the momentum transfer, including also the time-like region.
I discuss in particular the consequences for the proton charge radius and its relatives, the proton and neutron magnetic radii. The so extracted proton charge radius has shown an incredible consistency over many decades. I will also briefly discuss upcoming experiments and issues that need to be addressed to increase the precision of such determinations. Finally, I present a novel method to extract the proton charge radius from J/ψ decays.

Monday Parallel Session: Unitary/Boson Systems (AudiMax) / 140

Unraveling Universal Correlations: Gaussian Characterization of Systems Near the Unitary Limit

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In this talk, we present a summary of our recent research results on describing systems near the unitary limit using simple potentials, specifically Gaussian potentials[1-5].

In the parameter region where the energy of either the two-particle bound state or the virtual state is small, the physics can be effectively described by the scattering length and the effective range alone. Different systems with varying scales exhibit a universal correlation, independent of the specific type of interaction. This justifies the use of simple interactions such as Gaussian potentials.

We demonstrate how a Gaussian potential can be extended to capture the physics of systems with three or more particles. We present two approaches to utilizing the Gaussian characterization. The first approach focuses on describing two-particle sectors, such as two- and three-particle systems, enabling the prediction of energy properties of few-body systems at the unitary point. The second approach aims to describe the physical system up to the continuum, necessitating the inclusion of an additional three-body force to ensure system stability at the thermodynamic limit.

We also discuss potential avenues for improving the aforementioned framework and explore possible connections with traditional Effective Field Theory approaches.

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Monday Parallel Session: Few-body systems (Atrium Maximum) / 21

Dynamics of three-nucleon systems at 100 MeV

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The dynamics of the three-nucleon system can be very extensively tested by means of the deuteron-proton breakup reaction. Experimental studies of the *dp* system 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 cross sections as well as polarized observables (e.g. vector and tensor analyzing powers 1) are interesting for testing theoretical calculations based on various approaches [2 - 5] 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 [6] and our experimental results will be compared with theoretical calculations that were done in

this regime [7].
The presentation will concentrate on testing the 3NF and the Coulomb force effects for the differential cross section of the $^1H(d,pp)n$ reaction at beam energy of 100 MeV. The experiment was performed at KVI in Groningen, with the use of the BINA detector [1, 8].

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Monday Parallel Session: Few-body systems and astrophysics (Linke Aula) / 11

Direct measurements of nuclear reactions at stellar burning energies

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Thermonuclear reactions involving charged particles play a central role in stellar evolution. Knowledge of their rates is needed to answer fundamental questions about the origin of the elements. While direct measurement approaches are a powerful tool to study nuclear cross-section, the hindering effect of the Coulomb barrier makes measurement at energies of stellar interest extremely challenging. I will introduce two novel approaches to face this long-standing issue, which are being developed thanks to my ERC starting grant ELDAR.

I will first introduce future plans for underground measurement of nuclear reactions emitting charged particles at the deep underground accelerator LUNA-400 (INFN Gran Sasso, Italy). The cosmic silence afforded by the underground environment is key to carry out high-precision detection of extremely rare in-beam reaction events.

I will then describe the novel opportunities opened up by low-energy heavy ion storage rings such as the CRYRING (GSI/FAIR, Germany) for measurement of nuclear reactions directly at Gamow energies. I will introduce the unique technical requirements, first experimental results of the CRYRING Array for Reaction MEasurement (CARME), and near future plans.

Monday Parallel Session: Few-body systems (Atrium Maximum) / 15

Exploring nonlocal potentials in few-body reactions

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The dynamics of quantum few- and many-body systems is often modeled with local interaction models, mainly due to simplicity, though more microscopic or fundamental approaches yield nonlocal interactions. For few-cluster nuclear reactions the interactions usually are given in the local form of

real binding and complex optical potentials. We made a two-fold extension of that standard dynamics by developing a new nonlocal form of binding and optical potentials and simultaneously including the excitation of the nuclear core. Exact three-body Faddeev-type equations in momentum-space are solved for the description of nucleon transfer reactions (d,p) and (p,d) and deuteron inelastic scattering(d,d'). Example results for 10Be and 24Mg nuclei demonstrate a good reproduction of the experimental data and an improved consistency between the two-body (elastic and inelastic nucleon-nucleus scattering) and three-body description 1.

A different application of the nonlocality is presented in the context of local strongly repulsive interatomic potentials such as those between 4He atoms. Making a gradual extension of the original potential into a nonlocal form it becomes more smooth enabling to achieve well converged solutions of three- and four-body bound-state or scattering equations. An extrapolation back to the original potential yields the desired results such as the dimer-dimer scattering length or tetramer binding energies 2.

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Monday Parallel Session: Few-body systems and astrophysics (Linke Aula) / 131

^{6}Li as a three-particle system in the (p,^{3}He) reaction at astrophysical energies

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We present a theoretical study of the ^{6}Li + p $\rightarrow$ ^{3}He + α direct transfer reaction at collision energies from few keV to around the Coulomb barrier ($\sim$ 1.5 MeV in the center of mass). This lithium-depleting process is of interest from the astrophysical point of view [1], and is also important in relation to the so-called "electron screening problem", regarding different discrepancies observed between experimental and theoretical estimations of the role of atomic electrons in nuclear reactions at low energies [2]. It has been suggested that the issue might be connected to nuclear structure features of the involved nuclei [2], calling for more advanced studies.

Here, the ^{6}Li nucleus is described as a quantum-mechanical α+p+n system, making use of both past [3] and more recent calculations. We compare several structure configurations for the system ground state, displaying various degrees of deuteron clutering, which is sensitive to the interference of components in which the pair of transferred nucleons within ^{6}Li lies in different shells. The impact of the structure on the transfer reaction cross section is then evaluated within the first- and second-order Distorted-Wave Born Approximation. We find that effects connected to the ^{6}Li ground-state static deformation tend to cancel out at low energies, while configurations exhibiting stronger clustering consistently yield greater transfer cross sections [4].

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Monday Parallel Session: Unitary/Boson Systems (AudiMax) / 6

Universality in low-dimensional three-body systems

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We study a heavy–heavy–light three-body system confined to one or two space dimensions. Both the binding energies and corresponding wave functions are obtained for (i) no heavy-heavy interaction and (ii) a finite-range heavy-light interaction potential. We demonstrate that when the two-body ground-state energy approaches zero, the three-body bound states display a universal behavior, independent of the shape of the interaction potential [1, 2, 3]. Moreover, in this limit the three-body binding energies and wave functions are shown to converge to the respective ones found in the case of the zero-range interaction.

In addition, we explore the regime where the heavy–light subsystems have a weakly bound excited state 4. The associated two-body system is characterized by (i) the structure of the weakly-bound excited heavy–light state and (ii) the presence of deeply-bound heavy–light states. The consequences of these aspects for the behavior of the three-body system are analyzed. We find a strong indication for universal behavior of both three-body binding energies and wave functions for different weakly-bound excited states in the heavy–light subsystems.

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Monday Parallel Session: Few-body systems (Atrium Maximum) / 58

A nonsymmetrized hyperspherical harmonics approach for bound and scattering states in few-nucleon systems

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Combining the hyperspherical harmonics (HH) method with the Rayleigh-Ritz or Kohn variational principle leads to one of the most accurate techniques to study microscopically both bound and scattering states for nuclear systems with a number of nucleons $A \leq 4$ 1. However, describing systems with $A \geq 4$ remains a computational challenge. One reason for that is the rapid growth of the number of hyperspherical harmonics with A, for a given grand angular momentum. Another reason is the increasing difficulty with A to build a maximal set of linearly independent antisymmetric hyperspherical states for each considered set of total orbital angular momentum, total spin, and total isospin 2. In this contribution, I will present a new method to bypass this latter difficulty. In this approach, the wave function is expanded on a nonsymmetrized HH basis and then, antisymmetrized on-the-fly when solving iteratively the eigenvalue problem (in the bound-state case) or the linear systems (in the scattering case) resulting of the application of the Rayleigh-Ritz or Kohn variational principle. The efficiency and the accuracy of the method is tested on some nuclear systems with up to six nucleons, interacting via two-body forces. Possible future applications include the description of several important reactions, like the α+N scattering, the t+d⟶α+n "fusion"reaction, or the α +d⟶6Li+γ radiative capture.

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Monday Parallel Session: Few-body systems and astrophysics (Linke Aula) / 111

Radiative neutron capture rate of ^{11}B(n,γ)^{12}B reaction from the Coulomb dissociation of ^{12}B

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Radiative capture reactions with light neutron-rich nuclei are known to be important constituents at sites of explosive nucleosynthesis while producing seed nuclei for the r-process. One such important reaction is the ^{11}B(n,γ)^{12}B radiative neutron capture reaction, where the total reaction rate has significant contributions from the resonant (narrow-resonances) as well as the non-resonant continuum.

A paucity of experimental direct capture reaction data forces the determination of the rate of this reaction by indirect approaches. We will present the capture cross sections and the subsequent non-resonant rates of ^{11}B(n,γ)^{12}B reaction calculated by using the Coulomb dissociation as an indirect method through the finite range distorted wave Born approximation (FRDWBA) theory. We will try to bring out the importance of accounting for the proper nuclear structure of the nuclei involved. The reaction rates at the relevant astrophysical temperatures would also be compared with proton and α-capture reaction rates of ^{11}B extracted from the literature.

Monday Parallel Session: Unitary/Boson Systems (AudiMax) / 112

Unitary interaction geometries in few-body systems

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We present an analysis of systems of up to 5 particles which are characterized by a subset of resonantly interacting pairs. The focus is on the renormalization-group (RG) behaviour of the 3-, 4-, and 5-body, equal-mass ground states. The RG/scaling behaviour is studied as a function of the various possibilities to bind the respective systems with resonant pair interactions.
Based on numerical calculations for the pertinent spectra in the zero-range limit of the interactions, and by a supporting analytical argument, we conjecture two elemental universality classes associated with discrete scaling factors of 22.7 and 1986.1, respectively; Elemental, because an arbitrary set of resonant pair interaction belongs to either class.
We advance a graphical criterium for every pair-interaction set based on so-called {\it unitary graphs} which assigns the respective topology to one of the two classes. Finally, an outlook is presented on

the significance of the approach to the cluster-state-doubling phenomenon observed at thresholds defined by Efimov trimers.

Monday Parallel Session: Few-body systems (Atrium Maximum) / 126

Experimental studies of the three nucleon system dynamics in the proton induced deuteron breakup at 108 MeV

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Studies of few-nucleon systems form the basis for understanding nuclear interactions and properties of nuclei. The very accurate theoretical calculations for three nucleon systems should be confronted with a rich set of presice experimental data.

For this purpose, the BINA (Big Instrument for Nuclear-polarization Analysis) detection system has been installed at CCB (Cyclotron Center Bronowice) 1. The BINA setup is designed to study the elastic and breakup reactions at intermediate energies. It consists 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 [2, 3].

The data analysis and results of the first experimental run of proton-induced deuteron breakup at a beam energy of 108 MeV will be presented. The data are normalized to the known cross section for proton-deuteron elastic scattering 4. Differential cross section determined for a set of over 100 kinematic configurations of outgoing protons in the range of polar angles from 13 to 27 degrees and azimuthal angles from 10 to 190 degrees will be compared to state of the art theoretical calculations to study the role of the Three Nucleon Force, Coulomb, and relativistic effects.

Moreover, the research was extended by introducing a new detector, which enabled the determination of pn pairs from the breakup reaction and their direct comparison with the previously determined pp pairs for selected FSI configurations.

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Monday Parallel Session: Few-body systems and astrophysics (Linke Aula) / 86

Hydrogen burning on Nitrogen isotopes in CNO and HCNO-cycles

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We investigated the radiative proton capture on nitrogen isotopes ^{12}N, ^{13}N, and ^{14}N [1 - 4] in the framework of the MPCM and obtained the reaction rates and their parametrizations. There are two stable nitrogen isotopes ^{14}N and ^{15}N, and among short-lived nitrogen isotopes, the longest-lived are ^{12}N ($t_{1/2} = 11$ ms) and ^{13}N ($t_{1/2} = 9.965$ min).

We compare the reaction rates to understand the relevance of each process at a given astrophysical temperature. The radiative proton ^{12}N$(p,\gamma)^{13}$O, ^{13}N$(p,\gamma)^{14}$O, ^{14}N$(p,\gamma)^{15}$O, and ^{15}N$(p,\gamma)^{16}$O processes have the same Coulomb barrier, so the reaction rates will differ only due to the different values of the $S(E)$ and reduced mass μ of interacting particles in the entrance channel. The reduced masses of the pairs p^{12}N, p^{13}N, p^{14}N, and p^{15}N are always less than the proton mass and are within the range $0.9294 \leq \mu$(amu) ≤ 0.9439. Therefore, the impact of the reduced mass can be omitted, and the reaction rates depend entirely on the reaction S-factor 4.

The p^{15}N reaction is the fastest, and its rate dominates up to $T_9\tilde{a}0.175$. ^{14}N$(p,\gamma)^{15}$O is the slowest process up to $T_9\tilde{a}0.1$, and it controls the rate and time of nucleosynthesis cycles. The p^{15}N rate becomes dominant at temperature-explosive hydrogen burning scenarios in stars. Only in the temperature windows $0.18 \leq T_9 \leq 1.14$ and $0.66 \leq T_9 \leq 3$ the reaction ^{15}N$(p,\gamma)^{16}$O is slower than ^{13}N$(p,\gamma)^{14}$O and ^{14}N$(p,\gamma)^{15}$O reactions, respectively. Hence the p^{15}N reaction controls the rate and time of cycles of nucleosynthesis in these two temperature windows 4.

The ^{15}N$(p,\gamma)^{16}$O reaction rate shows a strong interference effect but minor sensitivity to the asymptotic constant.

The main difficulty in determining reliable reaction rates of ^{12}N$(p,\gamma)^{13}$O, ^{13}N$(p,\gamma)^{14}$O, ^{14}N$(p,\gamma)^{15}$O, ^{15}N$(p,\gamma)^{16}$O reactions for the CNO cycles is the uncertainty in the very low cross-sections at the Gamow range. Developments within the low-energy underground accelerator facility LUNA [5] and recent improvements in the detection setup [6] make taking direct measurements of nuclear reactions near the Gamow range feasible. This advantage has been demonstrated in the ^{14}N$(p,\gamma)^{15}$O reaction, which was successfully measured down to energies of 70 keV at LUNA [7].

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Monday Parallel Session: Unitary/Boson Systems (AudiMax) / 147

Dynamical vortex production and quantum turbulence in perturbed Bose-Einstein condensates

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We report investigations on dynamical vortex production and quantum turbulence emerging in periodic perturbed Bose-Einstein condensates, considering binary coupled mass-imbalanced systems, submitted to a stirring time-dependent perturbation. We also present some preliminary results on the case of dipolar single-atom systems under time-dependent periodic Gaussian perturbations.

Monday Parallel Session: Few-body systems (Atrium Maximum) / 80

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

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An experiment to investigate the $^{1}\mathrm{H}(d,pp)n$ breakup reaction using a deuteron beam of 300, 340, 380 and 400 MeV (150, 170, 190, 200 MeV/nucleon) and the WASA (Wide Angle Shower Apparatus) detector, has been performed at the Cooler Synchrotron COSY-Juelich. Due to almost 4π acceptance and moderate detection threshold of the WASA system, differential cross section data have been collected in a large part of the breakup reaction phase space. The set of proton-proton coincidences registered at Forward Detector at the beam energy of 170 MeV/nucleon has been analysed on dense grid of kinematic variables, giving in total around 5600 data points. The cross section data are compared to theoretical predictions based on the state-of-the-art nucleon-nucleon potentials, combined with three-nucleon force, Coulomb interaction or carried out in a relativistic regime. Quantitative analysis of the description of the cross section data provided by various theoretical calculations in terms of χ^2-like variables will be discussed. In addition, first results for the differential cross sections for selected kinematical configurations defined
by the polar angles θ_1 and θ_2 and the relative azimuthal angle ϕ_{12} for the deuteron breakup at 190 MeV/nucleon will be presented.

Monday Parallel Session: Few-body systems and astrophysics (Linke Aula) / 98

Valley Trions in Monolayer Transition Metal Dichalcogenidesin the Framework of the Method of Hyperspherical Harmonics

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A trion is the bound state of an exciton with another charged carrier, which can either be an electron (X^- trion) or a hole (X^+ trion). We develop the theoretical formalism and study the formation of valleytrions in transition metal dichalcogenides monolayers within the framework of a nonrelativistic potential model using the method of hyperspherical harmonics (HH) in four-dimensional space. There are intravalley and intervalley X^- trions, while due to the Pauli exclusion principle, the X^+ trion can only exist in the intervalley configuration. We solve the three-body Schrödinger equations with the Keldysh potential by expanding the wave functions of a trion in terms of the antisymmetrized HH. The antisymmetrization is based on the electron and hole spins and valley indexes. We present and discuss the origin of the binding energy difference between X^- and X^+ trions. Results of numerical calculations for the ground state energies are in good agreement with similar calculations for the Keldysh potential and in fair agreement with the reported experimental measurements for trions binding energies.
It is considered a long-range approximation when the Keldysh potential can be approximated by the Coulomb potential and a short-range limit when this potential is approximated by the logarithmic potential. In a diagonal approximation in both limits, the system of differential equations for the hyperradial functions is decoupled. Our approach yields the analytical solution for binding energies of trions in diagonal approximation for these two limiting cases - the Coulomb and logarithmic potentials. We obtained exact analytical expressions for energy eigenvalues and eigenfunctions for X^- and X^+ trions. The corresponding energy eigenvalues can be considered as the lower and upper limits for the trions binding energies.

Monday Parallel Session: Unitary/Boson Systems (AudiMax) / 39

Discrete scale-invariant boson-fermion duality in one dimension

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In this talk, I discuss discrete scale invariance in one-dimensional many-body problems of identical particles. I first classify all possible scale-invariant two-body contact interactions that respect unitarity, Galilean invariance, permutation invariance, and translation invariance in one dimension. By using these contact interactions, I then construct models of $n(\geq 3)$ identical particles that exhibit breakdown of continuous scale invariance to discrete scale invariance. Just as in the Efimov effect, these models enjoy a geometric sequence of n-body bound states and log-periodicity of n-body S-matrix elements for arbitrary $n \geq 3$. I also discuss that these results can be applied equally well to both bosons and fermions by using boson-fermion duality. This talk is based on the paper 1.

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Monday Parallel Session: NN and Currents (Atrium Maximum) / 27

Constraining Nuclear Currents for Electroweak Processes

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Nuclear interactions based on chiral effective field theory (χEFT) have achieved significant success in describing low-energy nuclear properties. This success can be attributed, in part, to the fitting procedure employed to determine the low energy constants (LECs), which
serve as the free parameters of χEFT nuclear interactions. However, the description of nuclear electromagnetic and electroweak observables at low and medium energies has not always been satisfactory. In this seminar, we will discuss a new approach used to constrain the LECs present in nuclear electromagnetic currents. Through specific examples, we will demonstrate the impact that this new procedure can have on the description of electromagnetic and weak processes for few-body systems at low and medium energies.

Monday Parallel Session: Lattice QCD and relativity (Linke Aula) / 123

Going to the light front with contour deformations

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I will discuss a new method to compute light-front wave functions and parton distributions using contour deformations. After solving the two-body Bethe-Salpeter equation of a scalar theory, the projection onto the light front is done through a combination of contour deformations and analytic continuation methods. The resulting light-front wave functions and distribution amplitudes are in

agreement with the Nakanishi method frequently used in the literature. To make contact with QCD, we studied several extensions towards unequal-mass systems and complex conjugate propagator poles, and first calculations of TMDs using contour deformations are underway.

Monday Parallel Session: Few-Nucleon Systems (AudiMax) / 10

High-precision collinear laser spectroscopy of $^{12}C^{4+}$

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In the last decade, advances in ab-initio atomic structure calculations enabled the determination of the nuclear charge radius purely from laser spectroscopy measurements and related QED calculations. Especially laser spectroscopy of muonic systems achieved remarkable results in μH 1, μD 2 and μHe 3 which led to the famous proton radius puzzle and questioned the lepton universality proposed by the Standard Model of fundamental interactions. Although convincing evidence for a smaller proton radius was observed in muonic hydrogen [4 –6], also measurements that support the larger proton radius are reported [7, 8] from atomic spectroscopy. Furthermore, only the nuclear charge radius of H was studied so far with muonic and atomic spectroscopy. Therefore, an extended comparison between muonic and electronic systems is demanded.
In order to expand the all-optical approach towards heavier atomic systems than hydrogen, precise atomic structure calculations for two-electron systems are needed since no laser addressable transitions exist in H-like systems beyond hydrogen. Related non-relativistic QED (NR-QED) calculations [9] made significant progress recently and surpassed the available experimental precision in many elements. In order to test these calculations beyond Li, high-precision collinear laser spectroscopy has been performed from the metastable $1s2s\,^3\mathrm{S}_1$ state with a lifetime of 21 ms to the $1s2p\,^3\mathrm{P}_J$ states in C^{4+} at the Collinear Apparatus for Laser Spectroscopy and Applied Science (COALA), situated at the Institute for Nuclear Physics at the TU Darmstadt.
This contribution will present the first high-precision laser spectroscopy in the isotopic chain of carbon and the first all-optical nuclear charge radius of ^{12}C. This project is supported by the German Research Foundation (Project-ID 279384907 –SFB1245).

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Monday Parallel Session: NN and Currents (Atrium Maximum) / 117

Impact of two-body current on magnetic dipole moments

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The nuclear magnetic dipole moment is one of the major probes to investigate the structure of an atomic nucleus. For odd-mass systems, the simplest limit is to consider only the last unpaired nucleon, known as the single-particle or Schmidt limit. The dominance of the single-particle structure relates to the robustness of a magic number in a nucleus, and therefore the magnetic dipole moment can provide an insight into the magic property of a nucleus. Very recently, the magnetic dipole moments of indium isotopes were measured and show the abrupt jump at N=82 towards the Schmidt limit, supporting the expected magic property at N=82. The experimental data were confronted with calculation results from the ab initio valence-space in-meidum similarity renormalization group (VS-IMSRG) approach. While the VS-IMSRG results follow the experimental trend, the reproduction of measured magnetic moments remained challenging. In light nuclei, the significance of the two-body current contributions is already reported, and one expects that the effect is also non-negligible in heavier systems.

In this presentation, starting with the one- and two-body current in chiral effective field theory combined with the VS-IMSRG framework, we will show the results of magnetic moments for some selected light to heavy nuclei. Also, we will discuss that the two-body current effect on the magnetic dipole moment can be more important as we increase the mass number.

Monday Parallel Session: Lattice QCD and relativity (Linke Aula) / 4

Consistent currents in relativistic models of strongly interacting systems

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We discuss a systematic method for constructing many-body electromagnetic current operators that are needed to ensure covariance and current conservation in phenomenological relativistic Hamiltonian models of
strongly interacting systems. The construction represents a general Hamiltonian in the Weyl representation. Momentum operators in this representation are replaced by gauge covariant derivatives and the part of the resulting operator that is linear in the electromagnetic field is extracted. Non-commuting operators are treated explicitly using Trotter methods. Because the resulting current is an operator, it can be consistently applied to different reactions.

Monday Parallel Session: Few-Nucleon Systems (AudiMax) / 142

Vector mesons and chiral perturbation theory

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We present an extended version of chiral perturbation theory that incorporates vector mesons in addition to pions and nucleons. This extension establishes a consistent framework by treating the

mass of vector mesons as heavy and their associated momentum as light, thereby defining a well-defined power counting rule.

In our proposed theory, contrary to the typical vector-meson dominance (VMD) model, vector mesons are introduced as auxiliary fields that can be entirely integrated out at the leading order. The genuine contributions of vector mesons are taken into account as loop corrections at higher orders.

Through our analysis, we demonstrate that the extended theory significantly improves the description of electromagnetic form factors of pions and nucleons compared to conventional Chiral Perturbation Theory (ChPT). This achievement enables the systematic incorporation of vector-meson dominance. Additionally, we derive the chiral nuclear force up to next-to-next-to-leading order (N2LO) and apply it to NN phase shifts, resulting in enhanced accuracy when compared to conventional ChPT forces. Our findings shed light on the role of vector mesons in low-energy nuclear dynamics.

Monday Parallel Session: NN and Currents (Atrium Maximum) / 64

Nucleon-nucleon interactions in the large-N_c expansion

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Considering QCD in the limit of the number of colors N_c being large provides important constraints on the nucleon-nucleon interactions. These constraints are particularly valuable for cases for which available data is limited (if it exists at all), such as for interactions that violate symmetries, e.g., parity and time reversal invariance, and operators contributing to neutrinoless double beta decay. In the absence of sufficient data, these constraints may prove useful in guiding both experiment and theory in prioritizing where to focus our efforts to gain a better understanding of these interactions. I will describe recent applications and also discuss the role of intermediate states containing the Delta isobar.

Monday Parallel Session: Lattice QCD and relativity (Linke Aula) / 92

The impact of quark many-body effects on exotic hadrons

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Co-authors: Makoto Takizawa [2]; Yasuhiro Yamaguchi [3]; Atsushi Hosaka [4]

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The constituent quark models successfully explain the features of the single hadrons. The hadron interactions are also well-reproduced. For example, the channel dependence of the short-range part of two-baryon interaction corresponds to those given by the Lattice QCD.

In this work, we investigate the exotic hadrons, $(q\bar{q})$-$(q\bar{q})$. The spin-dependent term of the one-gluon exchange force (CMI) has been well investigated and is known to be responsible for giving an attraction to form the exotic hadrons.

The most significant effect, however, comes from the internal structure in terms of the quark degrees of freedom. The effect of hadrons being composed of multiple quarks is incorporated into the present model as a spectroscopic factor (S-factor). This effect can be repulsive (because of the quark Pauli-blocking) or attractive (because of the many-body effect) and has strong channel dependence. The effect appears in the overlapping spacial region between the compact quark configuration and the two-hadron scattering states.

By using a quark-hadron hybrid model that includes both of the above effects, we investigate the T_{cc}.The T_{cc}, $\bar{u}\bar{d}cc$ $I(J^P)$=0(1^+), consists of two components: (A) cc spin-1 $\bar{u}\bar{d}$ spin-0 and (B) cc spin-0 $\bar{u}\bar{d}$ spin-1. Because of the symmetry, there is no cc spin-1 $\bar{u}\bar{d}$ spin-1 component with the isospin 0. For both of the components, the CMI is attractive, but their sizes are different. CMI in (A) is six times more attractive than in (B). On the other hand, the S-factor in (A) is repulsive, while it is attractive in (B). As a result of this cancellation, we found that without the long-range attraction from the pion exchange, the T_{cc} becomes a virtual state. Also, we found that T_{bb} is a deeply bound state because the S-factor effect reduces in a compact state.

Such a cancellation can also be seen in other exotic hadrons, such as the P_c. Our aim here is a comprehensive understanding of the mechanism to form the exotic hadrons.

Monday Parallel Session: Few-Nucleon Systems (AudiMax) / 55

Structure of resonance states in three-alpha systems

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In many phenomena of atomic nuclei, the α-particle (the ^{4}He nucleus) can be considered as effective degrees of freedom. In this contribution, recent works on structures of low-energy excited (resonance) states in ^{12}C nucleus in terms of 3α model will be presented.
Continuum 3α wave functions for angular momentum and parity states: 0^+, 1^-, 2^+, and 3^-, are obtained with phenomenological 2α- and 3α potentials by using Faddeev technique. These resonance states turn to be effective in explaining such reactions of ^{12}C$(\alpha, \alpha')3\alpha$. The wave functions in resonance states have some concentrations in amplitude near the origin, from which one can evaluate 3α configurations. These structures are, in general, mixtures of equilateral triangle and isosceles triangle (or bent-arm configuration) with various sizes. From the comparison of these structures, possible excitation mechanisms of 3α states, such as breathing-mode excitation and rotational excitation, are studied.

Monday Parallel Session: NN and Currents (Atrium Maximum) / 77

Efficient emulator for solving three-nucleon Faddeev equation with contact terms of chiral three-nucleon force at N4LO

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The ongoing progress in derivation the chiral two- and many-nucleon forces in the framework of chiral perturbation theory (χPT) [1,2] gives better and better understanding of nuclear phenomena, but also brings many challenges for application of these forces beyond the two-nucleon (2N) system.

While general operator form of three nucleon force (3NF) is currently known up to N4LO [3-6], its practical implementation to the bound systems and to the scattering problems is delayed. The main obstacles are necessity of consistent, with what is used in 2N force, regularization of the 3NF, performing partial wave decomposition of 3NF, and last but not least fixing it's free parameters. It is expected that at N4LO there are thirteen free parameters to be fixed from 3N data. Due to the computational complexity of 3N calculations it is unpractical to apply standard fitting methods in that case.
In this contribution, we focus on the latter problem and propose fast and efficient way to obtain approximated solution of 3N scattering problem [7-9] within the Faddeev approach. We apply that new emulator to investigate the importance of the 3NF N2LO and N4LO contact terms in elastic nucleon-deuteron (Nd) scattering. Specifically, we use the N4LO+ chiral semilocal momentum space regularized 2N chiral potential [10] supplemented by N2LO 3NF [11] and all subleading N4LO 3NF contact terms [5-6]. Inclusion of the N4LO 3NF contact terms yields an improved description of the elastic Nd scattering observables in a wide range of incoming nucleon energies up to 250 MeV. We will discuss both the new equations forming the emulator, the procedure for establishing the LEC values, the quality of the approximation made, and finally the results based on them showing the influence of the N4LO terms on the Nd cross sections and selected polarisation observables.

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Monday Parallel Session: Lattice QCD and relativity (Linke Aula) / 69

Influence of discretization error on the HALQCD baryon forces

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Baryon interactions, including nuclear force, are an essential component in nuclear physics especially in studies of few-body systems. There are already some useful phenomenological nuclear forces, thanks to a lot of experimental data. While, we suffer from uncertainty in hyperon interactions due to a lack of experimental data. In such case, it is very useful if we could derive baryon interactions based on the QCD, the fundamental theory of the hadron world, instead of relying on experimental data. We, HALQCD collaboration, have been working toward that goal in recent years. Our method uses numerical calculations of QCD on lattice. Specifically, we measure the spatial correlation functions of hadronic few-body systems and extract potentials of interactions from them1. For example, we have revealed flavor-spin structure of baryon interactions and existence of H-dibaryon in flavor SU(3) symmetric world2. We have just extracted all the S-wave baryon interactions from QCD at the physical point by performing a massive lattice QCD simulation on the Fugaku computer in Japan.

Recently, there was an alert about baryon interactions extracted from QCD on lattice. Namely, it was pointed out that the baryon interactions extracted from QCD on lattice strongly depend on the lattice spacing used3. Lattice QCD generally cannot avoid an error due to a finite lattice spacing, called the discretization error. The question is how large is its impact in baryon interactions. In response to this point, we began to study the dependence of the interactions on the lattice spacing.

We have performed calculations on three different lattices with different lattice spacing for the same quark mass. We will report our results in detail at the conference.

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Monday Parallel Session: Few-Nucleon Systems (AudiMax) / 25

Detailed studies of 12C structure and reactions

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We have investigated both algebraic models and geometric cluster models of alpha clusters in 12C, focusing on the structure of ground state, the first excited 0+ state and the second excited 2+ state in particular
with the purpoese a establishing if the rotational bands are compatible with rigid structures or rather if they are quantum mixture of different configurations.
In a first series of paper [1,2], we assume a rigid equailateral triangle shape and study in detail several properties that descend from the algebraic framework, such as the energy spectrum, electromagnetic observables and calculate the transition densities in order to extract elastic and inelastic cross-sections for various processes.
In a second series of papers [3,4], we solve the three-body Schrödinger equation with orthogonality conditions using the stochastic variational method with correlated Gaussian basis functions. The two-body density
distributions indicate that the main configurations of both the second 0+ and 2+ states are acute isosceles triangle shapes coming from 8Be(0+)+α configurations and find some hints that the second 2+ state is not an ideal rigid rotational band member of the Hoyle state band.

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Monday Parallel Session: NN and Currents (Atrium Maximum) / 91

Exploring non-implausible domain of low-energy constants in delta-full chiral effective field theory with history matching

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Recent breakthroughs in quantum many-body methods, computing, and emulators enabled us to statistically investigate nuclear systems and nuclear interactions. We employed a history matching approach to explore the low-energy constants (LECs) domain in delta-full chiral effective field theory. Different constraints such as scattering phase shift and few-body observables are iteratively incorporated into the history matching procedure to reduce the parameter domain. Our results revealed strongly correlated pairs of LECs and highlighted the LECs that remain poorly constrained even after the final wave of history matching.

Monday Parallel Session: Lattice QCD and relativity (Linke Aula) / 157

Two-body double pole and three-body bound states: physical and unphysical quark masses

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We solve the Faddeev bound-state equations for three particles with simple two-body nonlocal, separable po- tentials that yield a scattering length twice as large as a positive effective range, as indicated by some lattice QCD simulations. Neglecting shape parameters, the two-body bound state is a double pole. For bosons we obtain a cor- relation between three- and two-body energies. For nucleons, this correlation depends additionally on the ratio of effective ranges in the two two-body S-wave channels. When this ratio takes the value suggested by lattice QCD, our three-body energy agrees well with a direct lattice determination. When this ratio takes the experimental value, we find a three-body bound state with energy close to that of the physical triton.

Monday Parallel Session: Few-Nucleon Systems (AudiMax) / 28

S matrices of elastic α-^{12}C scattering at low energies in cluster effective field theory

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The elastic α-^{12}C scattering at low energies for $l = 0, 1, 2, 3, 4, 5, 6$ is studied in effective field theory. We discuss the construction of the S matrices of elastic α-^{12}C scattering in terms of the amplitudes of sub-threshold bound and resonant states of ^{16}O, which are calculated from the effective Lagrangian. The parameters appearing in the S matrices are fitted to the phase shift data below the p-^{15}N breakup threshold energy, and we find that the phase shifts are well described within the theory.

Monday Parallel Session: NN and Currents (Atrium Maximum) / 103

Momentum dependent nucleon-nucleon contact interactions and their effect on $p-d$ scattering observables

Authors: Elena Filandri[1]; Luca Girlanda[1]

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Starting from a complete set of relativistic nucleon-nucleon contact operators preserving parity and time reversal up to order $O(p^4)$ of the expansion in soft momenta p, we show that non-relativistic expansions of relativistic operators involve twenty-six independent combinations, two starting at $O(p^0)$, seven at order $O(p^2)$ and seventeen at order $O(p^4)$. This demonstrates the existence of two low-energy free constants that parameterize an interaction dependent on the total momentum of the pair of nucleons **P**.

These, through the use of a unitary transformation, can be removed along with other redundant terms in the two-nucleon (2N) fourth-order contact interaction (N3LO) of the Chiral Effective Field Theory, generating a three-nucleon (3N) interaction at the same order. We express its short-range component in terms of five combinations of low-energy constants (LECs) that parameterize the N3LO 2N contact lagrangian.

Within a hybrid approach in which this interaction is considered together with the phenomenological potential AV18, we show that the LECs involved can be used to fit very accurate data on the polarization observables of the low-energy $p-d$ scattering, in particular the A_y asymmetry. The resulting interaction is of the right order of magnitude for an N3LO contribution.

Monday Parallel Session: Lattice QCD and relativity (Linke Aula) / 130

Nucleon-nucleon interaction in manifestly Lorentz-invariant chiral effective field theory

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We propose a systematic approach to study the nucleon-nucleon interaction by applying time-ordered perturbation theory (TOPT) to covariant chiral effective field theory. Diagrammatic rules of TOPT, for the first time, are worked out for particles with non-zero spin and interactions involving time derivatives. They can be applied to derive chiral potentials at any chiral order. The effective potential, as a sum of two-nucleon irreducible time-ordered diagrams, and the scattering equation (Kadyshevsky equation) are obtained within the same framework. According to the Weinberg power counting, at leading order, we find that NN potential is perturbatively renormalizable, and the corresponding integral equation has unique solutions in all partial waves. Through evaluating the two-pion exchange contribution at the one-loop level, we formulate the NN interaction up to NNLO. A good description of phase shifts and deuteron properties is achieved by treating the full NNLO potential non-perturbatively.

Monday Parallel Session: Few-Nucleon Systems (AudiMax) / 159

Investigation of two-body system by using of a quasi exactly solvable method for a harmonic oscillator

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In this paper, we investigated the behavior of non-relativistic particles of two-body system by considering the Dunkl operator and reached two second-order differential equations about even and odd parities. We expressed the even cases and obtained the wave function in terms of the generalized Laguerre polynomials and normed constant. Also, we solved the odd term of Hamiltonian with the

QES method and we came directly to a general equation for energy. Also, we determined the exact solutions for arbitrary n through sl(2) algebra and reached to wave functions of the system. We have considered the harmonic oscillator and we separate the energy for singlet and triplet cases.

Tuesday Plenary Session (AudiMax) / 23

Electroweak properties of light nuclei in chiral effective field theory

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Electroweak properties of light nuclei not only shed light on the rich interplay between the electroweak and strong nuclear interactions but also help us provide constraints on astrophysical phenomena such as stellar/big-bang nucleosynthesis and on tests of fundamental symmetries. In this talk, I discuss recent progress in progress in chiral-effective-field-theory studies of electroweak observables in light nuclei with an emphasis on the quantification of theory uncertainties.

Tuesday Plenary Session (AudiMax) / 46

Pseudoscalar mesons and Emergent Hadronic Mass in the Standard Model

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The importance of the Higgs boson in the evolution of the Universe is well known. Yet, only a tiny fraction of the mass of the visible universe can be attributed to the Higgs mechanism alone. In fact, the overwhelming majority arises from the strong interactions of quantum chromodynamics, through a mechanism nowadays dubbed Emergent Hadronic Mass (EHM). Thus, weak and strong mass generation interfere constructively, giving birth to the plethora of hadrons that exists, and its properties. In this talk, we shall discuss how pseudoscalar mesons represent an insightful window in understanding these mass generating mechanisms and their implications, highlighting some important contributions of the Continuum Schwinger methods approach.

Tuesday Plenary Session (AudiMax) / 9

Free system of four correlated neutrons

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A fundamental aspect in low-energy nuclear physics is the interaction and correlation of neutrons at extreme conditions of very large neutron-to-proton asymmetry and low-density environment.

Multi-neutron systems provide an exclusive way to address such correlations. Their high impact potential has led to many experimental searches for such isolated systems over the last decades.
In this talk I will present our recent result, where using an α-knockout reaction from 8He isotope, we observed a low-energy peak in the four-neutron energy spectrum, with a resonance-like structure. A discussion on the interpretation of this observation is ongoing. The question is whether it is due to tetra-neutron correlation or other interaction between the neutrons, e.g. di-neutron correlations. Next-generation experiments using different reaction mechanisms and possibly detecting all four neutrons in coincidence, which are essential to conclude about its nature will be discussed.

Tuesday Plenary Session (AudiMax) / 36

Stability of light neutron rich nuclei

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Exploring and understanding the structure of the most neutron-rich nuclei is a primary goal of present day nuclear physics: this activity is due to advent of the RIBF and are driven by interest to understand better the interaction between the neutrons and the dynamics of neutron-proton unbalanced unstable nuclei.
In this presentation I will present an overview of our recent studies on
exotic neutron rich nuclei at verge or beyond the stability. Possible existence of exotic narrow resonant states in 4n, 4H-7H nuclei will be discussed.

Tuesday Plenary Session (AudiMax) / 26

The story behind the first 4n signal

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In 2002, when the quest for multineutrons had been running for 40 years without success and was already fading, a first positive signal consistent with a tetraneutron was observed at GANIL. We will go back to the motivations and anecdotes around that experiment, review the impact of this first result on the theoretical and experimental communities but also on the general public, and discuss the consequences it had on the re-triggering of the whole multineutron program.

Tuesday Plenary Session (AudiMax) / 76

The 4He spectrum

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In this contribution, we present some recent studies of the excited states of 4He nucleus, performed by accurately solving the four body scattering problem in the framework of the ab-initio hyperspherical harmonic method. The considered nuclear Hamiltonians include modern two- and three-nucleon interactions, derived using the chiral effective field theory approach.

First of all, we study the first excited state, which energy is slightly above the threshold for p+3H breakup, but below that of n+3He (this state is unbound due to the effect of the Coulomb repulsion between the protons 1). Recently, an electron scattering experiment has allowed the extraction of accurate monopole transition form factor F(q) data from the 4He ground state to this first excited state 2. Previous theoretical studies have shown that F(q) is very sensitive to the adopted nuclear interaction [3,4]. We will present new results for this observable obtained using the calculated four-body continuum wave functions.

Second, we present a study of the second excited state (a 0- resonance). For such a study, we exploit a recent measurement of the 3He(n,p)3H Ay observable using cold neutrons performed at ORNL [5]. In fact,
the energy of the process is close to the expected position of the 0- resonance. We found that the theoretical predictions for such observable are very sensitive to the interaction, in particular to the three-nucleon force.

Finally, we study the processes d(d,p)3H and d(d,n)3He at energies of interest for energy production and for big-bang nucleosinthesis [6]. In this case, we are sensitive to the presence of 1- resonant states in the 4He spectrum. We will present new results for the cross section and polarization observables of these processes and study the sensitivity to the position of 1- resonances.

These studies show that the spectrum of 4He is still poorly understood and that more accurate interactions between the nucleons are needed to quantitatively describe it.

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Tuesday Parallel Session: Few- and many-body systems (Atrium Maximum) / 137

Probing collective behavior in beryllium isotopes

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Ab initio nuclear theory provides not only a microscopic framework for quantitative description of the nuclear many-body system, but also a foundation for deeper understanding of emergent collective correlations. The beryllium isotopes embody the struggle between collectivity and shell effects resulting in, e.g., shape coexistence, parity inversion and intruder ground states. Here we probe the underlying correlations through the lens of approximate symmetries, specifically, Elliot's SU(3), a symmetry group associated with both nuclear deformation and rotation and with the harmonic oscillator. To this end, we decompose wave functions obtained with the no-core shell model by SU(3) symmetry and demonstrate that the collective behavior across the beryllium isotopic chain can be approximately understood in a simple SU(3) framework.

Tuesday Parallel Session: Few-body systems and hypernuclei (Linke Aula) / 51

Hypernuclear physics with pionless effective field theory

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Hypernuclear physics is a highly active field in the few-body sector, with significant astrophysical implications, such as in the description of neutron stars. However, hypernuclear systems are more difficult to be studied experimentally than standard nuclei, resulting in a shortage of data for model development and for the fit of realistic hypernuclear interactions. Past models have struggled to describe all observed hypernuclei, effective field theories have addressed this issue by providing a framework for creating theories with minimal parameters that can consistently describe lambda and double-lambda hypernuclei.

In this seminar, I will provide an overview of recent advancements in effective field theories for Lambda and double-Lambda hypernuclei, with a specific emphasis on the hypernuclear pionless theory. Additionally, I will review the various few-body methods and theoretical tools utilized to define and apply this theory. Lastly, I will outline the future prospects and potential applications of effective field theories in the field of hypernuclear physics.

Tuesday Parallel Session: AMO Systems (AudiMax) / 34

Quantum simulations with ultracold polar molecules and Rydberg atoms

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I will present our results on the properties and non-equilibrium dynamics of few-body quantum systems based on ultracold polar molecules, Rydberg atoms, or their mixtures, and their applications as quantum simulators. On the one hand, we investigated interacting ultracold molecules in a one-dimensional harmonic trap as a fundamental building block of molecular quantum simulators, where we observed an interesting interplay of intermolecular interactions, external fields, and trapping potentials [1,2]. On the other hand, we studied the non-equilibrium properties of a Rydberg electron interacting with a gas of spin-1/2 fermionic atoms and found the dynamical emergence of the Kondo screening cloud. Finally, we explored the quantum simulation of the central spin model with a Rydberg atom surrounded by polar molecules in optical tweezers 3.

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Tuesday Parallel Session: Few- and many-body systems (Atrium Maximum) / 148

Benchmarking electron-nucleus scattering within coupled cluster theory on 4He

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Neutrino oscillation experiments require good understanding of neutrino-nucleus interactions in the range of medium-mass nuclei, especially 40Ar and 16O relevant for DUNE and HyperK. Recently, we have started a program of calculating cross sections in the range of the quasi-elastic peak within the coupled cluster method combined with Lorentz integral transform.
In the first step we benchmarked our method for light systems, in particular 4He, where there are available predictions from various few-body methods. In my talk I will present our recent results for electron scattering on 4He: Coulomb sum rules, the longitudinal and the transverse responses. A special care is taken to remove the centre-of-mass spurious states that appear in the spectrum. Next, I will show the calculation of the spectral function and comparisons with the data in relativistic regime where the final state interactions can be neglected.

Tuesday Parallel Session: Few-body systems and hypernuclei (Linke Aula) / 68

Light hypernuclei in the framework of the NCSM and chiral EFT

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Due to the scarcity of hyperon-nucleon (YN) and the almost lack of hyperon-hyperon (YY) scattering data, hypernuclei with strangeness $S = -1, -2$ are indispensable laboratories to explore the underlying baryon-baryon (BB) interactions. In this work we study s- and light p-shell hypernuclei from a microscopic level employing the ab initio Jacobi no-core shell model (J-NCSM) in combination with BB interactions derived in the framework of chiral effective field theory (EFT). In order to speed up the convergence of the NCSM calculations, the employed interactions are softened with similarity renormalization group evolution. Impact of the evolution and of the chiral YN and NN potentials on the Λ separation energies in $A = 4 - 7$ hypernuclei will be discussed in details. We further explore the charge symmetry breaking (CSB) effect in the $A = 7,\ 8$ isospin multiplets employing YN interactions that include also the leading CSB potential. Finally, predictions of the chiral YY potentials for the s-shell $\Lambda\Lambda$ hyperuclei $({}^{4}_{\Lambda\Lambda}\mathrm{H}, {}^{5}_{\Lambda\Lambda}\mathrm{He}, {}^{6}_{\Lambda\Lambda}\mathrm{He})$ are briefly discussed.

Tuesday Parallel Session: AMO Systems (AudiMax) / 158

From Few-Body to Many-Body Physics in Ultracold Gases of Magnetic Dipolar Atoms.

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Ultracold quantum gases provide a pristine platform to study few-body and many-body quantum phenomena with an exquisite degree of control. The achievement of quantum degeneracy in gases of atoms with large magnetic dipole moments in their electronic ground states has opened new avenues of research in which anisotropic and long-range interactions play a crucial role. In my talk I will present related experimental findings in gases of open-shell lanthanide atoms, in particular erbium and dysprosium. I will discuss intriguing aspects of the few-body scattering of these atoms and show how this leads to the emergence of exotic many-body effects. The complex atomic structure of these atoms leads not only to large interatomic dipole-dipole interactions, but also to complex short-range scattering with a dense spectrum of Feshbach resonances. The tunable competition between short- and long-range interactions has allowed the discovery of novel stable many-body states where interaction effects beyond the mean field are crucial. These new phases include liquid-like droplets, droplet crystals, and supersolids, a paradoxical phase of matter that simultaneously exhibits solid and superfluid orders. After reviewing the experimental work of the past few years, I will outline perspectives for future research.

Tuesday Parallel Session: Few- and many-body systems (Atrium Maximum) / 31

Isospin correlations in isotope yields at intermediate and high energy heavy-ion collisions

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Isospin correlations in isotopic yields of fragments produced in peripheral asymmetric reaction systems ^{80}Kr + ^{40,48}Ca at 35 MeV/nucleon performed recently by FAZIA collaboration 1, have been studied in the framework of a statistical ensemble approach. Isotopic yields of light and intermediate mass fragments, emitted from the quasiprojectile (QP) sources, are compared both with each other and with the experimental results obtained for two reaction systems 2. The results indicated that the nucleon exchange between the target and projectile nuclei seems inevitable in order to reproduce experimental results. At relativistic energies, however, the nucleon exchange is very unlikely as shown in the analyses of ALADIN and FRS experimental data of projectile fragments produced in the peripheral and mid-peripheral relativistic heavy-ion collisions [3,4], including ^{112,124}Sn + ^{112,124}Sn, and ^{136}Xe + Pb at an incident beam energy of 1 GeV/nucleon, and measured with the high resolution magnetic spectrometer, the Fragment Separator (FRS) of GSI [5,6]. We discuss possible applications of the results for the production of hypernuclei that may have a broad distribution in masses and isospin extending beyond the proton and neutron driplines, as well.

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Tuesday Parallel Session: Few-body systems and hypernuclei (Linke Aula) / 118

Towards calibration of hyperon-nucleon interaction models using light hypernuclei

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The energy levels of light hypernuclei are experimentally accessible observables that contain valuable information about the poorly known interaction between hyperons and nucleons. In this contribution, I will report on our recent efforts to establish a reliable link between the low-energy properties of hypernuclei and the underlying hyperon-nucleon interactions.

In the first step, we studied light Lambda hypernuclei using the ab initio no-core shell model with realistic interactions obtained from chiral effective field theory. In particular, we quantified the precision of theoretical predictions of hypernuclear binding energies 1, as well as the lifetime of the hypertriton 2, that can be attributed to nuclear physics uncertainties. This knowledge is crucial for the use of binding energies to infer the hyperon-nucleon interaction. We studied both the convergence of the solution (method uncertainty) and the dependence on the nuclear Hamiltonian (model uncertainty). For the former, we implemented infrared correction formulas to extrapolate finite-space results to infinite model space while using Bayesian parameter estimation to quantify the resulting method uncertainties. For the latter, we employed a family of 42 realistic nuclear Hamiltonians 3 and quantified the deviation of predictions while keeping the hyperon-nucleon interaction fixed.

As a next step, we performed a global sensitivity analysis 4 of the energy spectra of light hypernuclei to identify the most influential low-energy constants in the leading-order chiral hyperon-nucleon forces [5]. For this purpose, we developed efficient and accurate emulators employing the eigenvector continuation method [6] and computed the binding energies for a wide range of the low-energy constants. We demonstrated the power of these emulators for calibration of hyperon-nucleon interaction models which has not been feasible yet due to the high computational cost.

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Tuesday Parallel Session: AMO Systems (AudiMax) / 22

Formation of the postronium antihydride $\bar{\mathrm{H}}\mathrm{Ps}$ molecules in low energy, 5-body $\mathrm{Ps} + \mathrm{H}^{+}$ collisions.

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The system consisting of positronium (Ps) and antihydrogen ($\bar{\mathrm{H}}$) atoms is known to exist in only one bound state of the positronium hydride ($\bar{\mathrm{H}}\mathrm{Ps}$) which is a hybrid atomcule that possesses both atomic and molecular properties. $\bar{\mathrm{H}}\mathrm{Ps}$ cannot be formed in purely 2-body $\bar{\mathrm{H}} + \mathrm{Ps}$ collisions, but it can be obtained when Ps collides with the antihydrogen ion $\bar{\mathrm{H}}^{+}$

$$\bar{\mathrm{H}}^{+} + \mathrm{Ps} \rightarrow \bar{\mathrm{H}}\mathrm{Ps} + \mathrm{e}^{+} \qquad (1)$$

whereby the binding energy is conveyed to the ejected positron. This collision presents a 5-body problem that we reduce to the 4-body problem and solve exactly using the technique of Gaussian Ex-

pansion Method (GEM) combined with the coupled rearrangement channels (CRC) method. The scattering matrix S and the cross sections are obtained from the coupled, non-local integro-differential equations that explicitly couple all open channels. The distinctive novel feature of our approach is the simultaneous use of several Jacobi sets of coordinates in the expansion of the multi-channel wave functions. That allows efficient and rigorous treatment of the scattering cross sections.

We present the so far unknown cross sections for the collisional rearrangement reaction (1) that depletes H^+ ions and results in the $\bar{\mathrm{H}}\mathrm{Ps}$ molecules.

The interest in the above collisions (1) stems from the fact that the $\bar{\mathrm{H}}^+$ ions are amenable to sympathetic cooling and, after photo-detachment of one positron, result in ultra-cold antihydrogen atoms that are to be used in ballistic experiments testing the gravitational interaction between matter and antimatter. The ongoing GBAR experiment at CERN 1 works on the production of $\bar{\mathrm{H}}^+$ ions in $\bar{\mathrm{H}} + \mathrm{Ps} \rightarrow \mathrm{H}^+ + \mathrm{e}^-$ collisions (the cross sections for this process have been recently calculated in our work 2). In this context reaction (1) is a scavenging process that depletes the newly formed $\bar{\mathrm{H}}^+$ ions that pass the positronium target chamber.

The cross sections for the rearrangement (eq. 1 or its charge comjugate) have not been calculated before and there are no experimental data. High accuracy theoretical results are hence important and timely as to aid and guide the experiments. We present the cross sections for the rearrangemet (1), the concomitant elastic scattering, and the reverse process $\bar{\mathrm{H}}\mathrm{Ps}+\mathrm{e}^+ \rightarrow \mathrm{H}^+ + \mathrm{Ps}$. We discuss the near-threshold features of the scattering cross sections and show that they comply with the expected behaviour stipulated by the Wigner's law. We also visualize, via the probability density plots, the mechanism of the rearrangement reaction (1) whereby H^+ shrinks and gets more tightly bound by capturing the electron, while the positron carries away the excess of energy.

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Tuesday Parallel Session: Few- and many-body systems (Atrium Maximum) / 104

The asymptotic behaviour of the many-body wave-function

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We study how short range correlations emerge from the nuclear wave-function.
To this end we analyze the asymptotic behaviour of the coupled cluster
many-body wave-function in the limit of highly excited two- and three-particles states.
We find that in this limit the different coupled cluster amplitudes
exhibit a recurring behaviour, factorizing into a common asymptotic two- or three-body term.
These asymptotic terms depend on the potential and in general are system
specific. They are connected to the 2- and 3-body zero-energy
Bloch-Horowitz operators.

Tuesday Parallel Session: Few-body systems and hypernuclei (Linke Aula) / 32

New studies of the $K^- pp$ 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 $\bar{K}NN$ were performed using different methods. 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 some experimental groups, but the estimated binding energies and decay widths of such state differ from each other and are far from all theoretical predictions. In particular, the most recent E15 experiment at J-PARC 1 reported the first clear signal of the $\bar{K}NN$ quasi-bound state with binding energy $42 \pm 3(\mathrm{stat.})^{+3}_{-4}(\mathrm{syst.})$ MeV, and width $100 \pm 7(\mathrm{stat.})^{+19}_{-9}(\mathrm{syst.})$ MeV.

In previous years we studied the quasi-bound state in the K^-pp system, the most recent results can be found in 2. Faddeev-type dynamically exact three-body AGS equations 3 with coupled $\bar{K}NN - \pi\Sigma N$ channels were solved with different input. Three models of the $\bar{K}N$ interaction were used, and two of them led to K^-pp binding energies close to the experimental values. However, the experimental width is much larger than ours. The present calculations aim to check, what could change the theoretical characteristics of the quasi-bound state. We will study the dependence of the results on the $\Sigma N - \Lambda N$ interaction models, on πN potential, which was excluded in the previous calculations, and will perform three-body calculations with three coupled channels: $\bar{K}NN$, $\pi\Sigma N$, and $\pi\Lambda N$.

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Tuesday Parallel Session: AMO Systems (AudiMax) / 12

Four Types of Atomic Experiments Proving the Existence of the Second Flavor of Hydrogen Atoms

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The Second Flavor of Hydrogen Atoms (SFHA) has been discovered theoretically and proven experimentally to exist for the 1st time –by analyzing atomic experiments related to the distribution of the linear momentum in the ground state of hydrogen atoms (J. Phys. B: At. Mol. Opt. Phys. 34 (2001), 2235). It was motivated by the huge discrepancy: the ratio of the experimental and previous theoretical results was up to tens of thousands. The gist of the theoretical discovery was that for the states of zero angular momentum (S-states), the so-called "singular"solution of the Dirac equation outside the atomic proton, which was usually disregarded, can be matched without any problem with the regular solution inside the proton with the allowance for the experimental fact that the charge density inside protons has the maximum at r = 0. So, for this second solution the wave function did not have a singularity at the origin and thus there was no reason to disregard this solution. This solution eliminated the above huge discrepancy between the theoretical and experimental results.
Later it was shown that the singular solution of the Dirac equation (with the allowance for the experimental charge distribution inside the proton) is legitimate for all discrete and continuum states of the zero angular momentum (Research in Astron. and Astrophys. 20 (2020) 109). Hydrogen atoms having only zero angular momentum states both in the discrete and continuous spectra constitute the second flavor of hydrogen atoms –called so by analogy with quarks, where, e.g., up and down quarks are called two flavors.
The primary property of the second flavor of hydrogen atoms is that, since they have only the S-states, then according to the selection rules they cannot emit or absorb the electromagnetic radiation: they remain dark (except for the 21 cm spectral line).
The 2nd experimental evidence of the existence of the SFHA was found by analyzing experiments on charge exchange of hydrogen atoms with incoming protons (Foundations 1 (2021) 265).
The 3rd experimental proof of the existence of the SFHA was obtained by analyzing experiments on

the excitation of n=2 states of atomic hydrogen by the electron impact (Foundations 2 (2022) 541). The 4th experimental proof of the existence of the SFHA was obtained by analyzing experiments on the excitation of the lowest triplet states of molecular hydrogen by the electron impact (Foundations 2 (2022)).
There are also two kinds of the astrophysical evidence of the existence of the SFHA. The first one is related to the puzzling observation of the redshifted 21 cm spectral line from the early Universe where it was found that the absorption in this spectral line was about two times stronger than predicted by the standard cosmology (Nature 555 (2018) 67). The qualitative and quantitative explanation of this puzzle by using the SFHA made the latter a candidate for dark matter (Research in Astron. and Astrophys. 20 (2020) 109).
The second astrophysical evidence of the existence of the SFHA related to recent perplexing observations that the distribution of dark matter in the Universe is smoother than predicted by Einstein' s gravitation (Monthly Not. Roy. Astron. Soc. 505 (2021) 4626). However, it turned out that this puzzle can be also explained qualitatively and quantitatively by using the SFHA (Research in Astron. and Astrophys. 21 (2021) 241).
The theoretical discovery of the SFHA was based on the standard Dirac equation of quantum mechanics without any change of physical laws. This presentation should motivate further experiments of the above three types –plus experiments on the formation of the molecular hydrogen ions by collision of protons with hydrogen atoms: the experiments that could yield yet another evidence of the existence of the SFHA.

Tuesday Parallel Session: Few- and many-body systems (Atrium Maximum) / 102

Experimental study of the hadronic interactions in two- and three-body systems with ALICE at the LHC

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Understanding the dynamics of hadrons with different quark content is crucial to solve fundamental aspects of QCD as well as for the implications on the structure of dense stellar objects, such as neutron stars. The scarce statistics and lack of data in reactions for unstable hadrons, containing in particular strange and charm quarks, affect the accuracy of the current theoretical description of the corresponding strong interaction. Additionally, the modelling of nuclei and hypernuclei requires a precise knowledge of three-body forces, for which a direct measurement is still missing. In the past several years the use of correlation techniques, applied to particle pairs produced in high-energy collider experiments, have been proven capable of complementing and expanding our existing knowledge of the hadronic interactions, particularly in the strangeness sector.

The present contribution provides an overview of the milestones reached by the ALICE Collaboration using the femtoscopy technique in pp collisions at $\sqrt{s}$ = 13 TeV. The main highlights are the unprecedented precision studies of the interaction of hadrons containing strange and charm quarks, alongside the extension of the analysis methods into the three-body sector aiming to experimentally isolate the three-body interaction contribution.

Tuesday Parallel Session: Few-body systems and hypernuclei (Linke Aula) / 113

An algebraic approach for the small systems of nucleons

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In the no-core shell model, the Jacobi coordinates are often used to describe few-body systems 1. These coordinates are convenient as they allow the explicit removal of a center of mass coordinate satisfying the requirement of translational invariance within the model space. For the description of the nucleus, the intrinsic coordinates are more natural, as it is independent of the external fields and the interactions between the nucleons depend only on the relative coordinates.

Another important requirement for the model space is the antisymmetry of the state vectors. The antisymmetry of the model space can be ensured using the Slater determinants. However, this approach is unsuitable for the Jacobi coordinates due to the complexity of the expressions for symmetric group permutation operators. To address this, you can employ the symmetric group algebra to find the antisymmetric model space. The symmetric group algebra for the few body systems is simple, but the situation differs for larger nuclei.

To overcome these challenges, we employ the so-called Λ operators 2. We construct these operators using the two-particle transposition operators of the appropriate symmetric group, taking into account the number of nucleons in the system. We construct the representations of these operators on a Harmonic Oscillator basis. The required representations of the transformations of the Jacobi coordinates are complicated and to solve this we introduce the algebraic approach for small systems.

This project has received funding from the Research Council of Lithuania (LMTLT), agreement No S-PD-22-9

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Tuesday Parallel Session: AMO Systems (AudiMax) / 38

Low-energy collisions between two indistinguishable tritium-bearing hydrogen molecules: HT+HT and DT+DT

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Tritium bearing hydrogen molecules are of a significant scientific interest, see Ref. 1 and, for instance, Tritium Laboratory Karlsruhe (TLK) reports at Karlsruhe Institute of Technology (Germany). In this work a quantum-mechanical close-coupling calculation is performed for elastic and inelastic 4-atomic collisions:
$\mathrm{HT}(j_1)+\mathrm{HT}(j_2)\to\mathrm{HT}(j_1')+\mathrm{HT}(j_2')$ and $\mathrm{DT}(j_1)+\mathrm{DT}(j_2)\to\mathrm{DT}(j_1')+\mathrm{DT}(j_2')$. Here H is a hydrogen atom, D is deuterium, and T is tritium. Global six-dimensional symmetrical H_2-H_2 potential energy surfaces (PESs) [2,3] have been adopted and appropriately modified for current 4-atomic systems. Specifically, we changed the position of the center of mass in HT and DT. In this presentation a special attention will be given to different geometrical modifications of the multidimensional H_2-H_2 potentials, as in Ref.4. State-resolved integral cross sections $\sigma_{j_1j_2\to j_1'j_2'}(\varepsilon_{kin})$ for quantum-mechanical rotational transitions $j_1j_2\to j_1'j_2'$ in HT and DT molecules and corresponding state-resolved thermal rate coefficients $k_{j_1j_2\to j_1'j_2'}(T)$ have been computed. The relationship between the rate coefficient $k_{j_1j_2\to j_1'j_2'}(T)$ and the cross section $\sigma_{j_1j_2\to j_1'j_2'}(\varepsilon)$ can be obtained through the following weighted average: $k_{j_1j_2\to j_1'j_2'}(T)=\sqrt{\frac{8k_BT}{\pi\mu}}\frac{1}{(k_BT)^2}\int_{\varepsilon_s}^{\infty}e^{-\varepsilon/k_BT}\times\sigma_{j_1j_2\to j_1'j_2'}(\varepsilon)\varepsilon d\varepsilon$, where k_B is Boltzmann constant, μ is reduced mass of the molecule-molecule system and ε_s is the minimum kinetic energy for the levels j_1 and j_2 to become accessible. Additionally, for comparison purposes, H_2+H_2/HD calculations for a few selected rotational transitions have also been performed. These energy transfer collisions are of fundamental importance in astrophysics, see for example Refs.[5-7],

papers 4 and Ref. [8]. The hydrogen molecules HT and DT are treated as rigid rotors in our calculations. A pronounced isotope effect is identified in the title collisions.

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Tuesday Parallel Session: Few-body systems (Atrium Maximum) / 153

Measurement of the alpha-particle Monopole Transition Form Factor at MAMI

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In this presentation, a new measurement of the monopole transition form factor of the ground state to the first exited state of the alpha-particle will be presented 1. The precision of the measurement exceeds significant the precision of existing data sets and allows for the determination of two coefficients in a low energy expansion.

The result are confronted with state-of-the art theoretical calculations including modern nuclear forces, which nevertheless fail to reproduce the data by a factor of about two.

In the outlook, the few body program at the MAGIX experiment at the new MESA accelerator will be presented. This experiment will be optimized to measure the low energy excitation of light gas targets with high resolution spectrometers using the high beam current of an energy recovery linac.

1 Phys. Rev. Lett. 130, 152502 (2023)

Tuesday Parallel Session: AMO Systems (Linke Aula) / 145

Discrete scale symmetry and non-integer dimensions in few-body systems at the unitarity limit

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Discrete scale symmetry exhibited by few-particle systems for resonant s-wave interactions is affected by squeezing or by reducing the embedding dimension. The Efimov geometrical separation ratio between the AAB bosonic bound states energies increases as the system is squeezed until the geometrical spectrum disappears for a critical non-integer dimension. This is found either by solving the generalization of the Skornyakov and Ter-Martirosyan equations in non-integer dimensions or by implementing, in configuration space, the Bethe-Peierls boundary conditions at zero-range.

Results for the one-body momentum density focusing on the dependence of the contacts on the non-integer dimension will be shown. Mass imbalanced systems with different cold-atom compositions are then explored. Going to more particles, we also provide a general discussion on how the discrete scaling symmetry presents itself in limit-cycles for particular bosonic systems. Following that, and beyond three particles, we will present results obtained by means of the Born-Oppenheimer approximation for two-heavy impurities immersed in squeezed light-boson systems in non-integer dimensions, which will be finally illustrated for lithium and two caesium atoms mixtures.

Tuesday Parallel Session: Reactions (AudiMax) / 29

Recent advances in microscopic optical potentials for nuclear reactions

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The optical potential is a well-known and successful framework to describe nucleon-nucleus scattering processes. Within this approach it is possible to compute the scattering observables for elastic processes across wide regions of the nuclear landscape and extend its usage to inelastic processes and other types of reactions such as nucleon transfer, capture or breakup. A phenomenological approach is usually preferred to achieve a good description of the data; however, it lacks predictive power due to the presence of free parameters contained in the model that need to be fixed. With the upcoming facilities for exotic nuclei, such as FRIB, we strongly believe that a microscopic approach, completely free from phenomenology, will be the preferred tool to make reliable predictions, assess the unavoidable approximations, and provide a clear physical interpretation of the process under consideration. The Watson multiple scattering theory provides a successful framework to derive such optical potential for the intermediate energy regime, which is obtained as the folding integral of the nucleon-nucleon scattering matrix and the nuclear density, that represent the two fundamental ingredients of the model. After two decades of advances in theoretical nuclear physics, it is now possible to calculate these two quantities using the same inter-nucleon interaction that is the only input of our calculations. Despite the good results obtained so far, there are still several extensions of the model currently under development, such as the inclusion of medium effects for low-energy calculations, the extension to heavier systems, the inclusion of double scattering effects, and the extension to inelastic scattering. The last one is particularly important for an entire class of experiments that usually need the subtraction of inelastic contributions to perform a correct data analysis. A summary of the past achievements along with a detailed explanation of the new challenges will be presented.

Tuesday Parallel Session: Few-body systems (Atrium Maximum) / 56

Program of Compton Scattering Studies on Light Nuclei at HIGS

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The High Intensity Gamma-Ray Source (HIGS) at Duke University delivers monoenergetic photon beams with high linear or circular polarization by backscattering of free-electron laser (FEL) photons 1. To exploit the unique capabilities of this facility, we are conducting an ambitious program of Compton scattering studies on light nuclei aimed at determining the nucleon electromagnetic polarizabilities. Our cryogenic target can liquefy ^{1}H, ^{2}H, and ^{4}He for the purpose of Compton scattering,

and we have recently upgraded the cooling (and recovery) system to enable us to liquefy ^{3}He as well. To measure the scattered photons, we have implemented two of the world's largest NaI detectors – BUNI (from Boston University) and DIANA (from University of Kentucky) – each having better than 2% photon energy resolution. We are also using an array of medium-sized NaI detectors to enhance our angular coverage and to serve as out-of-plane detectors for polarized photon measurements.
Initial experiments have been performed on ^{2}H and ^{4}He below 85 MeV with unpolarized photons [2,3]. Experiments on ^{2}H will elucidate the EM polarizabilities of the neutron (α_n and β_n) and provide high precision data for comparison with chiral Effective Field Theory calculations 4. We have obtained data on ^{2}H at two incident photon energies covering two backward angles ($150°$ and $115°$) with BUNI and DIANA and four forward angles with the other NaI detectors. The analysis of these two data sets is nearing completion.
In our first polarization experiment, we measured the photon beam asymmetry using linearly polarized photons at 81 MeV on the proton at three polar angles ($55°$, $90°$, $125°$). These data enabled us to accomplish one of the first extractions of the proton polarizabilities (α_p and β_p) from polarized data [5], and our results are compared to independent data from Mainz [6].
An approved experiment for unpolarized Compton scattering on ^{3}He will constitute the first Compton data ever taken on a ^{3}He target and will start running in Summer 2023. This will provide an alternate means of accessing the neutron EM polarizabilities in an entrance channel independent of the usual deuteron experiments. This is the motivation for the cryotarget upgrade to enable liquefying ^{3}He, which requires a lower base temperature than ^{4}He.
Overall, our Compton scattering program at HIGS is fairly broad, and this talk will provide an overview of the experimental activities. The results of our recent work will be reviewed, some preliminary data from our ongoing measurements will be shown, and prospects for future experiments and their impact will be discussed.

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Tuesday Parallel Session: AMO Systems (Linke Aula) / 7

Two- and Three-Particle Complexes with Logarithmic Interaction: Compact Wave Functions for Two-Dimensional Excitons and Trions

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In the framework of the effective mass approximation and assuming a logarithmic interaction between constituent charged particles, compact and locally accurate wave functions that describe bound states of the two-particle neutral and three-particle charged complexes in two dimensions are designed. Prime examples of these complexes are excitons and trions that appear in monolayers of Transition-Metal DichalCogenides (TMDCs). In the case of excitons, these wave functions led to 5-6 correct decimal digits in the energy and the diamagnetic shifts. In addition, it is demonstrated that they can be used as zero-order approximations to study magnetoexcitons via perturbation theory in powers of the magnetic field strength. For the trion, making a comparison with experimental data for concrete TMDCs, we established that the logarithmic potential leads to binding energies <=

25% greater than experimental ones. Finally, the structure of the wave function at small distances is established for excitons whose carriers interact via the Rytova-Keldysh potential.

This talk will be based on the forthcoming paper arXiv:2302.11928

Tuesday Parallel Session: Reactions (AudiMax) / 48

Many-channel cluster microscopic theory of resonance states and scattering in ^{9}Be and ^{9}B

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We applied a many-configurational microscopic cluster model to study the nature of high-energy resonance states in ^{9}Be and ^{9}B near ^{7}Li+d and ^{7}Be+d decay thresholds and to reveal the influence of the states on the astrophysical S-factors of the reactions ^{7}Li$(d,n)\,\alpha\alpha$ and ^{7}Be$(d,p)\,\alpha\alpha$ related to the cosmological lithium problem. Parameters of the above-mentioned resonance states in ^{9}Be and ^{9}B were established. The dominant decay channels were determined for each resonance state.

Two coupled three-cluster configurations $\alpha+\alpha+n$ and $\alpha+d+^3$H in ^{9}Be and $\alpha+\alpha+p$ and $\alpha+d+^3$He in ^{9}B were considered to invoke dominant binary channels in ^{9}Be and ^{9}B, respectively. The model is an extension of the three-cluster model, formulated in 1, which uses Gaussian and Oscillator basis to describe the internal structure of the binary systems and their asymptotic behavior. The model suggests a realistic description of energy spectrum of ^{9}Be and ^{9}B in a wide range of energy, where many decay channels of the nuclei are open.

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Tuesday Parallel Session: Few-body systems (Atrium Maximum) / 67

The three-proton correlation function

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The p-p-p correlation function is defined as

C$_{123}(Q) = \int \rho^5 d\rho\, d\Omega\, S_{123} |\Psi_s|^2 where \rho, \Omega$ are the hyperspherical coordinates and $\hbar^2 Q^2/M$ is the total energy of the system. The source is represented by a gaussian hypercentral profile

S$_{123} = \frac{1}{\pi^3 \rho_0^6} e^{-\rho^2/\rho_0^2}$

The three-proton wave function, Ψ_s, is calculated using the hyperspherical adiabatic basis

$\Psi_s = \frac{1}{(Q\rho)^{5/2}} \sum_{J^\pi,K} \sum_\nu u_\nu^K(\rho) \phi_\nu^{J^\pi}(\rho,\Omega)$

where $\phi_\nu^{J\pi}$ are the adiabatic basis elements having total angular and parity J^π, K is the grand angular quantum number labeling the regular channel in the asymptotic behavior of the hyperradial functions u_ν^K.

The finite range character of the source allows to use the free scattering wave function in the description of the three protons in most of the adiabatic channels except the lowest ones. Moreover, the proper antisymmetrization of the state has been performed considering the different possible combinations of symmetries in the spatial and spin parts of the wave function. In this preliminary study, the interaction between nucleons is modeled using a two-body Gaussian potential with parameters, range and strength, fixed to reproduce the pp scattering length and effective range. Moreover, the Coulomb interaction has been considered in its hypercentral form.

The correlation function can be measured using femtoscopy techniques at LHC by the ALICE collaboration. The obtained results are compared to the available data and have to be considered as a preliminary step in the complete treatment of the nuclear interaction and the asymptotic p-p-p scattering wave function.

Tuesday Parallel Session: AMO Systems (Linke Aula) / 128

Quantum-chaotic behavior of a particle interacting with independent scatterers

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A gas of interacting particles is a paradigmatic example of chaotic systems. It is shown 1 that, even if all but one particle are fixed in generic positions, the excited states of the moving particle are chaotic. They are characterized by the number of principal components (NPC)—the number of integrable system eigenstates involved into the nonintegrable one, which increases linearly with the number of strong scatterers. This rule is a particular case of the general effect of an additional perturbation on the system chaotic properties. The perturbation independence criteria supposing the system chaoticity increase are derived here as well. The effect can be observed in experiments with photons or cold atoms as the decay of observable fluctuation variance, which is inversely proportional to NPC and, therefore, to the number of scatterers. This decay indicates that the eigenstate thermalization is approached. The results are confirmed by numerical calculations for a harmonic waveguide with zero-range scatterers along its axis 2. Millions of eigenstates are calculated with an effective numerical method, based on properties of high-rank separable perturbations.
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Tuesday Parallel Session: Reactions (AudiMax) / 108

Measurement of spin correlation coefficient Cy,y for proton-3He elastic scattering

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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. Proton-^{3}He (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 p-^{3}He elastic scattering with the polarized ^{3}He target at intermediate energies ($E/A \geq 65$ MeV).

In the conference we present the measured spin correlation coefficient $C_{y,y}$ for p-^{3}He elastic scattering at 100 MeV at the angles $\theta_{\mathrm{c.m.}} = 46.9°–149.2°$ in the center of mass system 4. The experiment was performed using a 100 MeV polarized proton beam in conjunction with the polarized ^{3}He target at RCNP, Osaka University in Japan. Proton beams were injected to the target, and scattered protons were detected by using E-ΔE detectors which consisted of plastic and NaI(Tl) scintillators. The data are compared with rigorous numerical calculations based on realistic NN potentials as well as with the Δ-isobar excitation. The obtained results indicate that the $C_{y,y}$ expands the knowledge of the nuclear interactions with Δ-isobar or those including 3NFs that are masked in nucleon-deuteron elastic scattering.

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Tuesday Parallel Session: AMO Systems (Linke Aula) / 152

Linewidths of electron-impurity resonant states in semiconductor quantum wells

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Resonances in open quantum systems have been actively studied since the very birth of quantum mechanics [1,2]. Their linewidth broadenings caused by the finite lifetimes can be analytically estimated only in a few particular cases 3. In this sense, the analytically estimated linewidth broadenings of the electron-impurity resonant states by Monozon and Schmelcher 4 is a remarkable theoretical result which can be used as a reliable reference for qualitative estimations [5].
In the current report, using the complex-scaling calculations as a quantitative insight, we show how

the qualitative theoretical estimations made by Monozon and Schmelcher for the electron-impurity in very narrow quantum wells (QWs) can be improved and generalized to more practical case of the QW widths of order of the electron-impurity's Bohr radius [6]. In particular, we show that discovered by Fano [7] and confirmed by Monozon and Schmelcher the fourth-power scaling of the linewidth broadenings with respect to QW width holds only for very narrow QWs which are hardly be practically used in the spectroscopy of heterostructures [5]. In contrast to 4, we analytically and numerically demonstrate that for the real QWs the scaling of the linewidths with respect to the QW width appears to be linear. As a result, our studies shed light to the linewidth broadenings in the regimes inaccessible by the Fano theory of resonances. Moreover, many calculated resonant states of electron-impurity and electron-hole pairs in semiconductor QWs as well as their dependencies on the QW width as a parameter allow us to study formation of the exceptional points as a degeneracy of resonances in such systems [8,9].

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Tuesday Parallel Session: Few-body systems (Atrium Maximum) / 90

Lifetime-analysis of three-body resonance states

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We theoretically study the lifetimes of three-body resonance (quasi-bound) states. In particular, we are interested in how these lifetimes vary between one-dimensional and three-dimensional geometries. As an example, we consider a two-component three-body system with short-range pair-interactions that support several two-body bound states. Three-body resonance states are discrete eigenstates of the three-body Hamiltonian whose energies lie above one (or more) two-body bound state energies, i.e., they live within a continuum created from one of the lower-lying two-body thresholds. This can open a decay channel into a deeply bound dimer and a free particle, which manifests itself in an imaginary part of the energy eigenvalue. Recently, we have analyzed 1 this situation in a one-dimensional geometry, considering solely real energies and we have found a behaviour which converged smoothly and accurately to the one of three-body bound states. This has raised the question whether in the one-dimensional case the quasi-bound states are in fact bound states with real energy who are embedded in the continuum. With our current research we aim to shed more light onto this question by performing ab-initio calculations considering complex energies, which allows us to make statements about the lifetimes of these states.

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Tuesday Parallel Session: Reactions (AudiMax) / 106

Few nucleons scattering in pionless effective field theory

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We present a comprehensive theoretical study of low-energy few nucleon scattering for systems with A≤4. To this end, we utilize pionless effective field theory, which we employ at next-to-leading order. Our results indicate that the theory provides accurate predictions for the low-energy scattering parameters in all studied channels. These predictions match the best experimental evaluations and theoretical calculations available. Additionally, we confirm the recent finding that a four-body force is required at the next-to-leading order, which is only present in a single spin-isospin channel for nuclear systems.

Tuesday Parallel Session: Few-body systems (Atrium Maximum) / 122

Examples and counterexamples of renormalizability of an EFT in the nonperturbative regime

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An important feature of an effective field theory is its renormalizability, which implies that
one can apply a certain power counting to renormalized quantities and perform a systematic expansion of the calculated observables in terms of some small parameter.
When nonperturbative effects become relevant, the requirement of the renormalizability imposes nontrivial constraints on a choice of the effective interaction and the renormalization scheme. We discuss several instructive examples and counterexamples
of renormalizability to illustrate potential issues one has to deal with in the realistic calculations such as nuclear chiral EFT.

Tuesday Parallel Session: AMO Systems (Linke Aula) / 63

Three-body recombination between helium and silver atoms at cold collision energies

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Three-body recombination between helium and silver atoms is studied using hyperspherical coordinates. The three-body Schrodinger equation, represented in the slow variable discretized approach at short distances and in the adiabatic method at large distances 1 and using the potential-energy surface represented as the addition of realistic He-He and He-Ag pair interaction potentials 2, is solved using the R-matrix propagation method 4, in order to numerically calculate the three-body recombination rates for the the He+He+Ag→He_2+Ag and He+He+Ag→HeAg+He processes. Not only zero-angular momentum $J = 0$ states but also nonzero $J > 0$ states are considered in the calculations, allowing for treating the recombination processes at collision energies beyond the threshold

regime. The results of our calculations will be presented and discussed.
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Tuesday Parallel Session: Reactions (AudiMax) / 42

Meson exchange currents in the clothed-particle representation

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We would like to show one more fruitful application of the clothed-particle notion in the theory of electromagnetic interactions with nuclei. A constructing element of our consideration is the Campbell–Hausdorff expansion formula applied to the initial Noether current density operator

$J^\mu(0) = e^R J_c^\mu(0) e^{-R} = J_c^\mu(0) + [R, J_c^\mu(0)] + \frac{1}{2}[R,[R, J_c^\mu(0)]] + \ldots,$

(see Eq. (5.16) in 1), where $J_c^\mu(0)$ is the current density operator in which the bare operators $\{\alpha\}$ are replaced by the clothed ones $\{\alpha_c\}$ and R the corresponding generator of the unitary clothing transformation. This decomposition can be split into the one-nucleon

$J_{1N}^\mu(0) = \int d\mathbf{p}' d\mathbf{p}\, F^\mu(\mathbf{p}', \mathbf{p}) b_c^\dagger(\mathbf{p}') b_c(\mathbf{p}),$

two-nucleon

$J_{2N}^\mu(0) = \int d\mathbf{p}_1' d\mathbf{p}_2' d\mathbf{p}_1 d\mathbf{p}_2\, F_{MEC}^\mu(\mathbf{p}_1', \mathbf{p}_2', \mathbf{p}_1, \mathbf{p}_2) b_c^\dagger(\mathbf{p}_1') b_c^\dagger(\mathbf{p}_2') b_c(\mathbf{p}_1) b_c(\mathbf{p}_2)$

and more complicated current density operators, whose matrix elements being sandwiched between the strong Hamiltonian eigenvectors from the subsector of the full Fock space without clothed mesons determine the radiative amplitude of interest. Transition to these eigenvectors is regulated via the Okubo-Glöckle method [2, 3]. Special attention is paid to finding the two-nucleon contributions

$J_{2N}^\mu = \frac{1}{2}[R,[R, J_c^\mu(0)]]_{\text{two-nucleon}} + O(g^4)$

that can be interpreted as a meson exchange current. It is important to stress that the many-nucleon currents introduced in such a way do not depend on the choice of states with which we calculate the matrix elements. The new meson exchange currents have been compared with those obtained relying upon the Dyson-Feynman series for the S operator in the bare-particle representation. In our other contribution to the conference, we would like to show the application of these new currents to calculate the deuteron electromagnetic form factors.

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164

Popular Lecture: A Sun on Earth - Nuclear Fusion as a CO2-free energy source

In times of a shift towards a low CO2 energy supply and boosted by the recent success of laser fusion, the advantages of nuclear fusion in general has come into the focus of politics and private investors as an attractive energy source. This talk introduces the concept of magnetic fusion and outlines the path to a fusion reactor. The perspectives of magnetic fusion will be compared with those of laser fusion and the concepts of startups. The role of plasmas, in which energy is obtained from the fusion of hydrogen isotopes, and their physical properties are explained.

Wednesday Plenary Session (AudiMax) / 149

Baryon-Baryon Interactions from Lattice QCD

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The formalism of finite-volume quantisation allows for a rigorous treatment of hadronic resonances and interactions in lattice QCD. I review the status of calculations of baryon-baryon states by the Mainz and BaSc collaborations, with a particular focus on the H dibaryon and nucleon-nucleon interactions. The binding energy of the H dibaryon in
three-flavour QCD in the continuum limit has stabilised around values of 4-5 MeV. For nucleon-nucleon scattering in the same setup we can resolve S, P, D and F waves, using data from many lattice spacings and volumes. In the deuteron and dineutron S waves, virtual bound states are observed. Overall we find that discretisation effects tend to strengthen baryon-baryon interactions.

Wednesday Plenary Session (AudiMax) / 65

Near-term quantum simulation of nuclear dynamics

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Quantum computers hold great promise for exact simulations of nuclear dynamical processes (e.g., scattering and reactions), which are paramount to the study of nuclear matter at the limit of stability and in the formation of chemical elements in stars. However, achieving this goal presents both conceptual and technological challenges, from formulating model mapping, quantum algorithms and measurement schemes for the desired nuclear dynamics, to developing noise-resilient protocols that will enable useful results with near term quantum technologies, to preparing for fault-tolerant quantum computers and more. In this talk I will focus on hybrid quantum classical co-processing schemes and digital-analog simulations leveraging hardware-aware and problem-informed custom gates. I will show how such protocols can be used in the near term to achieve noise-resilient simulations of real-time evolution and state preparation, characteristic components in quantum simulation of scattering and other dynamical processes.

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Wednesday Plenary Session (AudiMax) / 119

Probing fundamental physics with Antihydrogen

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Antihydrogen, the bound state of an antiproton and a positron is an eminent system for testing fundamental symmetries of nature. It is calculable from first principles, and the standard model predicts

that its energy spectrum should be identical to that of hydrogen to any precision. Its neutrality lends itself to also be a probe of the weak equivalence principle for antimatter free fall.

The ALPHA collaboration, the only group to consistently trap antihydrogen, is pursuing an extensive programme where we probe the internal states of antihydrogen as well as it's gravitational behaviour. The presentation will include the latest updates from the experiment including the recent successful laser-cooling of trapped antihydrogen and recent attempts at measuring the influence of Earth's gravity on trapped antihydrogen.

Wednesday Plenary Session (AudiMax) / 8

Ab initio prediction of α(d,γ)6Li at Big Bang nucleosynthesis energies

Author: Chloë Hebborn[1]

Co-authors: Guillaume Hupin [2]; Kostas Kravvaris [3]; Peter Gysbers [4]; Petr Navratil [4]; Sofia Quaglioni [3]

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The radiative capture α(d,γ)6Li is the dominant process in the Big Bang Nucleosynthesis (BBN) of 6Li. It therefore strongly influences the abundance ratio of 6Li/7Li, for which observational data are three orders of magnitude higher than BBN predictions. Because of the low cross section and the large experimental uncertainties, it is crucial to have accurate predictions. In this talk, I will present an ab initio calculation of α(d,γ)6Li, where all nucleons are active and interacting through chiral-EFT nucleon- and three-nucleon forces. After reviewing the ab initio no-core shell model with continuum method, I will show our results 1 which are in excellent agreement with the recent LUNA data 2. I will also discuss the importance of each electromagnetic transitions on α(d,γ)6Li at BBN energies.

1 C. Hebborn, G. Hupin, K. Kravvaris, S. Quaglioni, P. Navrátil and P. Gysbers, Phys. Rev. Lett. 129, 042503 (2022).

2 Anders et al. Phys. Rev. Lett. 113, 042501 (2014).

*This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics, under the FRIB Theory Alliance Award No. DE-SC0013617 and by LLNL under Contract No. DE-AC52-07NA27344.

Wednesday Plenary Session (AudiMax) / 136

Neutrinoless double beta decay in effective field theory

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Neutrinoless double beta decay (NLDBD) is the most sensitive probe of lepton-number violation. Its discovery would be a clear signal of physics beyond the Standard Model, confirm the Majorana nature of neutrinos, and provide insight into scenarios of baryogenesis through leptogenesis. In

this talk, I will show how the calculation of the decay rate can be organized in a systematic way using effective-field-theory techniques. This will allow us to assess the impact of LNV interactions, originating at energies above the electroweak scale, on NLDBD, which takes place at nuclear scales. I will pay particular attention to the matching of the effective LNV interactions onto chiral effective theory, as well as the needed hadronic and nuclear matrix elements. Finally, I will give an overview of the resulting constraints on the sources of LNV.

Wednesday Plenary Session (AudiMax) / 24

From Few to Many: Recent Advances in Ab Initio Nuclear Structure Calculations

Author: Alexander Tichai[1]

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A first-principle description of atomic nuclei requires the use of two- and three-nucleon interactions combined with an efficient many-body solution for the nuclear state. In particular the treatment of chiral three-body operators provides a significant computational challenge due to high memory requirements. In the first part of my talk, I will discuss two complementary ways to cope with that challenge by approximating chiral three-nucleon forces, either from low-rank matrix factorizations 1 or normal-ordering techniques 2. The two frameworks are benchmarked in atomic nuclei, from triton up to lead.
In the second part, I will introduce the density matrix renormalization group (DMRG) approach and show how the DMRG outperforms traditional diagonalization-based approaches by using a factorized matrix-product-state representation of the many-body wave function. I will further discuss the use of entanglement entropies as a proxy for nuclear shell effects along medium-mass isotopic chains 3.
Eventually, the combination of accurate nuclear interactions with scalable many-body approaches will pave the way for further high-precision calculations in exotic nuclei.

1 A. Tichai, P. Arthuis, M. Heinz, K. Hebeler, J. Hoppe, T. Miyagi and A. Schwenk (in preparation, 2023)
2 K. Hebeler, V. Durant, J. Hoppe, M. Heinz, A. Schwenk, J. Simonis and A. Tichai, Phys. Rev. C 107, 024310 (2023)
3 A. Tichai, S. Knecht, A.T. Kruppa, Ö. Legeza, C.P. Moca, A. Schwenk, M.A. Werner and G. Zarand, arXiv:2207.01438 (2022)

Thursday Plenary Session (AudiMax) / 129

Chiral symmetry and nuclear interactions

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About three decades ago, Steven Weinberg came up with a beautiful idea of using the effective chiral Lagrangian to derive nuclear interactions, which has had a long lasting impact on nuclear physics. I will discuss achievements and challenges in advancing chiral effective field theory into a precision tool to study low-energy nuclear structure and reactions.

Thursday Plenary Session (AudiMax) / 16

Experiments of Few-Nucleon Scattering to Explore Three-Nucleon Forces

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Understanding the nuclear properties from bare nuclear forces is one of the main topic in nuclear physics. The importance of three-nucleon forces ($3N$Fs), which appear when more than two nucleons interact, has been indicated in various nuclear phenomena, such as few-nucleon scattering, binding energies of nuclei, and equation of state of nuclear matter.
Nucleon-deuteron (Nd) scattering, where numerically exact solutions of the corresponding Faddeev equations for any $2N$- and $3N$-forces are feasible, offers a good opportunity to study dynamical aspects of $3N$Fs, that are momentum, spin, and isospin dependences. 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 $3N$Fs. $3N$F effects are expected to be sizable in the four-nucleon 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.
With the aim of exploring the 3NFs experimental programs of Nd scattering as well as proton-^{3}He scattering using the polarized beam and target systems are on going at RIKEN, RCNP, and CYRIC in Japan.
In this conference we review these experiments and touch upon our future plan.

Thursday Plenary Session (AudiMax) / 41

Few-Body Physics in Finite Volume

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Simulating quantum systems in a finite volume is a powerful theoretical tool for extracting information about them. The observation that the real-world properties of states are encoded in how their discrete energy levels change with the size of the volume gives rise to a versatile approach that is relevant not only for nuclear physics, where lattice methods are now able to calculate few- and many-nucleon states, but also for other fields such as simulations of cold atomic systems.

This talk gives an overview of recent progress that has been achieved in the field of finite-volume relations and calculations. In particular, it discusses efficient techniques for simulating few-body systems in periodic boxes and presents finite-volume relations for charged particles, which are of particular relevance for nuclear physics because the vast majority of systems of interest in this field involves more than one charged particle.

Thursday Plenary Session (AudiMax) / 125

Halo and Pionless Effective Field Theories for Describing Nuclear Structures and Reactions

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Rare Isotope Beam (RIB) facilities provide a unique opportunity to investigate the structures and reactions of atomic nuclei near the drip line. Experiments have observed that some light nuclei with excess neutron or proton numbers exhibit a molecular-like structure consisting of a tightly bound core surrounded by a few loosely bound halo nucleons referred to as halo nuclei. The stability of these structures and their corresponding reaction mechanism play significant roles in the generation of nuclei in astrophysical environments.

The combination of effective field theory (EFT) with nuclear cluster models provides an excellent description of the structure and reaction of halo nuclei. This theory describes halo nuclei in effective core and halo-nucleon degrees of freedom, with interactions among each cluster represented by a series of contact interactions. Sharing similar formalism with the pionless EFT, the halo EFT allows for the analysis of renormalization in non-perturbative regimes, unveils novel near-threshold features in halo nuclei, and allows a model-independent systematic improvement of theoretical accuracies.

We introduce the foundations of halo EFT and its application in describing halo nuclei structures, photo-induced fragmentation reactions, neutron capture reactions, and other nuclear reaction processes 1. A novel power counting approach has been developed in our recent work to describe shallow P-wave resonances using nonlocal momentum-dependent contact interactions 2. This method has been applied to the ^{6}He system consisting of two neutrons and an alpha particle, accurately reproducing the neutron-alpha elastic scattering phase shift near the ^{5}He P-wave resonance as well as displaying the same renormalizability feature in calculating the ^{6}He bound state as the energy-dependent interaction formalism [3,4].

Furthermore, the formalism has been extended to study the doubly virtual Compton scattering process in deuteron. This study is critical for calculating the two-photon-exchange nuclear-structure corrections to the atomic spectrum in both electronic and muonic deuterium [5]. Combined with accurate spectroscopy measurements, the two-photon exchange calculation is instrumental for high-precision determination of nuclear charge and magnetic radii.

1 H.W. Hammer, C. Ji and D.R. Phllips, J.Phys. G 44, 103002 (2017).
2 Q. Li, S. Lyu, C. Ji and B. Long, arXiv:2303.17292 [nucl-th].
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[5] S.B. Emmons, C. Ji and L. Platter, J. Phys. G 48, 035101 (2021).

Thursday Plenary Session (AudiMax) / 156

Nonrelativistic conformal field theory and nuclear reactions

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We develop a formalism of nonrelativistic conformal field theory, which is then used to describe neutrons at low energies. We show that the rates of nuclear reactions with emission of a few neutrons in the final state show a power-law behavior in the kinematic region where the emitted neutrons have almost the same momentum. We show how corrections to this power-law behavior can be computed using conformal perturbation theory.

Thursday Parallel Session: Few-body systems (Atrium Maximum) / 33

Proton structure in and out of muonic hydrogen

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In this talk, I would like to discuss the theory of light muonic atoms in view of upcoming experiments, e.g., the measurement of the muonic-hydrogen ground-state hyperfine splitting with ppm accuracy. A particular focus will be on predictions of the two-photon-exchange corrections in muonic hydrogen and deuterium. Furthermore, I would like to discuss the hadronic-vacuum-polarization corrections to the hyperfine splitting.

Thursday Parallel Session: Few-body systems and halo nuclei (Linke Aula) / 30

Near threshold resonances and exotic decay of 11Be

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The ¹¹Be neutron halo nucleus decays into ¹⁰Be with a rate that exceeds expectations. Neutron disappearance into dark matter, beta decay of a halo neutron, or beta delayed proton decay have been offered as explanations. The discovery of an exotic near-threshold resonance supports the latter. The observations, however, also highlight a remarkable and not fully understood manifestation of quantum many-body physics near decay thresholds that includes restructuring of states due to decay, quantum features of sequential decay, and interplay between different channels including alpha and neutron decays.
In this presentation along with the specific case of ¹¹Be we discuss the theory of weakly bound and unbound quantum many-body systems.

Thursday Parallel Session: AMO Systems (AudiMax) / 18

Impurity as a witness of a few- to many-body crossover in low-dimensional degenerate gases

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Impurity atoms or molecules are often used by theorists and experimenters for studying a crossover from few to many-body physics in condensed matter systems, such as superfluid helium and ultracold degenerate gases. The presentation will offer a few examples of such studies in the context of quasi-one- and two-dimensional cold-atom systems with impurities. These examples provide insight into the limiting cases of the Bose polaron and angulon problems, which are characterized by the 'many-body dressing'of the impurity. Dependence of this dressing on a number of particles in the bath can be used to quantify a few- to many-body crossover for some ground-state properties of the system.

Thursday Parallel Session: Few-body systems (Atrium Maximum) / 144

Nuclear structure effects in the Lamb shift of muonic deuterium in pionless effective field theory

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In this presentation, I will discuss the results for the $O(\alpha^5)$ effects of the nuclear structure, the two-photon-exchange (TPE) corrections, in the energies of S-levels in muonic (μD) and ordinary (D) deuterium. They were recently obtained at next-to-next-to-next-to-leading order (N3LO) in the pionless effective field theory (EFT). At this order, there is a single low-energy constant that is fitted to the hydrogen-deuterium isotope shift. This constant generates a correlation between the deuteron charge and Friar radii. This correlation can be used to judge how well a deuteron charge form factor parametrization describes the low-virtuality properties of the deuteron. The pionless EFT evaluation of the TPE corrections in μD and D allows one to extract the deuteron charge radius r_d from the μD Lamb shift, the $2S-1S$ transition in D, and the $2S-1S$ hydrogen–deuterium isotope shift in a unified approach, giving values of r_d that are in agreement [1,2]. I will also discuss the role of the TPE corrections generated by the structure of the individual nucleons.

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Thursday Parallel Session: AMO Systems (AudiMax) / 146

Structure and field-induced dynamics of small helium clusters

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Co-authors: Dörte Blume [2]; Qingze Guan [3]; Reinhard Dörner [1]

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Small helium clusters are peculiar few body quantum systems. The helium dimer has a single weakly bound state of a huge spatial extent. About 80% of its probability distribution resides in the classically forbidden tunneling region 1. This is why such objects are termed "quantum halos". The helium trimer has two bound states, excited one of which is of Efimov nature 2. We utilize laser-triggered Coulomb explosion imaging for measuring spatial probability distributions of these quantum objects. Application of an additional laser pulse in a pump-probe manner allows us to observe the structural response dynamics of small helium clusters upon interaction with a strong laser field on a picosecond time scale.
The results of our experimental approach on He2 3 and He3 will be discussed.

1 S. Zeller et al., PNAS 113(51), 14651 (2016). DOI: 10.1073/pnas.1610688113
2 M. Kunitski et al., Science 348(6234), 551 (2015). DOI: 10.1126/science.aaa5601
3 M. Kunitski et al., Nature Physics 17(2), 174 (2021). DOI: 10.1038/s41567-020-01081-3

Thursday Parallel Session: Few-body systems and halo nuclei (Linke Aula) / 120

E1 strengths of two-neutron halo nuclei from halo effective field theory

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Due to their large spatial extension, two-neutron halo nuclei display a significant enlargement in the low-energy $E1$ strength distribution parameterizing the Coulomb dissociation cross section. Thereby the $E1$ strength is an important observable for halo nuclei, and by comparing theoretical calculations with experimental data, we can test our understanding of these exotic nuclear systems.

In this talk, I will present results from halo effective field theory (EFT) for the $E1$ strength distribution of the two-neutron halo nucleus ^{11}Li [M. Göbel et al., Phys. Rev. C 107, 014617 (2023)]. The distribution is obtained based on a three-body description of the ^{11}Li ground state via Faddeev equations. Final-state interactions (FSIs) subsequent to the $E1$ breakup are taken into account using a newly developed scheme allowing for the perturbative inclusion of multiple FSIs while conserving unitarity. This method uses the Moller scattering operators.

The calculations indicate that neutron-neutron FSI is the dominant FSI. Comparison with experimental data from RIKEN [T. Nakamura et al., Phys. Rev. Lett. 96, 252502 (2006)] shows good agreement within the EFT's uncertainty bands. Moreover, we also compare our approach with theory work by Hongo and Son [M. Hongo, D. T. Son, Phys. Rev. Lett. 128, 212501 (2022)], which employed different assumptions about the ^{11}Li halo. Finally, the $E1$ strength of ^{6}He in Halo EFT will be discussed.

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Thursday Parallel Session: Few-body systems and halo nuclei (Linke Aula) / 84

Wilsonian RG with a multitude of cutoffs applied to halo EFT

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Generalization of the Wilsonian renormalization group approach to few-body problems by introducing a multitude of cutoff parameters has been suggested in Ref. 1. In the framework of an effective field theory, similarly to the Gell-Mann and Low renormalization group, this approach offers the freedom of choosing optimal renormalization scheme in multi-dimensional space of renormalization scale parameters. Advantages of the generalized scheme compared to the standard Wilsonian renormalization group approach will be considered for an effective field theory of fine tuned halo states.

1 E.Epelbaum, J.Gegelia and U.-G. Meißner,
"Wilsonian renormalization group and the Lippmann-Schwinger equation with a multitude of cutoff parameters,"
Commun. Theor. Phys. **69**, no.3, 303 (2018)

Thursday Parallel Session: Few-body systems (Atrium Maximum) / 95

The hyperfine splitting in light muonic atoms

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[1] *Johannes Gutenberg-Universität Mainz*

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Spectroscopy in light muonic atoms provides a precision probe of the electroweak structure of light nuclei and has the potential to elucidate new physics. However, the uncertainties in the energy levels of muonic atoms are currently dominated by nuclear theory. In particular, theoretical predictions of the nuclear polarizabilities entering the two-photon exchange contribution to the energy levels must be improved. Here, we employ tools from effective field theory to investigate the two-photon exchange contribution to the hyperfine splitting of muonic deuterium.

Thursday Parallel Session: AMO Systems (AudiMax) / 100

Exotic pairing in few-body ultracold systems

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A system of a few attractively interacting atoms of lithium in one-dimensional harmonic confinement is investigated. Non-trivial interparticle correlations induced by interactions in a particle-imbalanced system are studied in the framework of the noise correlation. In this way, it is shown that evident signatures of strongly correlated fermionic pairs in the Fulde-Ferrell-Larkin-Ovchinnikov (FFLO) state are present in the system and they can be detected by measurements directly accessible within state-of-the-art techniques. The results convincingly show that the exotic pairing mechanism is a very universal phenomenon and can be captured in systems being essentially non-uniform and far from the many-body limit.

Thursday Parallel Session: Few-body systems and halo nuclei (Linke Aula) / 135

Leading-order EFT interactions for shallow states in different partial waves –avoiding the energy dependence

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The leading-order (LO) Halo EFT interactions for shallow states beyond S-waves exhibit non-negligible energy dependencies leading to difficulties related to the normalization. Recently, purely momentum-dependent potentials with square-root form factors have been investigated for the NN and the 3N system [e.g., S. R. Beane et al. (2022), R. Peng et al. (2022) , V. S. Timoteo et al. (2023)]. They have also been applied to the two-neutron halo nucleus ^{6}He [Q. Li et al. (2023)].

In this talk, I will present our work on developing a scheme of purely momentum-dependent LO potentials for shallow states in different partial waves. Thereby, we present a method to determine the minimal number of coupling constants necessary to renormalize the theory for a shallow state in an arbitrary partial wave. This in turn defines the LO potential which reproduces the effective range expansion of the T-matrix up to the effective range parameter (ERP) needed in order to have a renormalization scale independent T-matrix while it sets all higher order ERPs exactly to zero. We apply this formalism for both a shallow P-wave bound (e.g., ^{31}Ne) as well as a resonance (e.g., n-α system) state.

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Thursday Parallel Session: Few-body systems (Atrium Maximum) / 115

Emergence of ^{4}H $J^\pi = 1^-$ resonance in contact theories

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Pionless effective field theory (EFT) represents a highly convenient tool to describe the nuclear interaction at low energies. This theory has been used at its leading order (LO) to study various nuclear systems, however, it has failed to give bound nuclei with A > 4 [1,2,3,4].

In our recent study [5] we adressed low-energy p-wave n^3H scattering and the position of the ^{4}H($J^\pi = 1^-$) resonance using the LO pionless EFT. Results were obtained using three different numerical techniques: confining the system in a harmonic oscillator trap, solving the Faddeev-Yakubovsky equations in configuration space, and using an effective two-body cluster approach. Inspecting residual momentum-cutoff variation between 1 and 10 fm^{-1}, our numerical results strongly suggest a cutoff-stable/RG-invariant resonance in ^{4}H. The stabilization of a resonant state in a few-fermion system through contact interactions has a significant consequence for the powercounting of pionless EFT. It suggests the appearance of similar continuum states also in larger nuclei, like ^{6}Li, ^{7}Li, or ^{16}O, in which the theory at LO does not predict bound states. Such poles could then be moved to the correct physical position by the perturbative insertion of sub-leading orders, thus resolving the discrepancy between experimental data and pionless EFT.

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4 M. Schäfer, L. Contessi, J. Kirscher, and J. Mares, Phys. Let. B 816, 136194 (2021).
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Thursday Parallel Session: AMO Systems (AudiMax) / 62

Three-Body Cs(H_2,γ)La Nuclear Synthesis in Cuboctahedron CsH_2Pd_{12}

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Three-body $\mathrm{CsH_2}$ eigenvalues in a cuboctahedron $\mathrm{CsH_2Pd_{12}}$ molecule are calculated in the range from 0.01fm to several ten nano-meter in one stretch, by using 100 significant figure. We utilized five traditional potentials (nuclear Woods-Saxon, three-ion repulsive Coulomb, ion-Pd repulsive Coulomb, electron-ion-Pd effective, nuclear three-body short range) 1 and added a nuclear three-body long range force (3BLF) 2.
The electron's degrees of freedom are frozen for the three-body calculation. However, parameters of electron-ion-Pd effective potential are fitted to energies of $E^{\rm mol}_{\rm gd}$ and $E^{\rm mol}_{\rm 1st}$ which were obtained by the electron based Kohn-Sham equation. Several three-body resonance states are obtained, where the nuclear three-body La resonances strongly interfere with the three-body $\mathrm{CsH_2}$ molecular resonances. We found that the E2 transition times from four ion oscillation (IOS) states $J^\pi = 7/2^+$ to the La ground state $J^\pi = 7/2^+$ are very short with $\tau \approx 10^{-1} \sim 10^{-6}$[sec], for the five traditional potentials and $\tau \approx 10^{-2} \sim 10^{-8}$[sec] for the six potentials. For the the $\mathrm{CsH_2}$ ground state $\tau \sim 10^{24}$[sec] and the first excited state $\tau \sim 10^4$[sec] which are very stable. Our ultra-low energy critical values C_{low}= (density)×(energy)×(duration-time)= 7.50×10^5[sec·Pa] ~1.75×10^{10}[sec·Pa] are almost the same as the critical values of *thermal nuclear fusion*: C_{high}= (density)×(energy)×(duration-time)=1.16×10^6[sec·Pa] or more.

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2 Shinsho Oryu, J. Phys. Commun. {**6**} 015009 (2022).

Thursday Parallel Session: Few-body systems (Atrium Maximum) / 53

ϕ-meson photoproduction on the nucleon and 4He targets

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We investigate ϕ photoproduction on the nucleon and on the ^{4}He targets with a dynamical model approach by considering the Pomeron exchange, meson exchange, ϕ radiation, and nucleon resonance excitation mechanisms. The final ϕN interactions are included and described by the gluon-exchange, direct ϕN couplings, and the box diagrams arising from the couplings with πN, ρN, $K\Lambda$, and $K\Sigma$ channels. Our results for $\gamma p \to \phi p$ are in good agreement with the CLAS data. The coherent ϕ production on the ^{4}He target is described by using the distorted-wave impulse approximation. The predicted differential cross sections match with the LEPS data.

Thursday Parallel Session: Few-body systems and halo nuclei (Linke Aula) / 96

Nuclear model with explicit mesons

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We shall introduce a nuclear interaction model with explicit mesons where the nucleons do not interact directly but rather emit and absorb mesons which are treated explicitly on equal footing with the nucleons.

We shall show that the model is able to i) provide a bound neutron-proton state, the deuteron~1, and ii) adequately describe the threshold pion photo-production off protons~2.

Finally, we shall consider dressing of the bare nucleon with pions and investigate the resulting pion cloud of the nucleon.

1 D.V.Fedorov, Few-Body Systems 61:40 (2020)
2 D.V.Fedorov and M.Mikkelsen, Few-Body Systems 64:3 (2023)

Thursday Parallel Session: AMO Systems (AudiMax) / 49

Transverse motion of diffraction wavelets in a matter-wave beam-splitter

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Matter-wave interferometry with Bose-Einstein condensates (BECs) is a rapidly developing tool for precision measurements 1. A crucial element of matter-wave interferometers is a beam-splitter that employs the interaction of atoms with laser beams and creates superposition of macroscopically occupied momentum states.

We consider the Bragg beam-splitting of an off-axis BEC with three-dimensional Gaussian laser beams 2. The transverse position offset leads to the inseparability of the longitudinal and transverse motion during the pulse. Experimentally, this manifests as transverse momentum kicks. In order to describe both the Bragg oscillations between the momenta components and the motion of the BEC, we model the wavefunction of the condensate via a superposition of squeezed coherent states, initially separated by even multiples of laser photon momentum. We construct a Lagrangian field theory using the variational ansatz 3 that leads to a system of coupled Bragg-Schrödinger equations and Newtonian equations for the Bragg fragments. We compare our results with the (3+1)D numerical simulations, using realistic experimental parameters, and find a good agreement.
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2 A. Neumann, et al., Phys. Rev. A 103, 043306 (2021) \newline
3 R. Walser, et al. New J. Phys., 10(4), 045020 (2008)

Thursday Parallel Session: Few-body systems (Atrium Maximum) / 160

Unified tetraquark equations

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The four quark covariant equations are presented which are adjusted to the description of tetraquarks in terms of an admixture of two-body diquark-antidiquark and two meson states. These equations unify seemingly unrelated the most developed models of the tetraquark where the diquark-antidiquark and meson-meson interactions are realised via quark exchange mechanism in one of them and via constituent quark interaction in another. Besides, the coupling to the two quark channel is taken into account.

Thursday Parallel Session: Few-body systems and halo nuclei (Linke Aula) / 54

Hyperspherical cluster model for bosons: application to sub-threshold halo states in helium drops

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A hyperspherical cluster model has been developed to describe long-range behaviour of one particle removed from a few- or a many-body system. It has been applied to the ground and first excited states of helium drops with five, six, eight and ten atoms interacting via a two-body soft gaussian potential. Convergence of the hyperspherical cluster harmonics expansion is studied for binding energies, root-mean-squared radii and overlaps of the wave functions of two helium drops differing by one atom. It was shown that with increasing model space the functional form of such overlaps at large distances converges to the correct asymptotic behaviour. The asymptotic normalization coefficients that quantify the overlaps' amplitudes in this region are calculated.
It was also shown that in the first excited state one helium atom stays far apart from the rest forming a two-body molecule, or a halo. The probability of finding the halo atom in the classically-forbidden region of space depends on the definition of the latter and on the binding energy of the valence atom. The total norm of the overlap integrals, the spectroscopic factor, represents the number of partitions of a many-body state into a chosen state of the system with one particle removed. The spectroscopic factors have been calculated and their sum rules are discussed giving a further insight into the structure of helium drops.

Friday Plenary Session / 138

Stranger Things –Investigating Hyperon Structure at the Femtometer Scale

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During the last few years, our understanding of the proton size has increased tremendously thanks to efforts from theorists as well as dedicated experiments. Recent progress for the neutron triggers the question: What is the role of flavor in the strong interaction dynamics, that governs the femtometer structure of hadrons? With their strange quark content, the hyperons offer the perfect laboratory to answer this question. However, due to their short life-times (~10-10 s), most methods for measuring

the structure of nucleons are not applicable for hyperons. Luckily, the hyperons have an advantage: through their decays, they reveal their spin properties. This is in contrast to nucleons, for which dedicated polarimeter detectors are needed for this purpose. From the experimentally accessible spin properties, the complex time-like electromagnetic form factors can be reconstructed. Furthermore, the form factors enable the extraction of quantities such as the charge radius. In my talk, I will demonstrate how spin properties can be exploited in structure measurements, present recent results from the electron-positron experiment BESIII and discuss the next steps on our journey towards an understanding of how quarks and gluons form the matter we are made of.

Friday Plenary Session / 20

Constituent quark model. What have we learned about exotic states?

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In this contribution we present a rather personal overview of the most important results regarding the stability and general properties of states formed by two quarks and two antiquarks from the perspective of the constituent quark model (CQM). We will focus most part of the discussion on the different approaches that can be find in the literature for describing double-heavy four quark states, both $QQ\bar{q}\bar{q}$ and $Qq\bar{Q}\bar{q}$, within the CQM. Different approximations will be explored and discussed.

Friday Plenary Session / 74

Universality of Three Identical Bosons with Large, Negative Effective Range

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A consistent nonrelativistic Effective Field Theory exists for which the scattering length a is large and the effective range r_0 is large in magnitude but negative. Such systems can for example be found in heavy mesons. Observables depend then only on the universal ratio $\xi = 2r_0/a$, with $|r_0|$ fixing the overall distance scale. The two-body scattering amplitude displays two shallow S-wave poles whose position in the complex plane is determined by ξ. We investigate here how the bound-state energies of three identical bosons depend on ξ, for a two-body system with one bound and one virtual state, or with two virtual states. We compare our results with
those of Efimov's discrete scale invariance, as $|r_0| \to 0$ is reduced. In ontradistinction to that case, no three-body interaction is needed to stabilise the system. Instead, a well-defined ground state exists for a limited range of ξ around the "quasi-unitarity point" $\xi = 0$, and excitations for even smaller ranges. Interpreting the Efimov version $r_0 = 0$ as a low-energy theory, one matches the spectra to determine its scale-breaking parameter $\overline{\Lambda}$. We also compare the phase shifts for the
scattering of a boson on the two-boson bound state with that of the equivalent Efimov system.

Work conducted in collaboration with U.~van Kolck (Universit\´e Paris-Saclay,
CNRS/IN2P3 and University of Arizona)

Poster Session / 154

Boosting the generalized contact formalism

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The generalized contact formalism is an effective tool for describing short range correlations in the atomic nucleus and their impact of different observables. Working within the equal time formalism, in this contribution we examine the impact of Lorentz boost on the predictive power of the theory.

Poster Session / 61

A General Three-Body Interaction with the GPT-Potential

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A general three-body interaction could be generated by the two-body linear and nonlinear interactions which could appear in the very short and in the long range regions, although the three-body Faddeev equation is written in terms of a two-body linear interaction.
However, in the very short range, many meson or multi quark/gluon exchanges may take place which are taken into account by a "three-body short range force: $V_{\rm 3BSF}$". In the long range region, the linear three-body Faddeev equation can not be exactly described by a two-body long range potential.
In this context, we could employ a general three-body interaction $V_{\rm 3BF}$ by using the *general particle transfer* (GPT) potential $V_\alpha(\mathbf{r}_{\beta\gamma};n)$ 1, i.e.,
$\Big[V_{\rm 3BF}\Big]_{\alpha\beta} \equiv \Big[b_{\alpha\beta} + \big\{1/V_\alpha(\mathbf{r}_{\beta\gamma};n) + 1/V_\beta(\mathbf{r}_{\gamma\alpha};n)\big\}\Big]^{-1}$
$= V_\alpha(\mathbf{r}_{\beta\gamma};n)V_\beta(\mathbf{r}_{\gamma\alpha};n)/calV$
and
$calV = b_{\alpha\beta}V_\alpha(\mathbf{r}_{\beta\gamma};n)V_\beta(\mathbf{r}_{\gamma\alpha};n) + V_\alpha(\mathbf{r}_{\beta\gamma};n) + V_\beta(\mathbf{r}_{\gamma\alpha};n) \equiv (E - H_0)$,
with the three-body kinetic energy H_0 and the total energy E, respectively.
$b_{\alpha\beta}$ denotes a parameter which represents a border between the linear and the nonlinear interactions.
We obtain
$\Big[V_{\rm 3BF}\Big]_{\alpha\beta}$
$= V_\alpha(\mathbf{r}_{\beta\gamma};n)V_\beta(\mathbf{r}_{\gamma\alpha};n)/(E - H_0 + i\epsilon)$.
This formula is a generalized Alt-Grassberger-Sandhas (AGS) Born term which includes both the three-body short range force (3BSF), and the three-body long range force (3BLF).

1 Shinsho Oryu, ~~~~J. Phys. Commun. {\bf 6} 015009 (2022).

Poster Session / 73

Effective theory for few-body physics in the Gaudin-Yang model

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A topic of high interest in the field of cold atoms and molecules is the crossover from a Bardeen-Cooper-Schrieffer (BCS) superfluid with loosely bound Cooper pairs to a Bose-Einstein condensate (BEC) of tightly bound dimers (molecules). While the crossover can be investigated experimentally near Feshbach resonances, there is a lack of analytical solutions providing insights into the crossover physics 1. Considering a one-dimensional spin-1/2 Fermi gas, the exactly solvable Gaudin-Yang (GY) model can describe the BCS-BEC crossover in the form of a transition from a (BCS-like) gas of loosely bound fermion pairs to a Tonks-Girardeau gas of tightly bound fermion pairs (dimers) 2. We note, however, that already the exact Bethe-ansatz (BA) solution of the GY model without external potential becomes complicated rapidly for increasing number of particles whereas the GY model is not even exactly solvable if external potentials are present. Due to this, most investigations considering the experimentally relevant case of an external potential are numerical 3. We propose to use the effective field theory (EFT) framework to reduce the complexity of the GY model solution to the most relevant physics and possibly 'enable'analytical insights for the GY model with external potential. To achieve this goal, we set up an effective theory for fermions and dimers by investigating the few-body physics of fermion-dimer and dimer-dimer scattering within the BA-solution of the GY model.

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Poster Session / 72

Getting LQCD calculations outside the box

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Lattice quantum chromodynamics (LQCD) calculations of few nucleon systems started a new era of ab-initio predictions in nuclear physics. To obtain physical quantities, the finite-volume LQCD numerical results have to be extrapolated to free space. This extrapolation is traditionally performed using the Lüscher formula for the two-body case and its generalizations to larger systems. Recently, another method was introduced, where an effective field theory (EFT) is fitted directly to the finite-volume results and subsequently used to predict free-space results.

In this project, we aim to compare the two approaches. To mimic the LQCD results we use the nucleon-nucleon Minnesota potential solved in a box with periodic boundary conditions. The binding energies of systems of up to four nucleons are solved using the stochastic variational method (SVM). Fitting the next-to-leading order (NLO) pionless EFT to the finite-volume energies we use it to extract the free-space binding energies and scattering parameters. The same free-space quantities are also obtained through the Lüscher formula, and thus approaches can be compared on the same ground.

Poster Session / 143

A ~ 80 systems: shell structure and astrophysical implications

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With their few proton and neutron particles, the A=80 isobars, numbering about twelve nuclei distributed from the proton-rich side to the neutron-rich one, are of a great importance in nuclear structure studies. These nuclides are found along rapid proton capture (rp) process. They make it possible to develop our knowledge about the nucleon-nucleon interaction close to the astrophysical processes pathways. Consequently, the experimental and theoretical determination of their properties and their decays permits to simulate and to model the astrophysical explosive phenomena.
In order to compute the spectroscopic properties of A=80 isobars, we have performed shell model calculations in the framework of nuclear shell model by means of NuShellX@MSU nuclear structure code. The used valence space consists of the (f7pg9) proton and neutron orbitals outside of 56Ni doubly magic core with new single particles energies. The investigation study is based on the use of several effective interactions taking into account the core polarisation, the nuclear monopole effect and the similarity with 100Sn and 56Ni mass regions. The gotten results are in good agreement with the measured and available data. This agreement makes it possible to validate the effective theoretical approach.

Keywords: A=80 isobars, rapid proton capture process, NuShellX@MSU nuclear structure code, spectroscopic properties.

Poster Session / 133

Entanglement in few-particle scattering events

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We investigate the spin-entanglement in few-particle scattering following the analysis carried out by Beane et al. [Phys. Rev. Lett. 122, 102001 (2019)]. Our calculations are focused on the entanglement entropies of scattering processes involving Spin-1/2 and Spin-1 particles.
The entropies are evaluated using scattering data for neutron-proton and neutron-deuteron scattering and, taking into account the Coulomb interaction, also for proton-proton, proton-deuteron and deuteron-deuteron scattering.
In all cases, different entanglement entropies are compared and analyzed regarding their suitability as a measure of entanglement for the given process.

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Poster Session / 132

Even Zr Isotopes Investigation Near rp-process Path

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Proton-drip line nuclei offer significant information about nuclear structure and nucleon-nucleon interaction. Their positions, far from beta stability and close to the astrophysical rp-process path, give them a great importance in both theoretical and experimental studies. This provides the opportunity develop our knowledge about nuclear systems and lead to improve the theoretical nuclear models. Zr isotopes are good candidates for this. Due to its wide existence, from proton drip-line to neutron one, they provide important information about the nuclear interaction. In order to emphasize the importance such instable systems, we carry out some spectroscopic calculations in the framework of nuclear shell model. These calculations aim to investigate even Zr isotopes nuclear structure properties by means of NuShellX@MSU nuclear structure code. The used effective interaction is founded on the sn100pn original one, considering the similarity between 100Sn and 56Ni neighboring nuclei. The obtained results have been compared to the available experimental data in order to improve the efficiency of our new interaction.

Poster Session / 127

Ab-inito calculation of ^{4}He+n s-wave scattering within baryonic effective field theory at next to leading order

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In this work, we investigate elastic neutron scattering on ^{4}He within the context of baryonic effective field theory, specifically focusing on the $J^\pi = \frac{1}{2}^+$ channel. By employing the stochastic variational method, we solve the 5-body problem without making any prior assumptions about system clusterization. Our calculated scattering length and effective range exhibit excellent agreement with experimental observations.

Poster Session / 116

Constraining fundamental physics from ab initio nuclear theory

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Recent global analysis of Fermi decays within a dispersion relation framework and the corresponding V_{ud} determination have revealed tension with the Standard Model (SM) expectation of Cabibbo-Kobayashi-Maskawa (CKM) matrix unitarity, theoretical confirmation of which would indicate a deficiency within the SM weak sector. Extracting V_{ud} requires electroweak radiative corrections (EWRC) from theory to be applied to the experimentally obtained ft-values. Novel calculations of the pieces sensitive to hadronic structure, i.e., the γW-box, are at the heart of the recent tension. Moreover, to further improve on the extraction of V_{ud}, a modern and consistent treatment of the two nuclear structure dependent corrections is critical. These corrections are (i) δ_C, the isospin symmetry breaking correction (ii) δ_{NS}, the EWRC representing evaluation of the γW-box on a nucleus. Preliminary estimations of δ_{NS} have been made in the dispersion relation framework, however the approach cannot include effects from low-lying nuclear states which require a true many-body treatment. Via collaboration with C.Y. Seng and M. Gorshteyn and use of the Lanczos continued fraction method, these corrections are now calculable within the ab initio no-core shell model (NCSM). The NCSM is a nonrelativistic quantum many-body theory for describing low-lying bound states of s- and p-shell nuclei starting solely from nuclear interactions. We will present preliminary results for δ_{NS} and δ_C determined in the NCSM for the ^{10}C $\rightarrow$ ^{10}B beta transition, with the eventual goal of extending the calculations to ^{14}O $\rightarrow$ ^{14}N and ^{18}Ne $\rightarrow$ ^{18}F.

Poster Session / 109

Cluster Effective Field Theory calculation of electromagnetic breakup reactions with Lorentz Integral Transform method

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We present the study of the inclusive photo-disintegration reaction $\gamma + {}^9\mathrm{Be} \rightarrow \alpha + \alpha + n$ at low-energy regime, including calculations of the $\alpha\alpha n$ three-body binding energy of ^{9}Be and the reaction cross section. The inverse process of the $^9\mathrm{Be}$ photo-disintegration, including both sequential and direct reactions combining two α and a neutron into ^{9}Be, represents an alternative path to the $^{12}\mathrm{C}$ formation in a neutron-rich environment, therefore it is a reaction of astrophysical interest.
The shallow binding of $^9\mathrm{Be}$ below the $\alpha\alpha n$ three-body threshold and the deep binding of α indicates a clear separation of energy scales. For this reason, it can be studied as a three-body *effective* clustering system where neutrons and α-particles interact with each other through effective potentials. In the literature one finds calculations where α-α and α-n potentials of phenomenological character have been used. Here we present an attempt to use potentials derived from Halo Effective Field Theory (EFT) 1. Given these effective potentials as an input, we solve the bound-state problem using the Non-Symmetrized Hyperspherical Harmonics (NSHH) method 2. Then, via the Lorentz Integral Transform (LIT) method 3, we calculate the cross section of the $^9\mathrm{Be}$ photo-disintegration reaction in the low-energy regime. The key quantity to be calculated is the nuclear current matrix element. At low energy Siegert theorem ensures that the use of the dipole operator allows to take into account both the effect of the one-body convection current as well as that of two-body currents (or even of three-body ones in case of the inclusion of both two- and three-body forces). As a consequence, two types of calculations can be made: the calculation of the nuclear convection current as the nuclear current operator 4 and the calculation of the dipole operator matrix elements. This allows to quantify the contribution of *higher*-body currents, which are automatically included in the latter calculation. We will discuss the results focussing in particular on the interplay between these two contributions, driven by the EFT parameters, and in connection with the experimental results.

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Poster Session / 105

Resonances of exotic helium-like systems

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In the last decades, exotic few-body atoms, in which an electron is replaced by an exotic particle, have attracted great scientific interest. These systems are indeed very useful to determine accurately the properties of their constituting exotic particles (e.g. antiprotons or mesons). For instance, an antiproton can be captured by a helium atom in a high orbital momentum state (typically L = 30 to 35) to form the so-called antiprotonic helium, a three-body system made of an alpha-particle, an electron, and an antiproton. This atom is in a high-L quasibound resonant state with very narrow width, hence long Auger lifetime. The radiative transitions between these quasibound states enable one to study these systems experimentally, and the recent study of antiprotonic helium led to the up-to-now most precise value of the antiproton mass [1,2]. Similar studies have been conducted with other exotic atoms, such as the pionic helium [3,4].

In order to give a comprehensive theoretical understanding of those systems, I will present a method for computing non-relativistic resonance energies and widths of three-body exotic atoms (namely, antiprotonic helium and pionic helium), for a wide range of the total orbital momentum L. I developed an approach combining the Lagrange-mesh method in perimetric coordinates [5–7] and the complex Kohn variational principle [8,9] in order to obtain the S-matrix related to the emission of the electron from the three-body system. By extrapolating this S-matrix in the complex plane from the real axis [10], the energies and widths of the states are determined. These widths are directly related to the Auger lifetimes of the system. I will show that this approach is suited for studying very accurately the resonances of these systems for a wide range of the orbital momentum L.

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Poster Session / 99

Preparation for Spin Correlation Coefficients Measurement in Polarized Deuteron-Polarized Proton Scattering Experiment

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An adequate probe to investigate detailed characteristics of the Three Nucleon Forces (3NFs) is few-nucleon scattering experiment. Comparison between high-precision data in few-nucleon scattering (differential cross sections, various spin observables) and theoretical predictions based on rigorous numerical calculations enable us to extract information within the nuclear force. From an extensive performance of deuteron-proton elastic scattering at intermediate energies (70-300 MeV/nucleon) by a group in RIKEN, clear signatures of 3NF effects were confirmed in results of the cross section, whereas deficiencies of current 3NF models were revealed by those of spin observables.

In view of determining the 3NFs, we now plan to measure the spin correlation coefficients for polarized deuteron-polarized proton scattering at 100 MeV/nucleon. Polarized deuteron-polarized proton scattering experiment will be performed at RIKEN RIBF facility, using the polarized deuteron beam provided via the polarized ion source and the polarized proton target system based on triplet dynamic nuclear polarization (triplet-DNP) method. Polarized cross sections of particles scattered in left, right, up, and down directions will be measured with a detector system incorporating multi-wired drift chambers (MWDCs) and plastic scintillators. Data taken will be utilized to fix the low energy constants (LECs) in chiral effective field theory.

The polarized proton target and the detector system, both of which have been newly developed for the polarized deuteron-polarized proton scattering experiment, underwent a beam test at HIMAC in December 2022.

The following measurements have taken place:

- Quantification of target (naphthalene) crystal's polarization decrease from bombardment of 200 MeV proton
- Efficiency measurement of the MWDCs
- Derivation of target polarization from yield asymmetry measurement.

In this presentation, details on the planned polarized deuteron-polarized proton scattering experiment at 100 MeV/nucleon and the results from the beam test at HIMAC will be given.

Poster Session / 97

On Exactly Solvable Two-Body Problem in Two-Dimensional Quantum Mechanics

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It is well known that exactly solvable models play an extremely important role in many fields of quantum physics. After the discovery of graphene in 2004 the study of a few particle systems in novel 2D materials became very important 1. We consider two particles problem in three-dimensional (3D) coordinates space that are exactly solvable for a given central two-particle interaction *V(r)* and find the analytical solution with the same potential in two-dimensional (2D) space. The Schrodinger equation is applied to a 2D problem of two mass points confirmed in a circle, trapped in magnetic field, interacting via Kratzer potential, modified Kratzer potential, Coulomb potential, exponential potential, Yukawa potential, and Morse potential.

In the framework of the Nikiforov-Uvarov method 2 we transform Schrodinger equations with the corresponding potential into a second order differential equation via transformations of coordinates and particular substitutions into equations of the hypergeometric-type. The solution for wave functions is obtained in terms of special functions such as a hypergeometric function, confluent hypergeometric function, and solutions of the Kummer's, Laguerre's, and Bessel's differential equations.

We obtained exact analytical expressions for energy eigenvalues and eigenfunctions. Comparison is made between the two- and the three-dimensional cases. Interesting aspects of the solutions unique to the 2D cases are discussed.

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Poster Session / 94

Extensive and accurate energy levels, wavelengths, transition rates, line intensity ratio and plasma parameters for the Ne VIII, Fe XXIV and Kr XXXIV spectrum of Plasma interest

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Extensive and precise investigations have been conducted on lithium-like neon, iron, and krypton, focusing on the energy levels, wavelengths, weighted oscillator strengths, transition rates, line intensity ratios, and plasma parameters of their lowest 35 odd and even parity states arising from the $1s^2nl(n = 1{-}6, 0\ l\ n{-}1)$ configurations. Accurate atomic data determination is considered to be the principal way to effectively solve the future energy problem as a clean and infinite energy resource 1 and it is being developed internationally via the International Thermonuclear Experimental Reactor (ITER) Project 2. Both experimental and theoretical spectroscopic studies have been performed in the last few years in order to estimate the power loss from the impurities in the forthcoming fusion reactors. These calculations involved the Multiconfigurational Dirac-Hartree-Fock (MCDHF) method 3 followed by the Relativistic Configuration Interaction (RCI) method. Electric-multipole (dipole (E1), quadrupole (E2)) and magnetic-multipole (dipole (M1), quadrupole (M2)) transition rates were also determined. The calculations incorporated Breit interactions and quantum electrodynamics effects (QED) as perturbations within the extensive relativistic configuration interaction (RCI) approach. Comparison of our findings with existing theories in the literature and data from the NIST database revealed a substantial level of agreement. Additionally, the line intensity ratio and plasma parameters (plasma temperature and electron density) were determined. These comprehensive and coherent results have significant implications, aiding in the identification of observed spectral lines in astrophysical studies [4, 5], and contributing to the effective control of nuclear fusion reactions in tokamak plasmas [6, 7].

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Poster Session / 93

Effective mass of a nucleus incteracting with neutron superfluid

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Neutron stars are among the most exotic and extreme objects in the universe, consisting primarily of neutrons packed together at incredibly high densities. In the inner crust of these stars, the neutrons are believed to form a superfluid. In this superfluid, the nuclei (clusters of protons and neutrons) are thought to be immersed and interact with the surrounding neutrons. The study of these nuclei has important implications for understanding the properties and behavior of neutron stars and advancing our comprehension of the fundamental laws of physics. A critical aspect of studying the behavior of nuclei immersed in superfluid neutrons is understanding their effective mass. It is affected by strong interactions with the surrounding particles.

I will present our recent findings on nonequilibrium dynamics in the deep layers of a neutron star. Our research employs cutting-edge numerical techniques based on density functional theory, utilizing a Brussels-Montreal functional specifically designed for astrophysical problems.

Poster Session / 87

Radiative neutron capture on 6-8Li isotopes in the cluster model

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In the consistent approach, total cross-sections and reaction rates of radiative neutron capture on lithium isotopes $^{6-8}$Li in the temperature range from 0.01 to 10 T_9 within the framework of the modified potential cluster model (MPCM) with forbidden states are considered [1-3]. These reactions are of significant astrophysical interest as a part of the chain of primordial nucleosynthesis processes of the Universe [4,5].

Estimation of reaction ^{6}Li$(n, \gamma_{0+1})^7$Li has been done in our work 1 in the context of comparison with the isobar-analog reaction ^{6}Li$(p, \gamma)^7$Be [6]. The role of ^{7}Li$(n, \gamma_{0+1})^8$Li reaction in BBN is examined in 2.

Our first calculation of reaction ^{8}Li$(n, \gamma_{0+1})^9$Li is considered in 3. Now we re-estimate this process for reaction ^{8}Li$(n, \gamma_{0+1})^9$Li with renewed characteristics. The effect of the value of the asymptotic constant on the behavior of the total capture cross-sections is studied. Compared with our previous results, the total cross sections for radiative capture at energies in the range from 0.01 eV to 5 MeV are obtained, which generally agree with the results of experimental measurements. Furthermore, an approximation of the obtained capture rate by a simple analytical expression is executed.

The comparison of the obtained reaction rates of the $^{6-8}$Li(n, γ) processes is performed. These results are directly related to the discussion of the lithium problem ^{6}Li/^{7}Li ratio.

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Poster Session / 85

Accurate determination of radiative properties in the carbon iso-electronic sequence by using the MCDHF method

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Extensive research has been conducted in recent years to determine the accurate atomic data and uncertainties associated, as they are crucial for interpreting a large amount of high-resolution data obtained by astrophysicists. In other way, the need for this research is primarily due to the upcoming ITER project (International Thermonuclear Experimental Reactor), which requires precise and complete spectroscopic studies, both experimental and theoretical, to estimate power loss caused by impurities in future fusion reactors 1.
As previously published [2, 3, 4, 5, 6], we continue to study a more complex system, the atomic structure for C-like ions. Energy levels, wavelengths, weighted oscillator strengths and transition probabilities are calculated for the 20 lowest levels of $2s^2 2p^2$, $2p^4$ and $2s^1 2p^3$ configurations of C-like ions with Z= 10-22.
The calculations were carried out using in first the GRASP2018 code based on the multiconfiguration Dirac-Hartree-Fock (MCDHF) [7]. To assess the accuracy of results, we performed in parallel other calculations using the FAC (Flexible Atomic Code) code [8] in order to provide theoretically the most accurate data. Transition probabilities are reported for all types of transitions (E1, E2, M1 and M2 transitions). Breit interactions and quantum electrodynamics effects are included in the Relativistic Configuration Interaction (RCI) calculations. Comparisons were made with other data found in the literature and a good agreement was found which confirms the reliability of our results. We identified some new data that are calculated for the first time. This computational approach enables us to present a consistent and improved data set of all important transitions of the Carbon iso-electronic spectrum, which are useful for identifying transition lines in further investigations.
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Poster Session / 83

Relativistic Calculations of Electron and Positron Scattering Length for Argon

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Scattering length is one of the most useful parameters used to describe low-energy electron-atom and positron-atom collisions. It is defined as a radius of a hard sphere in the zero-energy total cross section, where the sign represents the type of interaction: it is positive for repulsion and negative for attraction. Such data is mainly used in low-temperature systems such as Bose-Einstein condensate and Fermi-Dirac condensate. The calculations are done using the multi-configurational Dirac-Hartree-Fock (MCDHF) method to account for electronic correlations using the GRASP2018 package 1. Calculations are performed for electron scattering and positron scattering. Calculations for positron may be done in two different ways: as an electron with negative energy travelling back in time and simply by treating the positron as an electron with a positive charge. Moreover, the polarization potential is added since it plays a crucial role in the long-distance electron/positron correlation which is particularly important for very small energies and leads to the proper calculation of the scattering length. Scattering length is calculated at zero energy limit by two methods: using the asymptotic behaviour of wave function and by graphical fit at the close distance to the target.
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Poster Session / 82

Borromean states in a one-dimensional three-body system

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We explore the Borromean states of a one-dimensional quantum three-body system composed of two identical heavy particles and a different particle of smaller mass. There is no heavy-heavy interaction potential and no bound state supported by the heavy-light one. The three-body spectrum and corresponding wave-functions are calculated numerically within the Faddeev approach. In addition, we have investigated the properties of this Borromean state as well as the region of the system parameters where the state occurs.

Poster Session / 81

Microscopic theory of infinite nuclear matter and connections to the nuclear energy functional

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In our contribution, we shall discuss our work at the interface of nuclear *ab initio theory* and nuclear density functional theory (DFT).

DFT is a powerful and versatile method in nuclear structure theory, with a wealth of application to ground state and collective excitations over the whole nuclear chart, as well as infinite nuclear matter 1.
The key object on which DFT is based on is the nuclear energy density functional (EDF). Current phenomenological EDFs, which are constrained by experimental measurements of nuclei close to magicity, are rather successful in reproducing stable nuclei. However, there are well-known shortcomings when they are applied e.g. to nuclei far from the stability valley of current interest for experimental nuclear physics and for their impact on modeling astrophysical scenarios. New strategies should thus be explored.

Our work aims at exploiting parallel developments in *ab initio* nuclear theory to devise a new methodology to build new EDFs. The motivation lies in the fact that *ab initio*, that describe nuclear systems starting from the interactions between their constituent nucleons, allows to determine the properties of nuclei and nuclear matter in a potentially unbiased way 2. However, *ab initio* can be applied to heavy systems only in few selected cases and at a very high computational cost. Therefore, a combination of the flexibility of the DFT approach and the accuracy of *ab initio* has to be searched for 3.
We will present infinite nuclear matter conducted within the frameworks of Quantum Monte Carlo (QMC) and Self-consistent Green's function (SCGF). Specifically, QMC calculations of the equation of state (EOS) and the response of nuclear matter to a static potential 4 are shown, and we motivate that matching the *ab initio* and the DFT static response [5] allows to set constraints on the gradient terms of the EDF.
Then, a new, state of the art approximation scheme for the SCGF method, the so-called algebraic diagrammatic construction (ADC) that has been employed successfully to study finite nuclei, is applied to nuclear matter [6].
The overall purpose of our research is to establish a closer map between our microscopic understanding of nuclear structure based on nuclear forces and the effective, "high-level" description of nuclear systems provided by DFT.

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Poster Session / 79

Two-dimensional transverse charge distributions of the Δ baryon:

Interpolation between the nonrelativistic and ultrarelativistic limits

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In this talk, we present the results of a recent investigation on the behavior of the charge distributions of the Δ baryon,both unpolarized and transversely polarized, as a function of longitudinal momentum (P_z) in a Wigner phase-space perspective. Specifically, we examine how the charge distributions change as P_z increases from 0 to ∞. We find that the charge distribution of a longitudinally polarized Δ baryon remains spherically symmetric regardless of P_z. On the other hand, for a transversely polarized Δ baryon along the x-axis, a quadrupole contribution emerges at rest ($P_z = 0$), and as P_z increases, electric dipole and octupole moments are induced. The current analysis reveals that the induced dipole moment dominates over higher multipole contributions and drives the deformation of the Δ baryon's charge distribution. These findings provide insights into the underlying physics of the Δ baryon and its charge structure.

Poster Session / 78

Strangeness of the gravitational form factors

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The gravitational form factors (GFFs) of the nucleon encode information on the structure of the mass, spin, and mechanical properties. In this talk, we present results from a recent investigation on the GFFs of the nucleon in flavor SU(3) symmetry, highlighting the flavor structure of the GFFs within the framework of the SU(3) pion mean-field approach. We show how much momentum fraction of the nucleon is carried by the s-quark and discuss the role of the s-quark contribution to the nucleon mass decomposition by comparing it to the rest energy of the nucleon. Furthermore, we present the flavor decomposition of the intrinsic quark spin and orbital angular momentum, which satisfy Ji's sum rule. The current results indicate that the total angular momentum of the nucleon is dominated by the u-quark contribution, with Ju ~ 0.52, while the d and s-quark contributions are small, with Jd ~ −0.06 and Js ~ 0.04. Additionally, we investigate the hidden contribution to the D-term of the nucleon and find that all of the quark contributions is negative. The magnitude of the d-quark contribution to the D-term is found to be the largest in magnitude, comparable to that of the u-quark contribution.

Poster Session / 70

$D^*_{s0}(2317)$ as a DK molecular state

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In the present talk, we present a molecular nature of the charmed strange $D^*_{s0}(2317)$ state. The $D^*_{s0}(2317)$ state has a mass approximately 40 MeV below the D^0K^+ threshold, and the upper limit of the width is known to be 3.8 MeV. Its favorable spin-parity assignment is believed to be $J^P = 0^+$, the parity conservation being assumed. Since $D^*_{s0}(2317)$ only decays into the isospin breaking process, the $\pi^0 - \eta$ mixing for the $D_s\pi^0$ channel is taken into account in our calculation. We solve the coupled integral equations to obtain a fully off-mass shell T-matrix in the momentum space. The u-channel exchange amplitudes in DK channels generate dynamically a DK bound state, which can be identified as the $D^*_{s0}(2317)$ meson. We also discuss the uncertainty of the results with the coupling constants varied.

Poster Session / 66

Ab initio description of the antiproton-deuteron annihilation

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Low-energy antiprotons are known to be promising tools to probe the nuclear structure 1. In particular, the measurement of antiprotonic atom decays and nucleon-antinucleon annihilation products is expected to provide reliable data to study the tail of nuclear densities, which has motivated the antiProton Unstable Matter Annihilation (PUMA) project 2 at CERN. Although a qualitative picture of what will happen in the PUMA experiments is known, a fully microscopic treatment of the antiproton-nucleus systems remains to be developed. Our main aim is to solve the few-body Schrodinger equation for the cases accessible by *ab initio* methods. It is also of paramount importance to test the model-dependence of physical observables relative to the nucleon-nucleon and nucleon-antinucleon interactions input.

Optical potentials are traditionally used to account for the complex annihilation dynamics 3. We considered an alternative approach based on a coupled-channel potential, where the annihilation is modelled by the addition of effective meson channels 4. The model-dependence is investigated by considering the microscopic calculation of the antiproton-deuteron annihilation: the scattering lengths and the resonance energies of the antiprotonic states are computed by solving the Faddeev equations in configuration space [5], and then compared to those obtained with optical models [6].

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Poster Session / 59

Radiative Capture $d(\alpha,\gamma)\,^6\mathrm{Li}$ Reaction in Cluster Effective Field Theory

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The $d(\alpha,\gamma)^6$Li reaction that produces ^{6}Li was the primitive reaction in the standard BBN framework. As a consequence of the importance of the reaction, we study the radiative capture process of deuteron on alpha through the cluster Effective Field Theory. In detail, we outline the calculation of the amplitude and S-factor of the capture process leading to the formation of ^{6}Li. The contribution of two-body currents is also studied. In order to evaluate the accuracy of the approach, we compare the S-factor of the dominant transitions (E1, E2) of the reaction up to next-to-leading order with the results of the model-dependent theoretical calculations and experimental data. The consistency of the results shows the strength of the EFT to describe the few-body systems in low-energy regimes.

Poster Session / 57

Constraining the two-nucleon force in chiral EFT from three-nucleon data

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In previous works, the two-nucleon potential has been successfully determined to a high-precision level in the framework of chiral effective field theory. Nonetheless, there are still some free parameters of this potential, which cannot be extracted from two-nucleon data. The goal of the work presented in this talk is to adjust these parameters using three-nucleon data. Because of the high computational cost of three-nucleon scattering calculations, the scattering amplitude will be obtained using an emulator. The performance of this emulator will be investigated and discussed. This study does not only contribute to a better understanding of three-nucleon scattering data but may also improve ab-initio calculations of few- and many-body systems.

Poster Session / 45

Ab Initio Study of Low-Energy Antiproton-Nucleus Systems

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Despite a century after the discovery of neutrons by E. Rutherford, few details are known for sure about this particle. For example, neutron halos, prototypical examples of the quantum realm, were discovered a few decades ago from indirect measurements. In an ambitious attempt, the PUMA experiment at CERN 1 will use the antiproton's unique property, i.e., the annihilation process's sensitivity to the nuclear density's tail, to study the neutron/proton distribution asymmetry at the surface of the nuclei. To support the experimental endeavor, we aim to provide theoretical guidance

to answer the key questions of the experiment. To study the antiproton's annihilation as a probe for the nuclear surface, we rely on the high-fidelity ab initio reaction method and Effective Field Theory (EFT). To begin with, we will introduce various nucleon-antinucleon ($N\bar{N}$) interactions in our nuclear reaction tools and develop the ability to compute low-energy antiprotonic atomic states, the so-called quasi-bound states, and reaction cross-sections of light-nuclei antiprotonic systems. In other words, we introduce $N\bar{N}$ optical potentials into the No-Core Shell Model combined with the Resonating Group Method (NCSM/RGM) 2 to study the sensitivity of the many-nucleon observable to $N\bar{N}$ optical potential models and EFT-derived potentials. This exploration will give important information on the properties of the $N\bar{N}$ system below the threshold and determine the current theoretical uncertainties. Furthermore, we aim to compute annihilation properties of antiprotonic systems made from Helium to Oxygen stable isotopes with the high-precision EFTs for the nuclear sector before the advent of experimental data. The overarching goal is a unified description of nuclei and antiprotonic atoms within the theory used in both sectors.

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Poster Session / 43

Bayesian Analysis of a Modified Power Counting in Chiral Effective Field Theory

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Chiral effective field theory (χEFT) is an approach to describe the force between nucleons as arising from the more fundamental principles of quantum chromodynamics. A vital part is to have a power counting (PC) that describes the relative importance of the EFT order-by-order contributions to nuclear observables. The definition of the PC is not unique, and the fact that nuclear systems are non-perturbative makes finding a proper PC a non-trivial problem. We have done a Bayesian analysis of a renormalization-group invariant PC at leading order (LO) 1, and we analyze the posterior probability density of the low-energy constants (LECs) for momentum cutoffs in the range 400 − 4000 MeV. We find multi-modal posteriors for the LECs, some overly repulsive P-wave phase shifts, a decent LO description of scattering observables and a slight under-binding of the deuteron. In this PC corrections beyond LO are included perturbatively. Recent developments regarding the analysis of higher orders will also be presented.

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Poster Session / 40

Heavy baryon spectroscopy in a quark-diquark approach

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We report progress on calculations of the heavy-light baryons Σ_c and Λ_c and their excitations with $J^P = 1/2^+$ and $3/2^+$ using functional methods. The three-quark Faddeev equations are reduced to two-body equations by employing a covariant quark-diquark approach. The interaction amounts to a quark exchange between quarks and effective diquarks, and the ingredients are determined via a rainbow-ladder truncation. A partial-wave analysis reveals the presence of orbital angular momentum components in terms of p waves, which are non-relativistically suppressed. A diquark contribution analysis reveals the distribution of scalar and axialvector diquarks, of equal and unequal flavors, in the heavy-light baryon spectrum.

Poster Session / 35

Three-charge-particle systems in the framework of coupled coordinate-space few-body equations

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We study three-charge-particle low-energy elastic collision and particle-exchange reaction with special attention to the systems with Coulomb and an additional nuclear interaction employing a close-coupling expansion scheme to a set of coupled two-component few-body equations [1,2]. First we apply our formulation to compute low-energy elastic scattering phase shifts for the d+(t$\mu^-)_{1s}$ collision, which is of significant interest for the muon-catalyzed-fusion D-T cycle. Next, we study the particle-exchange reaction d+(pX^-)→ p+(dX^-) with the long-lived elementary heavy lepton stau X^-, which can play a critical role in the understanding of the Big-Bang nucleosynthesis and the nature of dark matter. We also study the total cross sections and rates for two particle-exchange reactions involving deuteron (d), triton (t), and antiprotons (p^-) e.g., $\mathrm{p}^- + (\mathrm{d}\mu^-)_{1\mathrm{s}} \to (\mathrm{pd})_{1\mathrm{s}} + \mu^-$ and $\mathrm{p}^- + (\mathrm{t}\mu^-)_{1\mathrm{s}} \to (\mathrm{p}^-\mathrm{t})_{1\mathrm{s}} + \mu^-$, where μ^- is a muon. The effect of the final state short-range strong (p^-d) and (p^-t) nuclear interactions is significant in these reactions, which increases the reaction rates by a factor of $\sim$3.

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Poster Session / 13

Perturbative EFT model of core excitations in one-neutron halo nuclei

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Halo nuclei are fascinating short-lived nuclear objects found near the dripline.
In standard reaction models, halo nuclei are usually described as an inert core with one or two weakly bound neutrons. However, some breakup data suggest that the excitation of the core to its excited states to have a significant influence in the dynamics of the reaction 1. In order to shed more light on this phenomenon, we study the typical one-neutron halo nucleus ^{11}Be and we propose a simple structure model of it based on the rigid rotor model. We assume the core to be weakly deformed, which we treat at the first order of perturbations to couple it to its 2^+ first excited state. In this way, we explicitly account for core excitations as a new degree of freedom while still describing the interaction between the core and the neutron in halo-EFT 2.
Our calculations were performed using the calculable R-Matrix method on a Lagrange mesh 4. We have been able to reproduce with a good agreement, the coupled-channels results 3, improve the halo-EFT model 2 and bring another physical insight on the structure of the bound states of ^{11}Be.

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Poster Session / 5

Multichannel effects and universality in three-body physics of strongly interacting Lithium-7

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We study the apparent disagreement between experimental measurement of three-body observables in ultracold lithium-7 and the predictions of universal theory, which has shown to be generally accurate in describing the other alkali-metals. For this purpose, we apply a sophisticated numerical approach based on an expansion and subsequent diagonalisation of the full three-body Hamiltonian in momentum space. With this method, we are able to take into account both realistic molecular interactions with many low-lying dimer states, and the complete three-body hyperfine basis that underpins the multichannel nature of the problem. Our results show that multichannel effects in lithium-7 shift the three-body parameter away from the universal prediction and towards the current experimental data. By analysing partial recombination losses, we find that this sensitivity can be attributed to a strong coupling to specific three-body hyperfine channels, which have often been neglected in earlier studies. In addition, we apply our methods to the computation of the Efimov binding energy, and compare directly with state-of-the-art experiments.

Poster Session / 3

Ground and dipole-excited states in neutron-rich 8He

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Light nuclei at the driplines exhibit fascinating phenomena, such as the formation of diluted structures where a tightly-bound core is surrounded by a halo of one or more weakly-bound nucleons. Among them, ^{8}He is the only four-neutron halo, and it is the most exotic nucleus on Earth, having the largest neutron-to-proton ratio in the nuclear chart (N/Z = 3). This makes it an interesting challenge for ab initio nuclear theory.

In this talk, I will present recent coupled-cluster calculations of ground and dipole-excited-state properties of ^{8}He 1, based on state-of-the-art chiral effective field theory interactions. In particular, I will discuss our predictions for the dipole polarizability, accompanied by an analysis of our theoretical uncertainty 2, and compare our results to new experimental data by the SAMURAI collaboration.

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Poster Session / **2**

Nuclear structure corrections to the Lamb-shift in light-muonic atoms

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Spectroscopy experiments in muonic atoms allow for the extraction of the nuclear charge radii of the lightest nuclei with unprecedented precision. The measurement of the Lamb shift in muonic hydrogen 1 and the related emergence of the proton radius puzzle have motivated an experimental campaign devoted to other light muonic atoms, such as muonic deuterium 2 and helium 3. For these systems, nuclear polarizability effects are the largest source of uncertainties 4 and consequently the bottle-neck for exploiting the experimental precision. Combining advanced few-body techniques and effective field theories developed for studies of nuclear structures and reactions [5], we are able to provide precise determinations of the nuclear polarizability effects in light-muonic atoms and to reliably quantify the associated uncertainties [6]. I will review our recent calculations and present an outlook for the future.

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