AARHUS UNIVERSITY

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EFB23

23RD EUROPEAN CONFERENCE ON FEW-BODY PROBLEMS IN PHYSICS

DEPARTMENT OF MATHEMATICS, AARHUS UNIVERSITY, DENMARK

8TH-12TH AUGUST 2016

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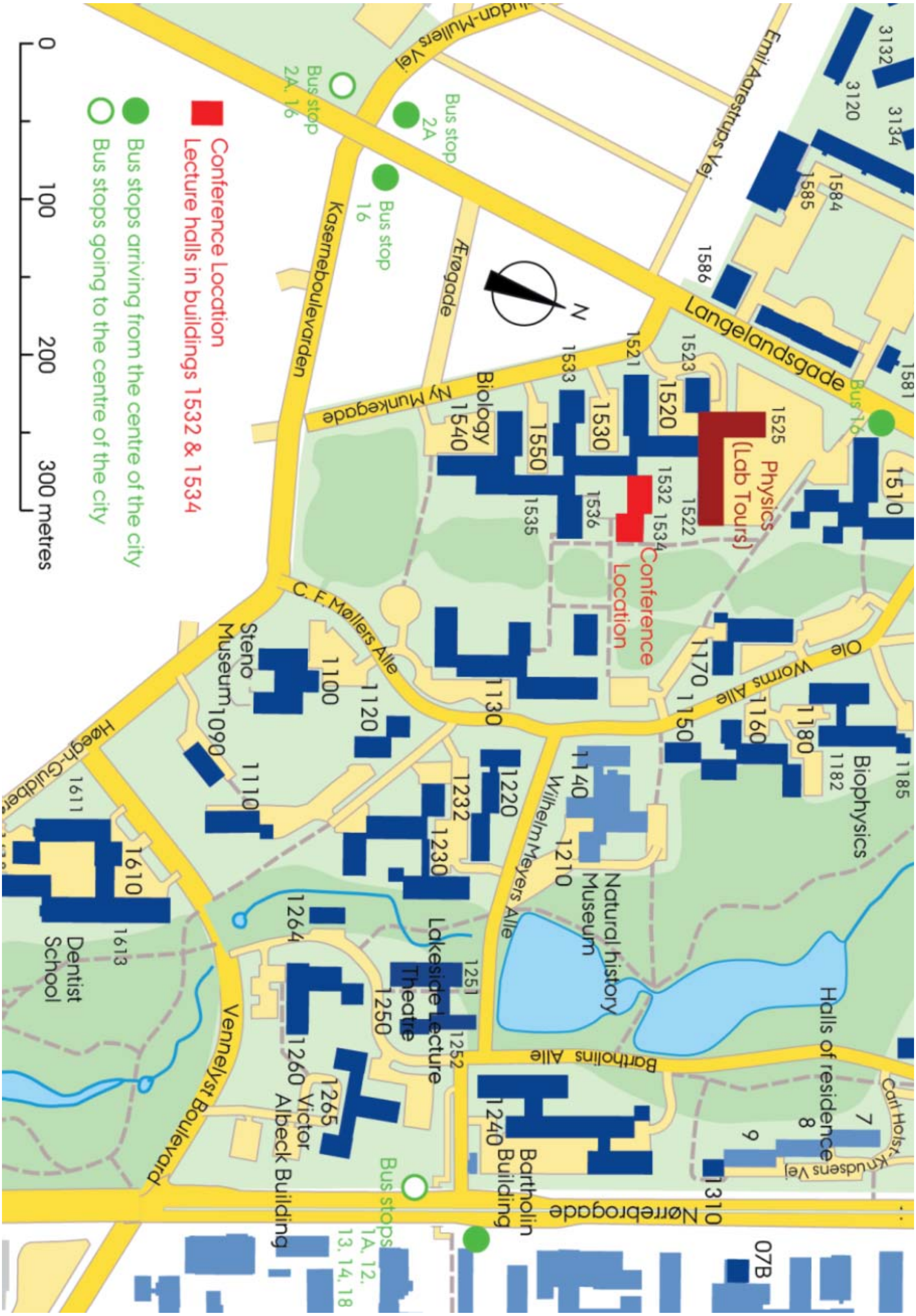
http://conferences.au.dk/efb23


Conference Location
Lecture halls in buildings 1532 & 1534
Bus stops arriving from the centre of the city
Bus stops going to the centre of the city
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100
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300 metres
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Physics
(Lab Tours)
Conference
Location
Langelandsgade
Emil Aarestrups Vej
Kaserneboulevarden
Ny Munkegade
Ærøgade
C. F. Møllers Alle
Ole Worms Alle
Wilhelm Meyers Alle
Bartholins Alle
Nørrebrogade
Vennelyst Boulevard
Bus stop 2A
Bus stop 16
Bus stop 2A, 16
Bus 16
Bus stops 1A, 12, 13, 14, 18
Biology
Biophysics
Steno Museum
Natural history Museum
Lakeside Lecture Theatre
Victor Albeck Building
Bartholin Building
Dentist School
Halls of residence
Carl Holst-Knudsens Vej
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Welcome Reception

All delegates and accompanying persons are invited to an informal reception at the Scandic Aarhus City Hotel (see map on final page) on Sunday the 7th of August from 17:00 to 19:00. Drinks and snacks will be served. Registration for the conference will be available at the reception.

Conference Location

The conference will take place at Aarhus University, Department of Mathematics, building 1534 (see map on page 2). The address is Department of Mathematics, Ny Munkegade 118, DK-8000 Aarhus C. The route to the lecture theaters will be sign-posted.

Registration/Information Desk

The registration desk will be open on Monday from 08:30 to 09:00 at the conference site. In addition the conference secretary will be available at the information desk each day from 09:00. Changes to the program, information on lab tours, excursions, local travel and other messages can be found at the information desk.

Lunch

A buffet lunch will be provided for all participants of the conference. Lunch will be held in a room close to the lecture theaters. The route will be sign-posted. Your conference badge will be required for entry to the lunches.

Badges

The name badge issued to you on registration is your admission to all scientific sessions, lunches and social events. You are kindly requested to wear your badge on all occasions. If the badge is lost, please contact the information desk.

Session chairs

We kindly ask the session chairs to be present in the auditorium at least 10 minutes before the beginning of the session.

Speakers

We kindly ask speakers to ensure that their computers are compatible with the video equipment in good time before the start of the session. Presentations in PowerPoint or PDF format can also be loaded onto the computers in the lecture theaters. Please contact the information desk in case of difficulties.

Prizes

The *Few-Body Award* to two young scientists will be presented on Wednesday at 09:00.

The establishment of the *Faddeev Medal* will be announced on Thursday at 10:20.

Posters

The poster session will take place on Wednesday evening in a room adjacent to the lecture theaters. The posters can be put up on Monday afternoon and they should be removed by Thursday afternoon.

The poster board can be chosen freely from the available ones. Please only use the magnets and tape provided for hanging posters on the boards.

The maximum size for a poster is A0 (84x119 cm) and should be in portrait format. No poster printers are available at the conference.

Internet access/Wi-Fi connection

Wireless internet access is available throughout the University campus.

If your home institution supports eduroam you should connect to the eduroam network with the username and password from your home institution.

Alternatively you can connect to AU-Guest network. After opening a browser, you will be asked to log-in via your account at Google, Facebook, LinkedIn, or Microsoft. If you do not have an account at one of these four services, please contact the information desk to obtain one.

Lab tours

On Tuesday afternoon, after the last session, there will be an opportunity for participants to take a tour of several laboratories in the Department of Physics and Astronomy. There are two tours to choose from:

Tour A - Storage Rings (ASTRID, ASTRID2, SAPHIRA, ELISA)

Tour B – Cold atom labs (BEC, Ion trap group)

Each tour will take about an hour to complete; groups will be escorted by a local guide. If you would like to take a tour, please see the detailed information at the information desk and sign up to participate. There is a limited number of people in any group and the deadline for signing up to join a tour is 15:00 on Tuesday.

Social Event

Excursion to the "Old Town" and Conference Dinner

The Old Town (Den Gamle By) is the world's first open-air museum of urban history and culture. More than 75 historical houses from all over Denmark shape the contours of a Danish town as it might have looked in Hans Christian Andersen´s days, with streets, shops, yards, homes and workshops.

The museum will be open only for EFB23 conference participants from 17:00 on Thursday evening. Upon arrival a welcome drink and snacks will be served at the town square or in the adjacent building (Møntmestergård). From 17:00 to 19:00 you can explore Den Gamle By at your own pace and enjoy the cozy streets. Visit the historical shops and houses such as the bookshop, the ironmonger and the bakery.

At 19:00 the Conference dinner will be served in a building adjacent to the town square (Bendtens Pakhus).

There is no additional cost for this event, the conference dinner is included in the registration fee. You need to present your conference badge at the entrance to the museum.

The Old Town is within walking distance of the conference site. Its location is indicated on the map on final page of this booklet.

Tip: Bring along practical footwear to walk the cobblestone streets.

$^{\varepsilon}\boldsymbol{FB}^{23}$ abstracts

Charge Symmetry Breaking in Light Hypernuclei

Achenbach P. (Mainz University, Germany)
A1 Collaboration

At the Mainz Microtron MAMI the high-resolution spectroscopy of decay-pions in strangeness electro-production is used to extract the Λ hyperon ground state binding energy in ${}^{4}_{\Lambda}\mathrm{H}$ [1]. This binding energy is used together with the ${}^{4}_{\Lambda}\mathrm{He}$ ground state binding energy from nuclear emulsion experiments and with energy levels of the 1^{+} excited state for both hypernuclei from γ-ray spectroscopy to address the charge symmetry in the strong interaction [2]. The full understanding of the large and spin-dependent breaking of this symmetry in the $A = 4$ hypernuclei still remains one of the open issues of hypernuclear physics.

[1] A. Esser et al. (A1 Collaboration), Phys. Rev. Lett. 114, 232501 (2016)

[2] Schulz F. et al. (A1 Collaboration), Nucl. Phys. A (2016), http://dx.doi.org/10.1016/j.nuclphysa.2016.03.015

Photonuclear studies of few-body systems at the High Intensity Gamma Ray Source (HIGS)

Ahmed M.W. (North Carolina Central University/TUNL/Duke University, Durham, NC, USA)

In recent years, experiments at the High Intensity Gamma Ray Source (HIGS) continue to provide precision data on few-nucleon systems over a broad energy range. The focus of these studies have been photodisintegration reactions on light nuclei (A=2-16) at low energies, and Compton scattering reactions on deuteron, helium, and lithium nuclei at higher photon energies but below the pion production threshold. These studies probe the nature of the strong nuclear force as manifested by the macroscopic properties of nucleons at large distance scales, and test nuclear structure models as predicted by the recent cluster and chiral-effective-lattice calculations. The investigations at higher energies measure the electromagnetic and spin response of nucleons to applied photon fields. An overview of the recently completed and planned experiments on light nuclei at HIGS will be presented.

Quasi-three body systems - properties and scattering

Amusia M.Ya. (Hebrew University, Jerusalem, Israel)

We investigate structure and processes in quasi-three-body systems. As the latter, we consider systems of three mutually interacting particles with masses m_e, m_μ, M that obey the inequality $m_e \ll m_\mu \ll M$. We assume that $m_\mu M$ forms a bound state. If mass ratio is $m_e/m_\mu \equiv \beta \ll 1$ then the three-body problem reduces to the two-body scattering or structure of m_e in the field of a bound system $m_\mu M$. We present the properties of considered systems as analytic expressions, namely expansions in powers of the parameter β. As a concrete object, we investigate the electron binding to muonic Helium ($e\mu He$) and scattering by muonic Hydrogen ($e + \mu He$). We pay main attention to the Lamb shift, predicting it for the $1s - 2p$ transitions with the uncertainty of 2 ppm (4 GHz), as well as $2s - 2p$ with uncertainty 0.6 GHz. To reach such an accuracy, we have calculated a number of corrections to the corresponding pure hydrogen values. The predicted numbers deserve experimental verification. While considering the hyperfine splitting of $e\mu He$ we found a non-power term of the order $\beta^2 \ln \beta$ in its expression and achieved good agreement with experiment. For the hyperfine splitting and Lamb shift, the considered system is similar to hydrogen, but with a large and easily polarizable "nucleus". On the contrary, the $e + \mu H$ cross-section is essentially different from that on ordinary Hydrogen in both ground and exited states. There are many other objects of investigation that one could treat using the developed analytic approach.

Role of atomic excitations in search for neutrinoless double beta decay

Amusia M.Ya. (Hebrew University, Jerusalem, Israel)
Drukarev E.G. *Chernysheva L.V.*

Beta-decay of an isolated nucleon is a well-studied three-body problem. In a nucleus two types of double beta-decay can proceed, with and without emission of neutrinos. Observation of the neutrinoless double beta decay would mean that the electron neutrino is a Majorana particle which coincides with its antiparticle. In this talk we consider neutrinoless double beta decay and demonstrate that the emitted electrons loose considerable amount of energy in collisions with electrons of the decaying atom. This loss is important for the determination of the type of the decay process. In search for the neutrinoless decay ejection of the electrons with the energy E equal to the mass difference between the ground states of the daughter and parent atoms is treated as the sign of the neutrinoless process. As it stands now, this decay have not been detected [1]. However the daughter atom can be in an excited state. This leads to the shift of the characteristic energy E to $E^{'} = E + \delta$. We calculate the value of δ in the shake-off approximation (this became possible since the value of E makes several MeV in these transitions) and estimated the corrections caused by the final state interactions between the beta electrons and the atomic shell. The sum over the final states was calculated by employing the closure condition. The electrons of the parent atom were described by the Hartree-Fock functions. We found that for the decays of germanium ($Z = 32$) and xenon ($Z = 54$) which are actual nowadays [1]$\delta \approx -400$ eV. We carried out nonrelativistic calculation for the shift of the limiting energy available for the ejected electrons in double beta decay caused by inelastic processes in electronic shell, and estimated the accuracy of the calculations. Our result confirm the earlier conclusions that the neutrinoless mode have not been observed yet.

[1] B. Schwingenheuer, Ann. Phys. (Berlin) **525**, 269 (2013).

Unstable nuclei in dissociation of light stable and radioactive nuclei in nuclear track emulsion

Artemenkov D.A. (V. I. Veksler and A. M. Baldin Laboratory of High Energy Physics, Joint Institute for Nuclear Research, Dubna, Russia)

Contribution of the unstable nuclei ^{6}Be, ^{8}Be and ^{9}B into dissociation of relativistic nuclei ^{7,9}Be, ^{10}B and ^{10,11}C is under study on the basis of NTE exposed to secondary beams of the JINR Nuclotron.

On the basis of angular measurements 27±5 % of events ^{7}Be→He + 2H can be attributed to ^{6}Be decays. Contribution of the configuration ^{6}Be + n to the ^{7}Be structure is estimated at a level of 8±1 % which is near the value of 5±1 % for the configuration ^{6}Li + p.

Distributions over the opening angle of α-pairs indicate to a simultaneous presence of virtual $^{8}Be_{g.s.}$ and $^{8}Be_{2+}$ states in the ground states of the ^{9}Be and ^{10}C nuclei. The core ^{9}B is manifested in the ^{10}C nucleus with a probability of 30±4 %. $^{8}Be_{g.s.}$ decays in ^{10}C "white"stars always arise through the ^{9}B decays. For ^{10}C "white"stars it have to be assumed that ^{6}Be and $^{8}Be_{g.s.}$ are produced as interfering parts of $2\alpha 2$p ensembles due to impossibility of separation of the ^{6}Be and $^{8}Be_{g.s.}$ decays. Selection of the ^{10}C "white"stars accompanied by $^{8}Be_{g.s.}$ (^{9}B) leads to appearance in the excitation energy distribution of $2\alpha 2$p "quartets"of the distinct peak with a maximum at 4.1±0.3 MeV.

$^{8}Be_{g.s.}$ decays are presented in 24±7 % of 2He + 2H and 27±11 % of the 3He of the ^{11}C "white"stars. ^{9}B decays are identified in "white"stars ^{11}C→2He + 2H constituting 14% of the ^{11}C "white"stars. As in the ^{10}C case $^{8}Be_{g.s.}$ decays in ^{11}C "white"stars almost always arise through ^{9}B decays. On this ground the channel ^{9}B + H amounts 14±3 %.

The $^{8}Be_{g.s.}$ nucleus is manifested in the "white"stars ^{10}B→2He + H with a probability of 34±7 % while ^{9}B constitute 14±4 %. Thus, the decays ^{9}B account roughly for a half of the $^{8}Be_{g.s.}$ statistics. This way, a ground appears to assume a additional contribution of virtual superposition $^{8}Be_{g.s.}$ - $^{8}Be_{2+}$ in the ^{10}B structure likewise the ^{9}Be case.

[1] The BECQUEREL Project WEB site: becquerel.jinr.ru.

[2] C. F. Powell, P. H. Fowler, and D. H. Perkins, Study of Elementary Particles by the Photographic Method (Pergamon, London, 1959), pp. 465472.

[3] P. I. Zarubin "Tomography of the cluster structure of light nuclei via relativistic dissociation"Lecture Notes in Physics 875, Clusters in Nuclei, vol. 3, 5193 (2014), Springer International Publishing (and references herein); arXiv: 1309.4881.

[4] N. K. Kornegrutsa et al. "Clustering features of the ^{7}Be nucleus in relativistic fragmentation"Few-Body Systems, Vol. 55, Nos 8-10, 2014, 1021-1024

[5] D. A. Artemenkov et al. "Charge topology of coherent dissociation of 11C and 12N relativistic nuclei"Phys. At. Nucl. 78, 794799 (2015); arXiv: 1411.5806.

The nuclear contact, momentum distribution, and the photoabsorption cross section

Barnea N. (The Hebrew University, Jerusalem, Israel)
Weiss R. Bazak B.

A few years ago, S. Tan suggested that the properties of universal quantum gases depend on a new characteristic quantity. This quantity, the contact, describes the probability of two particles coming close to each other, i.e. it is a measure of the number of close particle pairs in the system. Utilizing the contact, Tab's theory predicts the energy, pressure and other properties of the system. It was proven right in a series of ultracold atomic experiments. In my talk I will present a generalization of Tan's contact to nuclear systems, introducing the various nuclear contacts, taking into account all possible pair configurations. The leading neutron-proton contact is then evaluated from medium energy photodisintegration experiments. To this end, the Levinger quasi-deuteron model of nuclear photodisintegration is reformulated, and the bridge between the Levinger constant and the contact is established.

Three-body bound states of two bosonic impurities immersed in a Fermi sea in 2D

Bellotti F.F. (Aarhus University, Aarhus, Denmark)
Frederico T. Yamashita M.T. Fedorov D.V. Jensen A.S. Zinner N.T.

We consider the problem of two identical bosonic impurities immersed in a Fermi sea for a broad range of masses and for both interacting and non-interacting impurities in 2D. The pairwise interaction is described for an attractive zero-range potential since we are interested in universal properties, namely those that any potential with the same physics at low energy is able to describe. The problem is solved in momentum space and the two impurities a can attach to a fermion b from the sea and form three-body aab bound states.

The number of universal three-body bound states in vacuum is strongly mass-dependent and increases as one particle becomes much lighter than the others [1]. The energies of these states increase with increasing Fermi momentum k_F in both the cases of interacting ($E_{aa} \neq 0$) and non-interacting ($E_{aa} = 0$) impurities. Since the two- and three-body thresholds are also moving up as k_F increases, three-body bound states are found below the Fermi energy with positive energies. Furthermore, three-body aab states are supported when the two $ab-$subsystems are in a virtual state even for non-interacting impurities, which can be interpreted as a medium-induced Borromean state in 2D [2].

The fate of the states depends highly on two- and three-body thresholds. We study the stability of aab bound states as function of the Fermi momentum when the identical interacting bosonic impurities have the same mass as the fermions from the sea. Our results [2] indicate that cold atomic experiments may be able to deepen the knowledge of 2D three-body systems by looking at two impurities in the presence of a Fermi sea with which the impurities interact. Varying the Fermi momentum, it might be possible to measure the number of atoms lost in the trap, which must have a peak when the three-body system is close to either the two- or three-body continuum [3]. Different bound states may decay into different subsystems [2] and a larger number of bound states can be reached in highly asymmetric mass systems ($m_b/m_a \ll 1$) [1].

We present a mass vs. $\eta = \ln(k_F a_{2D})$ diagram, where a_{2D} is the two-dimensional scattering length, which extends the study about stability of the states as function of the Fermi momentum for a broad range of masses. Next, corrections due to particle-hole fluctuations in the Fermi sea are considered in the three-body calculations and we show that in spite of the fact that they strongly affect both the two- and three-body systems, these effects cancel each other and corrections to results presented in the previous diagram are small.

[1] Bellotti F.F. *et al.*, J. Phys. B 46, 055301 (2013)
[2] Bellotti F.F. *et al.*, New Journal of Physics 18, 043023 (2016)
[3] Kraemer T. *et al.*, Nat. Phys. 440, 3158 (2006)

Differential cross-sections for inelastic positron scattering off the hydrogen atom and helium ion

Belov P.A. (St. Petersburg State University, St. Petersburg, Russia)
Gradusov V.A. Volkov M.V. Yakovlev S.L. Yarevsky E.A.

The potential splitting approach combined with the complex scaling method [1] is applied to the scattering of the positron off the hydrogen atom and positive helium ion at the energies above the positronium formation threshold. In the potential splitting approach, the reaction potential is split into a finite range part and a long range tail part. The solution to the Schrödinger equation with the long range tail of the reaction potential is taken as an incoming wave. The total angular momentum representation is used. The numerical approach is based on the finite element method and has been already verified by calculating resonances in three-body quantum systems [2]. The differential cross-sections for excitation and rearrangement processes have been obtained and compared with the coupled-channel calculations [3]. The resonance structure in the cross-section is observed. The resonance positions calculated with the scattering observables are in a good agreement with the results of other authors as well as with the energy values obtained using the complex scaling technique.

[1] Volkov M.V., Yarevsky E.A. and Yakovlev S.L., Europhys. Lett. 110, 30006 (2015)

[2] Elander N. and Yarevsky E., Phys. Rev. A 57, 3119 (1998)

[3] Archer B.J., Parker G.A. and Pack R.T., Phys. Rev. A 41, 1303 (1990)

The three-body asymptotics with explicitly orthogonalized channels

Belov P.A. (St. Petersburg State University, St. Petersburg, Russia)
Yakovlev S.L.

We propose the method for solving the three-body scattering problem [1] which is based on the hyperspherical adiabatic expansion [2] of the Faddeev components in the asymptotic domain of the configuration space [3]. Asymptotically, the wave function components are expanded over an orthonormal basis of functions depending on the hyperangle. These basis functions are related to the eigenstates of the two-body subsystem and allow one to explicitly orthogonalize the elastic and breakup channels. As a result, we construct the asymptotic boundary conditions for the scattering problem in the hyperspherical adiabatic representation [4]. The application of the method makes it possible to solve the neutron-deuteron scattering problem above the three-body breakup and to obtain scattering amplitudes from the comparison of the solution with the asymptotics in the asymptotic domain [5]. The obtained results are validated by the analytical study of the scattering amplitudes for the model Faddeev equation [6].

[1] Faddeev L.D. and Merkuriev S.P., Quantum Scattering Theory for Several Particles Systems (Kluwer, Dordrecht, 1993)

[2] Macek J., J. Phys. B. 1, 831 (1968)

[3] Merkuriev S.P., Gignoux C., Laverne A., Ann. Phys. 99, 30 (1976)

[4] Belov P.A., Yakovlev S.L., Phys. Atom. Nucl. 77, 344 (2014)

[5] Belov P.A., Yakovlev S.L., Phys. Atom. Nucl. 76, 126 (2013)

[6] Belov P.A., Yakovlev S.L., Bull. Rus. Acad. Sci.: Phys. 80, 237 (2016)

Few-body precursor of the Higgs mode in a superfluid Fermi gas

Bjerlin J. (Mathematical Physics, LTH, Lund University, SE-22100 Lund, Sweden)
Reimann S.M. *Bruun G.M.*

We demonstrate that an undamped few-body precursor of the Higgs mode can be investigated in a harmonically trapped Fermi gas. Using exact diagonalisation, the lowest monopole mode frequency is shown to depend non-monotonically on the interaction strength, having a minimum in a crossover region. The minimum deepens with increasing particle number, reflecting that the mode is the few-body analogue of a many-body Higgs mode in the superfluid phase, which has a vanishing frequency at the quantum phase transition point to the normal phase. We show that this mode mainly consists of coherent excitations of time-reversed pairs, and that it can be selectively excited by modulating the interaction strength, using for instance a Feshbach resonance in cold atomic gases.

A new frontier: Few-body systems with spin-momentum coupling

Blume D. (Washington State University, Department of Physics and Astronomy, Pullman, WA 99164, USA)
Guan Q.

Traditionally, the coupling of the spin and momentum of particles has been investigated in condensed matter systems. More recently, synthetic gauge fields have been realized in cold atom systems, opening up an exciting alternative avenue for the study of phenomena governed by the coupling of the spin and momentum (often referred to as spin-orbit coupling). This talk will summarize our theoretical studies of few-body systems with spin-momentum coupling and short-range two-body interactions.

Structure of neutron-nich Sulfur isotopes

Bouhelal M. (Laboratoire de Physique Appliquée et Théorique, Université Larbi Tébessi, Tébessa, Algérie)
Labidi M. Haas F. Caurier E.

A 0 and 1 $\hbar\omega$ interaction called PSDPF [1] has been developed using a fitting procedure to describe the intruder negative parity states in sd shell nuclei which coexist, at relatively low excitation energies, with the 'normal' positive parity states. PSDPF describes relatively well the energy spectra of positive and negative parity states throughout the sd shell. It is well known that the electromagnetic transition (EMT) strengths are a stringent test of the interaction. Using PSDPF, the strengths (S), in W.u. of transitions connecting sd states of opposite parities (ex.: E1 and E3) can now be calculated and the needed effective charge values for E3 transition were adjusted. In the present work, we are interested to study the spectroscopic properties, energy spectra as well as the EMT, of neutron-rich Sulfur isotopes. The energy spectra of the even-even neutron-rich Sulfur isotopes have been calculated up to 7.4 MeV in ^{32}S, 6.5 MeV in ^{34}S and 6.2 MeV in ^{36}S and compared to available data [2]. The PSDPF describes, in general, quite well both positive and negative parity states in the studied isotopes. The energy differences between calculated and experimental energies vary from 26 to 460 keV in ^{32}S, from 3 to 400 keV in ^{34}S and from 11 to 180 keV in ^{36}S. States with collective character were determined. Concerning the EMT, we calculated the S(E3) in W.u. of these isotopes and compared them to the compiled data of Kibedi [3]. The obtained results are 20, 19 and 16 for ^{32}S, ^{34}S and ^{36}S, respectively, their corresponding experimental values are 30±5, 17±5 and 15±5, respectively. We remark that our results agree very well with experiment. A detailed discussion of the calculation and the comparison to experiment will be presented.

[1] Bouhelal M., Haas F., Caurier E., Nowacki F. and Bouldjedri A., Nucl. Phys. A 864, 113 (2011)

[2] http://www.nndc.bnl.gov/nudat2

[3] Kibedi T. and Spear R.H., Atomic Data and Nuclear Data Tables. 80, 35 (2002)

Electric properties of one-neutron halo nuclei in Halo EFT

Braun J. (TU Darmstadt, 64289 Darmstadt, Germany)
Hammer H.-W.

We exploit the separation of scales in weakly-bound nuclei to compute E2 transitions and electric radii in a Halo EFT framework. The relevant degrees of freedom are the core and the halo neutron. The EFT expansion is carried out in powers of R_{core}/R_{halo}, where R_{core} and R_{halo} denote the core and halo radius, respectively. We include the strong s-wave and d-wave interactions by introducing dimer fields. The dimer propagators are regulated by employing the power-law divergence subtraction scheme and matched to the effective-range expansion in the respective channel. Electromagnetic interactions are included via minimal substitution in the Lagrangian. We demonstrate that, depending on the observable and respective partial wave, additional local gauge-invariant operators contribute in LO, NLO and higher orders. Finally, we present the modifications needed for the extension of our work to higher partial-wave bound states and discuss the consequences for universality in such systems.

∗ This work has been supported by Deutsche Forschungsgemeinschaft (SFB 1245).

On the possible existence of 4n resonances

Carbonell J. (Institut Physique Nucléaire, Univ. Paris-Sud, IN2P3-CNRS, 91406 Orsay Cedex, France)
Hiyama E. Lazauskas R. Kamimura M.

We examine the possibile existence of a narrow resonance in the four neutron system as suggested by a recent experimental result in RIKEN [1]. Since any sensible modification of the nucleon-nucleon (NN) potentials or on the leading contributions of the three-nucelon (NNN) forces will strongly modify the nuclear chart, we have introduced [2] a phenomenological T = 3/2 three neutron force, in addition to a realistic NN interaction, as an artefact to acomodate a 4n resonance close to the threshold.

We inquired what whould be the strength of such a 3n force in order to generate a resonance compatible with the experimental findings. The reliability of the resulting three-neutron force in the T = 3/2 channel is examined, by analyzing its consistency with the low-lying T = 1 states of ^{4}H, ^{4}He and ^{4}Li and the ^{3}H + n scattering.

Two independent configuration space methods are used in solving the four-body problem: the Gaussian expansion method [3,4,5] to solve the Schrodinger equation and the Lagrange-mesh technique applied to solve the Fadeev-Yakubowsky equation [6]. The boundary conditions related to the four-body problem in the continuum are implemented by using the complex scaling method [7,8] and the position of the 4n resonances in the complex energy-plane are determined.

[1] K. Kisamori *et al.*, Phys. Rev. Lett. 116 (2016) no.5, 052501

[2] E. Hyama, R. Lazauska, J. Carbonell, N. Kamimura, Phys. Rev. C93 (2016) no.4, 044004

[3] M. Kamimura, Phys. Rev. A **38**, 621 (1988).

[4] H. Kameyama, M. Kamimura, and Y. Fukushima, Phys. Rev. C **40**, 974 (1989).

[5] E. Hiyama, Y. Kino, and M. Kamimura, Prog. Part. Nucl. Phys. **51**, 223 (2003).

[6] R. Lazauskas and J. Carbonell, Phys. Rev. C **72**, 034003 (2005), Phys. Rev. C **71**, 044004 (2005).

[7] Rimantas Lazauskas, Jaume Carbonell, Few-Body Systems 54 (2013) 967-972

[8] J. Carbonell, A. Deltuva, A.C. Fonseca, R. Lazauskas, Prog. Part. Nucl. Phys. **74**, 55 (2014).

State-of-the-art N3LO chiral interactions

Carlsson B. D. (Chalmers University of Technology, Göteborg, Sweden)
Ekström A. Forssén C. Hebeler K.

Chiral effective field theory (χEFT) is the method of choice for low-energy ab-initio calculations of nuclear properties. It contains a connection to the underlying theory of quantum chromodynamics, and can be systematically improved by the inclusion of higher orders. The inherent possibility to estimate the uncertainty of the method from omitted higher-order terms is crucial for its predictive power. Recently, the full next-to-next-to-next-to-leading order (N3LO) three-body force has been evaluated [1]. This opens up for a thorough investigation into the properties and quality of N3LO chiral interactions. In this talk I will show how such interactions have been obtained, using a simultaneous fit of all low-energy constants (LECs) to available pion-nucleon and nucleon-nucleon scattering data and $A = 2, 3$ bound-state properties. To make this possible and at the same time fully exploiting the advantages of χEFT, we have developed the capability [2] to (i) include estimates of the model uncertainty directly in the fit to data and (ii) use an efficient implementation with automatic differentiation to attain efficient and machine-precise first- and second-order derivatives of the objective function with respect to the LECs. I will also present preliminary results for ^{4}He and ^{16}O with estimates of the uncertainties and comparisons with χEFT predictions at lower orders.

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Solutions of the Bethe-Salpeter equation for fermion boson system

Colasante D. (Phys. Dept. Rome Univ. "Tor Vergata")
Pace E. Salmè G. Frederico T. Viviani M.

After more than half century, in the last few years, to solve the Bethe-Salpeter equations (BSEs), both homogeneous (bound states) and inhomogeneous (scattering states), directly in Minkowski space is becoming feasible (see, e.g. [1-4]). The ladder BSE has been investigated both for a two-scalar interacting system and a two-fermion one, with massive exchanged bosons. The technique, based on an initial Ansatz for the actual solution has been greatly improved by the so-called Light-front projection, i.e. the integration on the $k^- = k^0 + k^3$ component of the interacting-pair relative momentum, The Ansatz is constructed by using the Nakanishi integral representation of the BS amplitude, and this makes possible and extremely effective the second ingredient, since one can analytically treat the singularities present in the BSE, crucial for the fermionic systems. In this contribution, for the first time the extension to an interacting fermion-scalar system, with different masses, will be presented as well as some preliminary numerical results. In perspective, since both the interaction kernel can be improved and self-energies can be included, our investigation is the needed initial step for elaborating new relativistic phenomenological models of composite systems, in hadron physics or other fields.

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Semi-Analytical Approach to the Impenetrable Particles in One-Dimensional Harmonic Traps

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I will introduce our newly developed semi-analytical approach to the strongly interacting two-component particles in one-dimensional harmonic traps. Here, I will go in details on how we use the hard-core properties of the particles in the strongly interacting regime to solve the 1D few-body system analytically. Further, I will illustrate the use of hyperspherical coordinates and some other transformations, which is used in order to solve the problem.

I will illustrate some of the main results for the 2+2 case in form of density-plots and energies for different kind of mass-imbalanced particles. At the end of my talk, I will talk about our on-going work on the 3+1 case and how we manage to solve such imbalanced systems. I will also introduce the audience for our another idea of how one can use the information obtained in strongly interacting and non-interacting limit to predict the wave function and its corresponding energy for any system with some finite arbitrary interaction strength. The talk will be based on the recently submitted articles [1] and [2].

[1] arXiv.org/abs/1511.01702
[2] arXiv.org/abs/1512.08905

Polarized ^{3}He target and final state interactions in SiDIS

Del Dotto A. (INFN - Sezione di Roma)
Pace E. Salmè G Scopetta S. Kaptari L.

At Jlab12, in order to get the flavor decomposition, the parton transverse-momentum distributions (TMDs) in the neutron will be studied through polarized Semi-inclusive deep-inelastic scattering (SIDIS) experiments on ^{3}He, where a high-energy pion (or kaon) is detected in coincidence with the scattered electron. To reliably disentangle nuclear and partonic degrees of freedom it is crucial to get an accurate theoretical description of both initial and final states. In a recent paper [1], we have carried out a study of a SIDIS process on polarized ^{3}He where a spectator nucleon-pair in a deuteron state is detected. Within a non-relativistic framework, we have taken into account the very challenging issue of the final state interaction, between the observed deuteron and the remnant, through a distorted spin-dependent spectral function, based on a generalized eikonal approximation. The ^{3}He initial state was taken from the careful calculation with the AV18 NN interaction performed by the Pisa group. In this contribution, the extension to the standard SIDIS, where a pion (or a kaon) is detected, and the recoiling nucleon-pair can be in any state, will be presented [2] together with preliminary results illustrating the possibility of a reliable extraction of the neutron TMDs. It has to be pointed out that a Montecarlo for the analysis of the forthcoming JLAB experiment on polarized ^{3}He is under construction, exploiting our treatment of the final state interaction.

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Nucleon transfer reactions in few-body nuclear systems

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Three- and four-body scattering is described solving Faddeev-Yakubovsky or equivallent Alt-Grassberger-Sandhas integral equations for transition operators in momentum-space [1]. Several realistic nuclear interaction models are used; the Coulomb force between charged particles is taken into account via the screening and renormalization method.

In the three-body sector we calculate the proton transfer reaction (d, n) in the system consisting of a nuclear core and two nucleons. For a weakly bound final nucleus as ^{8}B or ^{17}F the calculation of the (d, n) reaction is more demanding in terms of the screening radius as compared to the (d, p) reaction. The calculations using nonlocal optical potential provide quite successful description for the differential cross section of the $^{16}\mathrm{O}(d, n)^{17}\mathrm{F}$ reaction, especially for the transfer to ^{17}F excited state $1/2^+$, confirming the one-proton halo nature of this state [2].

In the four-nucleon sector first calculations above the breakup threshold emerged few years ago and mostly were limited to nucleon-trinucleon elastic scattering and charge-exchange reactions [3]. Following recent developments in the description of deuteron-deuteron elastic scattering [4], we present the current work in progress on (d, p) and (d, n) transfer reactions in deuteron-deuteron collisions up to 25 MeV lab energy. Differential cross sections, deuteron analyzing powers, outgoing nucleon polarization, and deuteron-to-neutron polarization transfer coefficients are calculated. Due to the large spatial size of the deuteron, the calculation of transfer reactions is more demanding in terms of partial waves as compared to nucleon-trinucleon scattering. This manifests itself in a complicated angular dependence of observables, exhibiting a number of local minima and maxima. Nevertheless, well converged results are obtained and good overall agreement with the experimental data is found. The total breakup cross section is calculated as well via the optical theorem.

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Antiferromagnetic Heisenberg Spin Chain of a Few Cold Atoms in a One-Dimensional Trap

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Murmann S. Zürn G. Bjerlin J. Becker D. Reimann S.M. Lompe T. Jochim S. Santos L.

We consider ultracold atoms with spin and strong spin-independent delta interaction in a one-dimensional harmonic trap. These systems fermionize in the limit of infinite repulsion. Moreover, they form a spin chain [1] and the interactions between the spins are given by a Heisenberg model [2]. Such spin chains have been realized recently in Selim Jochim's group in Heidelberg with a few atoms in the antiferromagnetic state and the spin configuration has been detected [3]. We will first develop the theoretical model for the description of spin chains consisting of fermionized particles and then apply it to the experiment. Finally, we present momentum distributions of large systems in various regimes [4].

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The strong decay mode $J/\psi p$ for the pentaquark states $P_c^+(4380)$ and $P_c^+(4450)$ in $\Sigma_c\bar{D}^*$ molecular scenario

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Lü, Qi-Fang

The strong decay channels of $P_c^+(4380) \to J/\psi p$ and $P_c^+(4450) \to J/\psi p$, under the $\Sigma_c\bar{D}^*$ molecular state ansatz, are estimated with the various spin-parity assignments. Our results show that all the P-wave $\Sigma_c\bar{D}^*$ assignments are excluded, while the S-wave $\Sigma_c\bar{D}^*$ pictures for $P_c(4380)$ and $P_c(4450)$ are both allowed by the present experimental data. Moreover, the $J^P = 3/2^-$ $\Sigma_c^*\bar{D}$ and $\Sigma_c^*\bar{D}^*$ molecules are also discussed in the heavy quark limit, and we find that the $\Sigma_c^*\bar{D}$ system for $P_c(4380)$ is possible [1]. More experimental information on spin-parities and partial decay widths and theoretical investigations on other decay modes are needed to clarify the nature of the two P_c states. Finally, the production of the neutral P_c states is also discussed [2].

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Many-body localisation and spin-charge separation in strongly interacting one-dimensional disordered systems

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Recently, the topic of many-body localisation (MBL) has received a lot of interest both theoretically and experimentally [-1,2]. During this time there has also been a drive to obtain solutions for multicomponent few-body systems in the strongly interacting regime [3,4]. These two topics have been largely developed separately. However, the generality of the latter as far as external potentials are concerned – including random and quasi-random potentials– and their shared spatial dimensionality (i.e. one dimension), makes it a potentially interesting way of dealing with MBL in the strongly-interacting regime. Here, we look into using these advances together. By using tools developed for few-body systems (the Aarhus code CONAN [5] in particular) we look to gain insight into MBL in spin systems. In this case, charge and spin degrees of freedom are well separated, and while a disordered potential will result in the localisation of particles [6], i.e. the charge – in the strongly interacting limit, there is the possibility for the spins to be delocalised, or localised independently of the particles localisation or absence thereof. We will present our results for up to 20 particles (spins), and discuss the different "phases" (localised, delocalised and mixed) that the spin degrees of freedom can have.

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Recent results in nuclear chiral effective field theory

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Remarkable progress is being made towards quantitative understanding of nuclear forces and electroweak exchange current operators in the framework of chiral effective field theory. I will present the status of nuclear chiral EFT and discuss selected applications of the recently developed fifth-order nucleon-nucleon potentials [1], along with the novel approach to quantify the theoretical truncation errors [2], to nucleon-deuteron scattering and low-energy properties of light nuclei [3].

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Program of Compton Scattering Studies on Light Nuclei at HIGS

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Compton at HIGS Collaboration

The High Intensity Gamma Source (HIGS) at Duke University delivers intense monoenergetic photon beams with high degrees of linear or circular polarization by backscattering of free-electron laser (FEL) photons [1]. To exploit the unique capabilities of this facility, we have begun an ambitious program of Compton scattering studies on light (A = 1-6) nuclear targets with the objective of determining the nucleon electromagnetic polarizabilities. A new state-of-the-art unpolarized cryogenic target system has recently been developed at HIGS that can liquefy hydrogen, deuterium, ^3He and ^4He for the primary purpose of Compton scattering. An initial commissioning run on ^4He was performed in September 2015 as a precursor to longer runs on hydrogen/deuterium in the future. Experiments on deuterium will elucidate the electromagnetic polarizabilities of the neutron (α_n and β_n) and provide high precision data for comparison with chiral Effective Field Theory calculations [2] and also with recent data coming from MAX-Lab at Lund [3,4]. Our first production run on deuterium at $E_\gamma = 65$ MeV was performed in April 2016, and we obtained excellent statistics in the 300-hour running period. A follow-up deuterium run is planned at $E_\gamma = 85$ MeV for June 2016. A new proposal for Compton scattering on ^3He was just approved by the HIGS PAC – this experiment would constitute the first Compton data ever taken on a ^3He target and is expected to run in Spring 2017. This would provide an alternate means of accessing the neutron electromagnetic polarizabilities in an entrance channel independent of the usual deuteron experiments. Another experiment that is planned in the future will measure the photon beam asymmetry for 85-MeV linearly polarized photons incident on an unpolarized proton target to get a model-independent determination of the proton polarizabilities (α_p and β_p) – these data will be compared with recent results from Mainz in the energy range 80-150 MeV [5]. In this talk, an overview of the Compton program at HIGS will be presented, preliminary results from the recent deuterium experiments at 65 and 85 MeV will be shown, and prospects for future measurements and their impact will be discussed.

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From J/ψ to LHCb pentaquarks

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Since the mythical date of November 1974, when the J/ψ particle was discovered, two important dates have recently appeared in the field of the charm physics. In 2003 Belle collaboration discovered two new states, the $X(3872)$ and the $D_s(2317)$, whereas CLEO collaboration measured the properties of the $D_s(2460)$. In 2015 the LHCb collaboration found two exotic structures in the $J/\psi p$ channel that are compatible with pentaquark states. None of these particles can be accommodated in the predictions of the naive (but successful quark models).

Constituent quark models have achieved a reasonable description of the low-lying states of the meson and baryon spectrum. However, as we approach a two-particle threshold, the residual interaction between them can form molecular states. Then, one can expect molecular structures near each meson-meson or baryon-meson threshold. These structures can coincide or not with the quantum numbers of a $q\bar{q}$ or qqq state. This is the case of the new states because they all are in the vicinity of a threshold. It is worth to notice that the description of this type of structures is tricky from a theoretical point of view because the strength of the residual interaction is usually model dependent and one can generate spurious states if this interaction is not under control.

In this work we use to study these new structures, a constituent quark model [1] that has been applied to a wide range of hadronic observables, and therefore, it has all parameters completely constrained . The model has been able to reproduce the properties of the X(3872), described as a mixture of $c\bar{c}$ and $D\bar{D}^*$ states [2]. Moreover the spectrum of the P-wave charm-strange mesons are well reproduced if DK and $DK*$ structures are taken into account [3].

As the $P_c^*(4380)$ and $P_c^*(4450)$ states lie near the $\bar{D}\Sigma_c^*$ and the $\bar{D}^*\Sigma_c$ thresholds we investigate possible molecular structures with this composition. We found a $\bar{D}\Sigma_c^*$ bound state with $J^P = \frac{3^-}{2}$ and M=4385 MeV/c^2 decaying to $J/\psi p$ and $D^*\Lambda_c$ which may be identified with the $P_c^*(4380)$ pentaquark, although the predicted width is smaller than the experimental one. With respect to the $P_c^*(4450)$ pentaquark we found three candidates in the $\bar{D}^*\Sigma_c$ channel with $J^P = \frac{1^-}{2}$, $J^P = \frac{3^-}{2}$ and $J^P = \frac{3^+}{2}$ and almost degenerated masses around M=4460 MeV/c^2. Finally we predict two more pentaquark states: a $\bar{D}\Sigma_c$ bound state with $J^P = \frac{1^-}{2}$ and mass M=4321 MeV/c^2 and a $\bar{D}^*\Sigma^*{}_c$ with $J^P = \frac{3^-}{2}$ and mass M=4523 MeV/c^2.

Our results show that a constituent quark model which is able to describe the ordinary spectrum of charmonium is also able to provide a good description of the new states reported recently, when molecular structures are included in the calculation.

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Benchmark results for few-body hypernuclei

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In view of an increasing interest in the physics of hypernuclei, accompanied by an intense experimental activity, it is necessary to understand how well theory is able to account for experimental results, discriminating among different interaction models. To this aim it is important to understand the degree of accuracy of the methods used to solve the Schrödinger equation for systems with strange and non-strange baryons. Therefore we will present benchmark results obtained in light hypernuclei with four different few/many-body methods and different NN and NY potentials. The perspectives for extending the calculations to more complex interactions and to systems with double strangeness will be discussed.

Electromagnetic selection rules for ^{12}C in a 3 α cluster model

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The recent successful application of the algebraic cluster model [1] to the energy spectrum of ^{12}C has brought a new impetus on spectroscopy of this and other $\alpha-$conjugate nuclei. In fact, known spectral properties have been reexamined on the basis of vibrations and rotations of three α particles at the vertexes of an equilateral triangle and new excited states have been measured that fit into this scheme [2]. The analysis of this system entails the application of molecular models for rotational-vibrational spectra to the nuclear context and requires deep knowledge of the underlying group-theoretical properties, based on the $\mathcal{D}_{3h}$ symmetry, similarly to what is done in quantum chemistry. We have recently analyzed [3] the symmetries of the model and the quantum numbers in great depth, reproducing the all-important results of Wheeler [4] and we have derived electromagnetic selection rules for the system of three α particles, finding, for example, that electric dipole E1 and magnetic dipole M1 excitations are excluded from the model. The lowest active modes are therefore E2, E3,$\cdots$ and M2, M3, $\cdots$ although there are further restrictions between certain types of bands. The selection rules summarized in the table below provide a clear way to decide if a certain state belongs to the alpha cluster model or not and they might help to the further unravel the electromagnetic properties of ^{12}C. With the perspective of new facilities (such as ELI) where photo-excitation and photo-dissociation experiments will play a major role, a complete understanding of e.m. selection rules as a tool to confirm or disprove nuclear stucture models, is mandatory.

$\Gamma(in.) \leftrightarrow \Gamma(fin.)$	Electric	Magnetic
$A_1' \leftrightarrow A_1'$	E2,3,$\cdots$	M4,6,7,$\cdots$
$E' \leftrightarrow E'$	E2,3,$\cdots$	M2,3,$\cdots$
$A_1' \leftrightarrow E'$	E2,3,$\cdots$	M2,3,$\cdots$

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Four-boson scale symmetry breaking and limit cycle

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We present an approximate solution to the four-boson bound state by solving the scale-symmetric form of the Faddeev-Yakubovski (FY) equations with contact interaction at large momentum. For that, we generalize the Danilov technique [1] used to treat the zero-range three-boson problem, exploring the scale symmetry of the Skorniakov-Ter-Martirosian equation, leading to the well-known log-periodic solution carrying the three-body scale. Within our approach, we show that the geometrical ratio between two consecutive tetramer energies (obtained in the zero energy limit for the triton binding) is given by $\exp(2\pi/s_4)$, with $s_4 = 1.25167$. This new limit cycle, which is independent of the trimer one, was verified numerically by solving the FY equations at the unitary limit [2]. Our approximate analytical solution is consistent with this values.

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Three-body wave functions in the continuum. Application to the Coulomb case

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In this work we investigate the connection between discretized three-body continuum wave functions, in particular via a box boundary condition, and the wave functions computed with the correct asymptotic behaviour. The three-body wave functions are in both cases obtained by means of the adiabatic expansion method. The information concerning all the possible incoming and outgoing channels, which appears naturally when the continuum is not discretized, seems to be lost when the discretization is implemented. In this work we show that both methods are fully equivalent, and the full information contained in the three-body wave function is actually preserved in the discrete spectrum. Therefore, in those cases when the asymptotic behaviour of the wave function is not known analytically, i.e., when the Coulomb interaction is involved, the discretization technique can be safely used.

Also, when applied to three-body systems interacting only through the Coulomb potential, this method provides the regular three-body Coulomb wave functions for the problem under investigation. A method to obtain the corresponding irregular Coulomb wave functions is also described. These regular and irregular Coulomb functions can be used in order to extract the S-matrix for reactions where, together with some short-range potential, the Coulomb interaction is also present. The method is illustrated with the three-alpha system.

***Ab initio* calculations of light hypernuclei**

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Navrátil P. Wirth R. Roth R. Gal A.

In the present contribution we report on *ab initio* calculations of light nuclear systems with strangeness. Recently, we developed the no-core shell model (NCSM) technique with strangeness degrees of freedom and applied this method in calculations of light Λ hypernuclei [1]. Two equivalent formulations of hypernuclear NCSM were developed, both of which include explicit Λ and Σ hyperons together with $\Lambda - \Sigma$ conversion requiring a proper treatment of different baryon species and coupled-channel interactions. The first formulation utilizes a many-body harmonic oscillator (HO) basis defined in relative Jacobi coordinates and allows to perform calculations in very large model spaces for few-body hypernuclear systems. With increasing number of particles a formulation of the NCSM in a basis of Slater determinants of single-particle HO wave functions becomes more efficient. In our calculations we employed state-of-the-art realistic two- and three-body interactions derived from chiral perturbation theory. We used chiral SU(3) hyperon–nucleon interactions at LO [2], together with N3LO nucleon–nucleon [3] and N2LO three-nucleon [4] interactions. We demonstrated that the NCSM is a powerful and reliable technique to study hypernuclear systems from first principles. It allowed us to perform for the first time systematic *ab initio* calculations of light s- and p-shell Λ hypernuclei as well as to study topical issues such as charge symmetry breaking in mirror hypernuclei [5]. In this talk I will briefly introduce the hypernuclear NCSM and report on our recent results.

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Break-up channels in muon capture on ^{3}He and ^{3}H

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Muon capture reactions on light nuclei have been investigated experimentally and theoretically for many years. While early results were described in Refs. [1-3], more recent theoretical work, focused on the $\mu^- + ^2\text{H} \rightarrow \nu_\mu + n + n$ and $\mu^- + ^3\text{He} \rightarrow \nu_\mu + ^3\text{H}$ reactions, was summarized in Refs. [4-6].

In Ref. [7], we combined our expertise from momentum space treatment of electromagnetic processes [8-9] and from the potential model approach developed in Ref. [4] to confirm earlier predictions for the $\mu^- +^2 \text{H} \rightarrow \nu_\mu + n + n$ and $\mu^- +^3 \text{He} \rightarrow \nu_\mu +^3 \text{H}$ reactions and to obtain for the first time realistic estimates for the total rates of the muon capture reactions on ^{3}He in the $n + d$ and $n + n + p$ break-up channels. Although the bulk of our results in Ref. [7] was acquired with the single nucleon weak current operator, we could also include two-nucleon weak current operators from Ref. [10].

Muon capture on ^{3}H has attracted less attention. Theoretical studies of this reaction were started in the seventies of the 20th century [11-13] and continued in the eighties [14]. Those early calculations were performed predominantly in the configuration space, using two-nucleon potential models available at that time.

We decided to investigate this reaction, since it allows one to study the neutron-neutron interaction and the three-neutron force acting exclusively in the total isospin $T = 3/2$ state. Besides, its study is for us the natural next step after the $\mu^- +^3 \text{He} \rightarrow \nu_\mu + n + n + p$ reaction has been considered. In this contribution we present results for the total and differential capture rates obtained for the first time with modern semi-phenomenological forces. Our predictions for the three-body break-up of ^{3}H are calculated with the AV18 [15] potential, augmented by the Urbana IX three-nucleon force, incorporating all final state interactions.

We believe that our momentum space framework, which allows us to describe capture reactions on all the $A \leq 3$ nuclei, constitutes a firm base for the future, when fully consistent results for the nuclear forces and electro-weak current operators derived within chiral effective field theory become available.

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Mystery of ^{9}He, exotic neutron rich light nuclei, and a way to them through their isobar analog states

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The original interest to the ^{9}He spectrum is evidently related with an unusual N to Z ratio which is 3.5. During the last 25 years the properties of the lowest states in ^{9}He were under intensive experimental and theoretical investigation. It appears that the nuclear structure of these states ($1/2^{+}$ and $1/2^{-}$) can not be explained on the ground of our present knowledge. Indeed, different experiments including a recent one [1, see history there] of (d,p) reaction induced by a rare ^{8}He beam, claimed a narrow (100 keV) $1/2^{-}$ first excited state. Various model calculations including recent ab initio approaches [2] could not reproduce experimental results giving ten times larger widths for the $1/2^{-}$. This clear contradiction between experiment and contemporary theory could be a sign of an unusual nuclear structure at the border of nucleon stability.

We used a relatively novel experimental technique of obtaining information on neutron rich exotic nuclei through their analog states in neighbouring nuclei populated in resonance reactions with rare beams. We have made measurements of the ^{8}He+p resonance elastic scattering to obtain information on T=5/2 levels in ^{9}LI. We used ^{8}He beam with energy of 4 MeV/A and intensity 10^{4}pps provided by the TRIUMF facilities. The measurements of the excitation function were made by Thick Target Inverse Kinematics method [3-5] (TTIK). As a result, our high resolution and high counting statistics study[6]of the excitation functions for the ^{8}He+p elastic scattering did not reveal any narrow structures which could be related with the claimed states in ^{9}He. However we observed a strong Wigner cusp at the threshold of decay of ^{9}Li into the ^{8}Li(T=2,0^{+}) +n channel. This finding gave evidence for the presence of a l=0 resonance as the isobar analog of the ^{9}He ground state. Evidently, these results show for a new binding energy of ^{9}He as well as its different properties. I'll present the results of this work and its consequences for some very exotic nuclei, and consider the perspective of the present experimental approach for future studies.

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Universality studies in the heavy-heavy-light Efimov system

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With the advent of recent experimental investigations[1-3] of Efimov physics in heavy-heavy-light (HHL) systems such as Cs-Cs-Li, it is of increasing interest to understand which aspects exhibit the role of van der Waals universality. Much of the interest is in discovering the degree of universality and its role in controlling the positions and the lineshapes of recombination resonances, as well as other features in the spectrum. This talk will review some of the ongoing theoretical investigations of these aspects and show some comparisons with experimental results.

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Antinucleon-nucleon interaction in chiral effective field theory

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We present results of an exploratory study of the $\bar{N}N$ interaction within chiral effective field theory [1]. The $\bar{N}N$ potential is derived up to next-to-next-to-leading order, based on a modified Weinberg power counting, in close analogy to pertinent studies of the nucleon-nucleon interaction. The low-energy constants associated with the arising contact interactions are fixed by a fit to phase shifts and inelasticities provided by a recently published phase-shift analysis of antiproton-proton scattering data.

Based on this $\bar{N}N$ interaction we provide predictions for the proton electromagnetic form factors G_E and G_M in the timelike region, close to the $\bar{N}N$ threshold. It turns out that the steep rise of the effective form factor for energies close to the $\bar{p}p$ threshold can be explained solely in terms of the $\bar{p}p$ interaction. The corresponding experimental information is quantitatively described by our calculation. Furthermore, we show that the enhancement in the $\bar{p}p$ near-threshold invariant mass spectrum measured in J/ψ and ψ' decays can be likewise understood in terms of the $\bar{p}p$ interaction [3].

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Solvable Models for a Few Atoms in a Few One-Dimensional Wells

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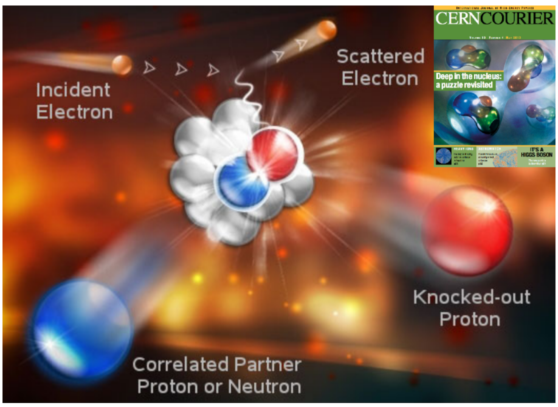
This project identifies networks of one-dimensional, few-particle, few-well models that can be smoothly connected by tuning trap shape and two-body interaction parameters. Solvable models within these networks are identified and analyzed by exploiting symmetries in few-body configuration space and phase space. In one-dimension, ordering permutation symmetry is particularly effective for generating new models. Ordering permutation symmetry is distinct from particle permutation symmetry and arises when there are similar regions in configuration space that are completely disconnected due to unitary interactions and/or infinite well barriers. Experiments with a few atoms or with ultracold gases trapped in effectively one-dimensional wells are analyzed by comparison with nearby solvable models using approximation schemes like perturbation theory or variational methods. The transition from systems with a few particles in a few wells to systems with many particles in large lattices can be explored using these techniques.

Short-Range Fermion Correlations: From neV to MeV

Hen O. (Laboratory for Nuclear Science, MIT)

The atomic nucleus is composed of two different kinds of fermions, protons and neutrons. If the protons and neutrons did not interact, the Pauli exclusion principle would force the majority fermions, usually neutrons, to higher average momentum. In this talk I will present results from high-energy proton and electron scattering experiments, which show that short-range interactions between the fermions form correlated, high-momentum, neutron- proton pairs. Thus, in neutron-rich nuclei the probability of finding a high- momentum ($k > k_{\mathrm{Fermi}}$) proton (a minority Fermion) is greater than that of a neutron (a majority Fermion). This has wide ranging implications for atomic, nuclear, atomic, and astro physics, including neutrino-nucleus interactions, the EMC effect, the NuTeV anomaly, the nuclear symmetry energy and more. This feature is universal for imbalanced interacting Fermi systems and can also be observed experimentally in two-spin states ultra-cold atomic gas systems.



Combining few-body cluster structures with many-body mean-field methods

Hove D. (Aarhus University, Aarhus, Denmark)
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Nuclear cluster physics implicitly assumes a distinction between groups of degrees-of-freedom, that is the (frozen) intrinsic and (explicitly treated) relative cluster motion. We formulate a realistic and practical method to describe the coupled motion of these two sets of degrees-of-freedom.

We derive a coupled set of differential equations for the system using the phenomenologically adjusted effective in-medium Skyrme type of nucleon-nucleon interaction. We select a two-nucleon plus core system where the mean-field approximation corresponding to the Skyrme interaction is used for the core [1]. A hyper-spherical adiabatic expansion of the Faddeev equations is used for the relative cluster motion [2]. The coupled equations are solved by iteration, where the fixed three-body structure gives rise to an external field on the core nucleons, and the nucleon-core potential for the three-body calculation is obtained with the nucleon-nucleon interaction folded into the core mean-field wave function. The Pauli principle is accounted for by excluding the states occupied by core nucleons, and vice versa, in each of the iterative steps.

We shall specifically compare both the structure and the decay mechanism found from the traditional three-body calculations with the result using the new boundary condition provided by the full microscopic structure at small distance. The extended Hilbert space guaranties an improved wave function compared to both mean-field and three-body solutions. We shall investigate (i) how borromean halos emerge from the initial mean-field structure, (ii) structures of ^{22}C (^{20}C+n+n) and ^{34}Ne (^{32}Ne+n+n), and (iii) both structure and decay mechanism of the most important rapid-proton waiting points around $A \simeq 70$ [3].

In conclusion, we have developed a method combining nuclear few- and many-body techniques without loosing the descriptive power of each approximation at medium-to-large distances and small distances respectively. The coupled set of equations are solved self-consistently, and both structure and dynamic evolution are studied.

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Structure and decay at rapid proton capture waiting points

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The location of the proton dripline is essentially known from experiments. However, both structures and decay mechanisms are still not determined, although of great importance for the synthesis of heavy nuclei. In particular, the rapid-proton process is stalled at the so-called waiting points [1] with borromean structure where two protons are bound even though one proton is unbound. The weak binding suggests that the three-body treatment is appropriate as demonstrated for a number of lighter systems at both nucleonic driplines.

We use the three-body assumption to investigate the region around $A \simeq 70$, where we compute reaction rates for the radiative capture of two protons [2]. One key quantity is here the photon dissociation cross section for the inverse process where two protons are liberated from the borromean nucleus by photon bombardment. We find a number of peaks at low photon energy in this cross section where each peak is located at the energy corresponding to population of a three-body resonance. Thus, for these energies the decay or capture processes proceed through these resonances. However, the next step in the dissociation process still has the option of following several paths, that is either sequential decay by emission of one proton at a time with an intermediate two-body resonance as stepping stone, or direct decay into the continuum of both protons simultaneously. We show that the preferred decay mechanism is sequential and direct for high and low energy, respectively.

The astrophysical reaction rate is obtained by folding of the cross section as function of energy with the occupation probability for a Maxwell-Boltzmann temperature distribution. The reaction rate is then a function of temperature, and of course depending on the underlying three-body bound state and resonance structures. We show that a very simple formula at low temperature reproduces the elaborate numerically computed reaction rate. The key ingredient is the dominating resonance energy and its width, which shall be discussed in detail.

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Four-body treatment of inclusive breakup of Borromean nuclei

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Frederico T. Carlson B.V.

We derive an expression for the inclusive breakup cross section of Borromean nuclei within a four-body model. The observed particle is treated as a spectator. The cross section is found to be similar in structure to that of two-fragment projectiles[1], and is proportional to the matrix element with a source function $\hat{\rho}_{x_1,x_2} = (\chi^{(-)}_{b,DWBA}|\Psi^{(+)}_{4B})$, where b is the observed fragment, and x_1 and x_2 are the interacting fragments (in e.g. ^{6}He $= \alpha + n + n$, b is α and x_1 and x_2 correspond to the neutrons). The DWBA + corrections version of the theory is obtained using Faddeev-Yakubovski equations representing the four-body wave function $|\Psi^{(+)}_{4B} >$. The Faddeev approach to the inclusive breakup of two-fragment projectile of Ref.[2] is used as a guide. Application of the theory to the spectrum of α's in the $^6\mathrm{He} + {}^{208}\mathrm{Pb} \rightarrow \alpha + (n + n + {}^{208}\mathrm{Pb})$ reaction is presented.

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Studies of Final-State Interactions via Helicity Asymmetries in Exclsuive Pseudoscalar Meson Photoproduction off Deuteron

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CLAS Collaboration

Exclusive meson photoproduction off deuteron is a great tool to study final-state (FSI) interactions between the hadrons produced in the scattering of the incident photon off one of the target nucleons and the spectator nucleon. Final-state interactions are important for several reasons. On one hand, FSI in the reaction $\gamma d \to K^+\Lambda n$ allow to access the dynamics of Λn elastic scattering and provide a method of studying the hyperon-nucleon interaction that is complementary to hypernuclear spectroscopy. On another hand, as deuteron is often used as a neutron target, FSI in reactions such as $\gamma d \to pp\pi^-$ are physics mechanisms contributing to the reaction dynamics in addition to the quasi-free $\gamma n \to \pi^- p$ photoproduction off the bound neutron and their understanding is critical for the estimate of observables off the free nucleon. High-statistics exclusive measurements of meson photoproduction off deuteron provide information about the 3-momentum vector of the spectator nucleon. This allows not only to separate experimentally FSI from quasi-free production, but also to map the evolution of observables over the virtuality of the spectator-nucleon 3-momentum and to extract the free-nucleon observables through an extrapolation to nucleon virtuality of zero. In this talk we will show preliminary results for beam-helicity asymmetries for the reactions $\vec{\gamma} d \to K^+\Lambda n$, $\vec{\gamma} d \to pp\pi^-$, and $\vec{\gamma} d \to p\pi^+\pi^- n$ and their evolution over the spectator-nucleon virtuality. The data were obtained with the CEBAF Large Acceptance Spectrometer located in Hall B at Thomas Jefferson National Accelerator Facility in experiment E06-103. The reactions were initiated by circularly polarized photon beam with energies between 0.5 GeV and 2.5 GeV incident on unpolarized deuteron target. The experiment collected about 2×10^{10} events with multiple charged particles in the final state. The large statistics provides statistically meaningful FSI event samples and allows to extract beam-helicity asymmetries over a wide range of spectator-nucleon momentum, while the large detector acceptance allows to probe various parts of the reaction phase space where different FSI may dominate. We will present a model-independent interpretation of our $\vec{\gamma} d \to K^+\Lambda n$ results in terms of Λn elastic scattering, which is important for the study of the hyperon-nucleon interaction via FSI in hyperon photoproduction. These results are part of a bigger program to extract a large set of polarization observables for hyperon photoproduction in order to constrain the free parameters of hyperon-nucleon potentials, which are critical for the understanding of hypernuclear matter and neutron stars. We will also discuss the extraction of polarization observables for the $\gamma n \to p\pi^-$ and $\gamma p \to p\pi^+\pi^-$ reactions (off a free nucleon) using our helicity asymmetries for the reactions $\vec{\gamma} d \to pp\pi^-$ and $\vec{\gamma} d \to p\pi^+\pi^- n$ (off a bound nucleon), respectively.

Three-body potentials in α-particle model of light nuclei

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The α-particle (^{4}He nucleus) is, because of its stiffness, considered as a constitution of many of nuclear states. The ^{9}Be nucleus as α-α-n system and ^{12}C nucleus as α-α-α system are good examples of such a picture, and also have attracted researchers' interests because their reactions at low energies play important roles in nucleosynthesis processes at some stages in stellar evolution. As three-body systems, every complicacies arising from nucleon structure of the α-particle are assumed to be incorporated in their interactions: two-body potentials, $V_{\alpha\alpha}$ and $V_{\alpha n}$, and three-body potentials (3BPs), $V_{\alpha\alpha n}$ and $V_{\alpha\alpha\alpha}$. While the two-body potentials are constructed to reproduce available two-body observables, there is a large amount of ambiguity in 3BP's.

In this contribution, to reduce ambiguities in $V_{\alpha\alpha n}$ and $V_{\alpha\alpha\alpha}$, a possible relation between these 3BP's is derived using a simplified folding model. I will show that there exist some sets of $V_{\alpha\alpha\alpha}$ and $V_{\alpha\alpha n}$ that satisfy this relation, and that reproduce the observed properties of the first ^{12}C 0^+ resonant state (known as the Hoyle state) [1,2,3] and the cross section peak in the $^9\text{Be} + \gamma \to \alpha + \alpha + n$ reaction at energy just above the threshold. This makes a constraint on the 3BPs in the α-α-n and α-α-α systems to encourage calculations of these systems.

The constraint is expected to give an insight into the nature of the three-body states. For example, there has been a discussion on the peak of the $^9\text{Be} + \gamma \to \alpha + \alpha + n$ cross section: whether it comes from an α-α-n resonant state or virtual state [4]. I will show that the $V_{\alpha\alpha n}$ satisfying the constraint suggests that the peak has its origin from a resonant state.

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Investigation of the dp breakup and dp elastic reactions at intermediate energies at Nuclotron

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The main goal of the DSS project (DSS collaboration) is to investigate the spin structure of nucleon-nucleon and three nucleon short-range correlations via the measurements of the polarization observables in the deuteron induced reactions at intermediate energies at Nuclotron (Dubna, Russia). In this framework, dp nonmesonic breakup and dp elastic reactions are investigated using internal target station. The dp breakup data are obtained with the detection of two outgoing protons at the angles of $19^\circ - 54^\circ$ in lab. frame at the deuteron energies of $300 - 500$ MeV. They are and presented as two dimensional plots of deposited proton energies and via S curve variable for different kinematic configurations. The data on the differential cross sections of dp elastic scattering for the deuteron energies up to 2000 MeV are presented in angular range $70^\circ - 120^\circ$ in c.m. The further perspectives of the investigations using polarized deuteron beam as well as the studies of the $^3\mathrm{He}(d,p)^4\mathrm{He}$ reaction are discussed.

Nuclear Structure Contributions to Lamb shift in Light Muonic Atoms

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Nevo-Dinur N. Hernandez O.J. Bacca S. Barnea N.

The proton radius determined from recent measurements of the Lamb shift in muonic hydrogen [1,2] disagrees significantly with that measured from electronic hydrogen spectroscopy and electron-proton elastic scattering. Motivated by the proton radius puzzle, new Lamb shift measurements in other light muonic atoms have been performed at PSI. These new measurements aim to extract the nuclear charge radii with extremely high accuracies, crucially limited by the knowledge of nuclear structure contributions, rising from the two-photon exchange, to the atomic spectra [3].

Our collaboration has performed ab-initio calculations of the two-photon corrections to the Lamb shift in light muonic atoms. This effect is studied by evaluating energy-dependent sum rules of the nuclear electromagnetic response functions, where we combine the state-of-the-art nuclear Hamiltonians with the hyperspherical harmonics expansion few-body method [4] and the Lanczos sum rule method [5].

I will present the results for muonic deuterium, 3H, 3He, and 4He [6,7,8], and compare the achieved theoretical accuracies with the requirement from the Lamb shift measurements. I will further discuss our future investigations to shed light on the radius puzzle.

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Observation of attractive and repulsive polarons in a Bose-Einstein condensate

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The problem of a mobile impurity particle immersed in a reservoir plays a fundamental role in physics. Studying the dressing of a particle by a bosonic medium is essential in understanding many physical systems such as technologically important semiconductors, Λ particles in nuclear matter, and high temperature superconductors. Even elementary particles acquire their mass by coupling to the bosonic Higgs particle. It is therefore highly desirable to study an impurity particle in a versatile environment such as offered by cold atomic gases. However, despite intense theoretical investigation, the canonical scenario of a mobile impurity immersed in a Bose-Einstein condensate (BEC) has never been realized. We use radio frequency spectroscopy of ultracold bosonic ^{39}K atoms to experimentally demonstrate the existence of a well-defined quasiparticle state of an impurity interacting with a BEC [1]. We measure the energy of the impurity both for attractive and repulsive interactions, and find excellent agreement with theories that incorporate three-body correlations. The spectral response consists of a well-defined quasiparticle peak at weak coupling, while for increasing interaction strength, the spectrum is strongly broadened and becomes dominated by the many-body continuum of excited states. Crucially, no significant effects of three-body decay are observed. Our results open up exciting prospects for studying mobile impurities in a bosonic environment and strongly interacting Bose systems in general.

[1] N. B. Jørgensen et al. arXiv:1604.07883

On the microscopic structure of πNN, $\pi N\Delta$ and $\pi\Delta\Delta$ vertices

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Schweiger W.

We use a hybrid constituent-quark model for the microscopic description of πNN, $\pi N\Delta$ and $\pi\Delta\Delta$ vertices. In this model baryons consist not only of the $3q$ valence component, but contain, in addition, a $3q+\pi$ non-valence component. In the spirit of chiral constituent-quark models [1] pions couple directly to the quarks. In addition, an instantaneous confining force is assumed between the quarks. The point-form of relativistic quantum mechanics is employed to achieve a relativistically invariant description of this system [2]. Thereby the dynamics of both, the quarks and the pion, is fully taken into account. The physical picture of baryons B that emerges from this kind of model is that of a "bare" baryon B_0, i.e. an eigenstate of the pure confinement potential, that gets dressed by a pion loop. By analyzing the optical potential that is responsible for the renormalization of baryon masses due to pion loops, we are able to extract microscopic expressions for $\pi B_0 B_0'$ vertices. The corresponding couplings and form factors follow then from a covariant analysis of these vertices.

In our work we concentrate on the nucleon and the Delta. For scalar and isoscalar confinement the masses and (momentum-space) wave functions of the bare nucleon and Delta are identical due to $SU(6)$ spin-flavor symmetry. Taking a model for the common wave function and an appropriate value for the bare nucleon and Delta mass we have calculated $\pi N_0 N_0$, $\pi N_0 \Delta_0$ and $\pi\Delta_0\Delta_0$ couplings and form factors. It is thereby interesting to see, how non-relativistic $SU(6)$ spin-flavor relations between the different couplings [3] are modified by going over to a relativistic framework. As we calculate it, these are only couplings and form factors of bare baryons. But in our simple model these form factors coincide with those of the physical baryons and the coupling just gets renormalized by the probability to find the bare baryon in the physical one. In this way we are also able to make comparisons with corresponding couplings and form factors used in models based on pure hadron dynamics or derived from lattice-QCD calculations.

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Triton binding energy of Kharkov potential

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There are a number of high precision, one-boson-exchange two nucleon force V_{NN}, such as CD-Bonn, Nijmegen -I, -II, -93 and Argonne AV18 potentials. There is also EFT potential [1-3] based on chiral effective field theory. Kharkov potential [4] is introduced by using the Unitary Clothing Transformations (UCT) from bare particle representation to clothed-particle representation. In the potential a large amount of virtual processes induced with the meson absorption/emission, the $N\bar{N}$-pair annihilation/production and other cloud effects can be accumulated.

Except for Kharkov potential they are satisfied with usual nonrelativistic Lippmann-Schwinger (LS) equation:

$t(\vec{p},\vec{p'};E) = v(\vec{p},\vec{p'}) + \int v(\vec{p},\vec{p''})G_0^{nr}(p'')t(\vec{p''},\vec{p'};E)d\vec{p''}$.

where the nonrelativistic resolvent $G_0^{nr}(p)$ is given by $G_0^{nr}(p) = \frac{1}{E-p^2/m+i\epsilon}$, and t is the tow-body t-matrix. In the relativistic case the relativistic resolvent is $G_0(p) = \frac{1}{M-2\sqrt{p^2+m^2+i\epsilon}}$. Kharkov potential uses the LS equation with the relativistic resolvent.

In order to calculate the triton wave function we employ the Faddeev equations. The relativistic Faddeev equations have been solved not only for bound state [5] but for scattering state [6]. Kharkov potential need not a special identification from nonrelativistic potential to relativistic potential. We have been used an identification (CPS) [7] for usual potential.

The Lorenz boosted potential v_q for Kharkov potential can be written as well [8] :

$$v_q(p,p') = \frac{2\sqrt{m^2+p^2}+2\sqrt{m^2+p'^2}}{\sqrt{4(m^2+p^2)+q^2}+\sqrt{4(m^2+p'^2)+q^2}}v(p,p')$$
$$+\frac{1}{\sqrt{4(m^2+p^2)+q^2}+\sqrt{4(m^2+p'^2)+q^2}}\int \left(v(p,p'')v(p'',p') - v_q(p,p'')v_q(p'',p')\right)dp''.$$

The triton binding energies for some potential are demonstrated in Table 1. By using the CPS identification the relativistic binding energies (magnitude) is usually smaller than the nonrelativistic one. In the case of Kharkov potential it is the first time to show that the relativistic number is larger than the nonrelativistic one without any identification.

Table 1. The theoretical prediction of the triton binding energies resulting from the solutions of nonrelativistic (first row) and relativistic (second row) Faddeev equations. The channel is chosen only S-wave 5ch. In the second and third columns the CD-Bonn and AV18 potentials are applied with the identification [7], respectively. In the fourth column the number is calculated with Kharkov potential by the nonrelativistic approximation. In the last column the number is obtained with Kharkov potential by full relativistic scheme. Unit is in MeV.

	CD-Bonn (CPS)	AV18 (CPS)	Kharkov(nonrel.)	Kharkov
nonrel.	8.33	7.66	5.62	-
rel.	8.22	7.59	-	7.42

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Universal behavior of few-boson systems using potential models

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Few-boson systems are studied close to the unitary limit using potential models constructed to reproduce the minimal information given by the two-body scattering length a and the two-body binding energy or virtual state energy E_2. The particular path used to reach the unitary limit is given by varying the potential strength. In this way the energy spectrum in the three- and four-boson systems is computed. The lowest energy states show finite-range effects absorbed in the construction of level functions defined, for the three-boson system, as

$$\widetilde{\Delta}_3^n(\xi) = s_0 \ln\left(\frac{E_3^n + E_2}{E_u^n}\right). \qquad (1)$$

where $s_0 = 1.00624..$ is a universal number, E_3^n is the energy of level n and E_u^n is the energy of that level at the unitary limit. The angle ξ is defined and $E_3^n/E_2 = \tan^2\xi$. For the four-boson system the corresponding level function is

$$\widetilde{\Delta}_4^{n,m}(\xi) = s_0 \ln\left(\frac{E_4^{n,m} + E_2}{E_u^{n,m}}\right) \qquad (2)$$

where m indicates the deep ($m = 0$) or shallow ($m = 1$) four-body state attached to the three-boson state n with energy $E_4^{n,m}$. The energy of this level at the unitary limit is $E_u^{n,m}$ and the angle ξ is defined as $E_4^{n,m}/E_2 = \tan^2\xi$.

It will be shown that this level functions, calculated for example using a gaussian potential, can be used to describe the structure of real systems around the unitary limit as a helium trimer or tetramer. Moreover, taking into account that higher energy levels are free from finite-range effects, the corresponding level functions tend to the zero-range universal function. Using this property a zero-range equation for the four-boson system is proposed and the four-boson universal function is computed [1].

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

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Ciepał I.

An experiment to investigate the ^{1}H(d,pp)n breakup reaction using a deuteron beam of 340, 380 and 400 MeV and the WASA detector has been performed at the Cooler Synchrotron COSY-Jülich. The studied energy region, below but close to the pion production threshold, may provide information on various aspects of nuclear interactions, in particular on relativistic effects and their interplay with the three nucleon force (3NF). Calculations including various pieces of dynamics like 3NF [1], long-range Coulomb interaction [2] or relativistic effects, predict their influence to reveal with different strength at different parts of the breakup reaction phase space. Cross section observables are very sensitive to all of these effects. The calculations in relativistic regime have recently been performed for the ^{1}H(*d,pp*)n breakup reaction at the beam energies of 340, 380 and 400 MeV [3], clearly demonstrating importance of relativistic description at these energies.

The almost 4π geometry of the WASA detector gives an unique possibility to study interplay of all the effects in a large part a space. Currently, the data analysis is focused on the proton-proton coincidences registered in the Forward Detector with the aim to determine the differential cross sections on dense angular grid of kinematical configurations defined by the emission angles of the two outgoing protons: two polar angles θ_1 and θ_2 (in the range between 4^o and 18^o) and the relative azimuthal angle ϕ_{12}. Elastically scattered deuterons are used for precise determination of the luminosity. The main steps of the analysis, including energy calibration, PID and efficiency studies, and their impact on the final accuracy of the result, will be discussed.

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Asymmetric trimers within Faddeev approach

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The van der Waals molecules at ultralow energies are of a great interest in both experiment and theory. These systems are weakly bound and may be of Efimov nature [1]. The best known example of this phenomenon is the helium trimer where there are two bound states and an excited state of Efimov nature was theoretically predicted (see review [2]). Most recently this has been brilliantly confirmed experimentally [3]. Here we carry out calculations on the van der Waals trimers $^{7}Li^{4}He_2$ and $^{6}Li^{4}He_2$ using the differential Faddeev equations, which allows us to give accurate binding energies for both the ground and the exited state of the system. The results obtained indicate on the Efimov character of the excited state in both systems.

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Determination of energies of NN-singlet quasibound states in d+^{2}H→n+n+p+p reaction

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An experimental setup for determining energies of NN-singlet quasibound states in d $+^2$H $\rightarrow$ n + n + p + p reaction is described. The above reaction is unique as it can proceed through the formation of different singlet two-nucleon systems in its intermediate stage: d $+^2$H $\rightarrow$ (nn)^s + (pp)^s $\rightarrow$ n + n + p + p, or d $+^2$H $\rightarrow$ (np)^s + (np)^s $\rightarrow$ n + p + n + p. We proposed to determine the energies of the quasi-bound states of two-nucleon systems (nn, pp and np) in the unified experimental conditions. The experimental setup allows one to simultaneously detect two nucleons (n + n, p + p or n + p) from the breakup of a quasi-bound states, and the third additional particle (n or p). A kinematical simulation of the reactions performed showed that the analysis of the shape of the energy spectrum of breakup particle, detected at a certain angle, provides information about the energy of quasi-bound state. The preliminary data on energies of singlet states obtained in d $+^2$H $\rightarrow$ n + n + p + p reaction are presented.

Entanglement of Harmonically Trapped Dipolar Particles: harmonic approximation

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The study of many-body properties of various fabricated particle systems is presently the one of the most active areas of theoretical physics. In addition to ultracold atomic gases with short range interactions, systems with particles interacting through the long-range interaction potentials $1/r^d$ have been attracted considerable attention, which is due to the new experimental techniques that have opened up perspectives for achieving the van der Waals and dipolar interactions in polar molecule experiments. Particularly the research activity has expanded towards investigating the entanglement properties in various systems composed of N interacting particles, as entangled systems play an important role in many different research areas such as quantum information technology.

We study systems of identical dipolar particles (d=3) confined in quasi one-dimensional harmonic traps. Numerical results for the dependencies of the entanglement on the control parameters of the systems are provided and discussed in detail. In the limit of a strong interaction between the particles, we derive, within the framework of the harmonic approximation, the diagonal form of the asymptotic ground-state one-particle reduced density matrix, and investigate the nature of the degeneracy appearing in its spectrum. Most importantly, we show that the ground-state asymptotic occupancies, their natural orbitals, and the corresponding von Neumann entanglement entropy can be derived in closed analytic forms [1,2]. In particular, we provide the results for the dependence of the asymptotic von Neumann entanglement entropy on N. Furthermore, in order to gain some insight into the effect of d, the main entanglement features exhibited by the present systems are compared with those exhibited by the corresponding systems with charged particles.

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Systematic Study of Three-Nucleon System Dynamics in Deuteron-Proton Breakup Reaction

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Ciepał I Liptak A Kalantar-Nayestanaki N Kistryn St Kłos B Kuboś A Kulessa P Meschendorp J Parol W Skwira-Chalot I Stephan E Szpik K Włoch B Rusnok A Zejma J

The dynamics of three-nucleon systems is investigated quantitatively by comparing results of precise measurements with rigorous calculations. Observables for the d-p breakup reaction can be calculated on the basis of modern realistic nucleon-nucleon (NN) potentials, combined with models of three-nucleon (3N)force, within the coupled-channel framework by explicit treatment of the -isobar excitation or by the Chiral Perturbation Theory with all relevant NN and 3N contributions taken into account. Beside leading NN interactions and three nucleon force, mentioned above calculations may include different pieces of nucleon-nucleon dynamics, like the long-range Coulomb interaction or relativistic effects, which reveal their influence at different parts of the phase space. Differential cross section for elastic pd scattering and breakup reaction is very sensitive to all these effects. The precise experimental data of the breakup reaction obtained in wide phase space region at different incident beam energies are crucial for systematic studies of different parts of few-nucleon system dynamics and for verification of theoretical calculations which currently are being developed.

Experiments devoted to study such subtle ingredients of nuclear dynamics were carried out at KVI Groningen and FZ-Julich with the use of the p(d,pp)n breakup reaction at few different energies. As a continuation of these studies, with the use of proton beam and deuteron target, the first measurements at the new Cyclotron Center Bronowice (Krakw), at three proton energies (108, 135, 160 MeV), will be performed in may this year. The combination of large phase space coverage of the BINA detector system and wide range of accessible beam energies provides an unique possibility to study various aspects of the dynamics in three nucleon system, at regions of their maximum visibility. Preliminary analysis and the prospects for the future measurements will be presented.

Topological phase and half-integer orbital angular momenta in circular quantum dots.

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Mur V.D. Narozhny N.B. Lozovik Yu.E.

We show that there exists a non-trivial topological phase in circular two-dimensional quantum dots with an odd number of electrons. The possible non-zero value of this phase is explained by axial symmetry of two-dimensional quantum systems. The particular value of this phase (π) is fixed by T-invariance and the Pauli exclusion principle and leads to half-integer values of the angular orbital momentum for ground states of such systems. This conclusion agrees with the experimental data for ground-state energies of few-electron circular quantum dots in perpendicular magnetic field [1]. Hence, these data may be considered as the first experimental evidence for the existence of topological phase leading to half-integer quantization of the orbital angular momentum in circular quantum dots with an odd number of electrons.

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Observation of the Efimov state of the helium trimer

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In 1970 Vitali Efimov predicted remarkable counterintuitive behavior of a three-body system made up of identical bosons. Namely, a weakening of pair interaction in such a system brings about in the limit appearance of infinite number of bound states of a huge spatial extent [1]. The helium trimer has been predicted to be a molecular system having an excited state of this Efimov character under natural conditions without artificial tuning of the attraction between particles by an external field. Here we report experimental observation of the Efimov state of $^4He_3$ by means of Coulomb explosion imaging of mass-selected clusters [2]. Structures of the excited Efimov state of the $^4He_3$ (Figure 1A) are about eight times larger than those of the ground state (Figure 1B), which is in accordance with theory. Whereas the ground state corresponds to an almost randomly distributed cloud of particles [3], the excited Efimov state is dominated by configurations in which two atoms are close to each other and the third one farther away.

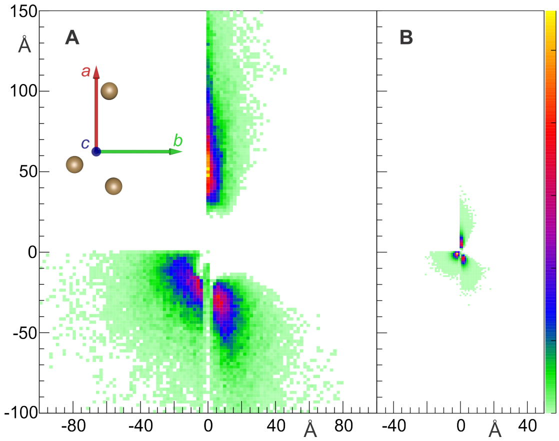

Figure 1. Structures of the helium trimer: A – excited state, experimental, B – ground state, theoretical. Three helium atoms of each trimer are plotted in the principal axis frame *abc*.

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Doubly excited resonance states of helium atom: complex entropies

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In last few years there has been a remarkable increase of interest in the quantum correlation of few-body systems because of the development of new experimental techniques that have opened up perspectives for their applications in quantum information technology. In particular, there has been a growing interest of two particle systems like helium atom and helium-like ions [1-4]. However, studies on the correlation in resonance states have not yet drawn much attention. Pont F.M. et. al. [5] suggested to associate the amount of quantum correlation in a resonance state with a real part of a linear entropy computed from complex-valued eigenvalues of a reduced density matrix determined in the framework of the complex-coordinate rotation method [6]. Within the framework of this approach, the properties of two-electron one-dimensional quantum dots near the autoionization thresholds have recently been investigated in [7].

Here, we explore correlations in doubly excited states of helium atom, $2s^2\ {}^1S^e$ and $2p^2\ {}^1S^e$. To this end, we first provide a diagonal form of a complex reduced density matrix of S-symmetry resonance states of two electron systems determined under the framework of the complex scaling method. We employ in our calculations the variational Hylleraas type basis function. With the use of the eigenvalues of the complex reduced density matrix, we determine the complex linear and von Neumann *entropies* and compare the results obtained with the entropies determined under the framework of the stabilization method in [8]. The results for the real parts of the complex *entropies* are in a very good agreement with those determined under the framework of the stabilization method. Our approach can be an alternative to the one based on the stabilization method when determining the real parts of the linear and von Neumann entropies of S-symmetry resonance states.

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Structure of bound and resonance states of ^{10}Be in a microscopic three-cluster model

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We study elastic and inelastic α+^{6}He scattering and spectrum of bound and resonance states in ^{10}Be. This investigation is carried out within a three-cluster microscopic model which was formulated in [1]. In this model nucleus ^{10}Be is represented as a three-cluster system $\alpha+\alpha$+^{2}n. We treat the ^{10}Be as a many-channel system which involves two coupled binary cluster configurations: α+^{6}He and ^{8}Be+^{2}n. ^{6}He= α+^{2}n and ^{8}Be= $\alpha+\alpha$ are considered to be weakly bound two-cluster subsystems, which can change their size on approaching the third cluster (alpha particle or dineutron). We shall use the term "cluster polarization" to mean such change of size of a two-cluster subsystem.

We demonstrated that the cluster polarization has a substantial impact on the energy of bound states and energy and width of resonance states as well. The inclusion of two unpolarized coupled cluster configurations was shown to have approximately the same impact on the spectrum of the ^{10}Be nucleus as allowing for cluster polarization within an isolated cluster configuration.

Aimed at finding how the shape of nucleon-nucleon potential affects spectrum of bound and resonance states, we involved three effective semi-realistic potentials in our calculations. The Majorana parameter of the Volkov and modified Hasegawa-Nagata potentials and the exchange parameter u of the Minnesota potential were adjusted to reproduce the 0^+ ground state of ^{10}Be with respect to the $\alpha+^6He$ threshold. However, the spectrum of bound and resonance states of ^{10}Be was found to be strongly dependent on the shape of nucleon-nucleon forces.

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Calculation of the S-factor S_{12} with the Lorentz integral transform method

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Deflorian S. Efros V.D.

Nuclear reactions in stars of the type $X_1 + X_2 \rightarrow X_3 + \gamma$ with charged baryons X_i lead to tiny cross sections due to the presence of the Coulomb barrier. A test of the Lorentz integral transform (LIT) method [1,2] for such a reaction is presented, namely for the astrophysical S-factor of the reaction $d + p \rightarrow {}^3\text{He}+\gamma$. As NN interaction the MTI/III potential is used. In addition to the LIT method results are also obtained for a conventional calculation with explicit continuum wave functions for the $(d + p)$-state via an application of the Kohn variational principle.

The LIT equation is solved using expansions on two different basis sets (hyperspherical harmonics (HH) basis as well as a basis with explicit use of both Jacobi coordinates (Jacobi basis)). It is shown that the Jacobi basis is much better suited, since different from the HH basis it leads to a high density of so-called LIT states in the energy region between the two-body and the three-body breakup threshold. Therefore the inversion of the LIT in the energy region of astrophysical interest can be made with a high precision allowing one even to give an error estimate of the obtained result. It is shown that the result and the error estimate can be systematically improved by an increase of the number of basis states of the Jacobi basis.

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Analysis of thermodynamic properties of BEC condensates using few-body methods

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Traditional few-body methods such as Fadeev and Faddeev-Yakubovsky approches, which are rigorous, work well as long as the number of particles is small. Thus for systems of large number of particles such as BEC condensates, these methods are not applicable. However, the study of BEC condensates, e.g. trapped ultracold dilute gases at large scattering length near a Feshbach resonance, are of importance. Recently we developed a method that uses a combination of correlated potential harmonics expansion and few-body method to study ground state properties BEC condensates near the Feshbach reseonance [1, 2, 3]. The method is realised by transforming the Jacobi polynomials into the associated Laguarre polynomials and has good convergence properties and compares well with other traditional and competing methods such as the mean-field approximation. In this work we extend the method to enable the calculation of the thermodynamic properties of the BEC systems. This requires the inclusion of higher angular momenta in the formalism. Preliminary calculations indicates the method is stable. We consider BEC condensates with up to 10^7 particles.

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Spin-motional coupling in assembled quantum gases

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The use of optical tweezers to trap and control single neutral atoms has become a promising method to assemble and study out-of-equilibrium quantum many-body systems. In such systems, the quantum statistics of the particles dramatically affect the particle dynamics and lead to coupling between the spin and motional degrees of freedom. For example, we have observed the dynamical generation of spin-entanglement between two ^{87}Rb atoms via the spin-exchange interaction and have verified that this entanglement is maintained after the spatial separation of the atoms. In this talk, I will discuss our use of the optical tweezer platform to prepare arrays of indistinguishable atoms, imprint a desired initial spin configuration, and then place the atoms in the same optical potential. Additionally, I will discuss our ongoing work to extend these capabilities to study a larger number of atoms, where the spin-motional coupling can lead to interesting and complex dynamics.

Few-body correlations in the spectral response of impurities coupled to a Bose-Einstein condensate

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Parish M.M. Jørgensen N. B. Wacker L. Skalmstang K. T. Christensen R. S. Bruun G. M. Arlt. J.J.

The behaviour of a mobile impurity particle interacting with a quantum-mechanical medium is of fundamental importance in physics. Ultracold atomic gases have greatly improved our understanding of the impurity problem owing to the high degree of control over experimental parameters such as interactions and atom population. I will discuss recent theoretical [1] and experimental [2] progress in exploring the properties of impurities interacting with a Bose-Einstein condensate. Here, a new experiment has demonstrated the existence of a well-defined quasiparticle state and a many-body continuum of excited states (Fig. 1), with no significant effects of three-body losses observed. The spectral response of the impurities to a radiofrequency pulse is accurately captured within a theory that includes three-body correlations systematically. The theory can capture Efimov physics in a many-body environment, which is likely to be observed in the next generation of experiments. Our results thus open up new windows on the study of strongly interacting Bose systems.

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The nucleon-nucleon interaction up to sixth order in the chiral expansion

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We have calculated the nucleon-nucleon interaction up to sixth order (N5LO) of chiral perturbation theory [1,2]. Previous calculations [3] extended only up to N3LO (fourth order) and typically showed a surplus of attraction, particularly, when the πN LECs from πN analysis were applied consistently. Furthermore, the contributions at N2LO and N3LO are both fairly sizeable, thus, raising concerns about the convergence of the chiral expansion. We show that the N4LO contribution is repulsive and, essentially, cancels the excessive attraction of N3LO. The N5LO contribution turns out to be considerably smaller than the N4LO one, hence establishing the desired trend of convergence. The predictions at N5LO are in excellent agreement with the empirical phase shifts of peripheral partial waves.

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Recent progresses in ab-initio studies of low-energy few-nucleon reactions of astrophysical interest

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In this talk, I will review the state-of-the-art for the theoretical studies of nuclear reactions of astrophysical interest involving few-nucleon systems, and I will consider both the "standard" phenomenological approach and the most recent chiral effective field theory framework. In particular, I will focus on the radiative capture of protons by deuterons in the energy range of interest for Big Bang Nucleosynthesis [1], and on some weak processes, as triton β-decay [2] and the proton-proton weak capture reaction [3]. At the end, an outlook for future work will be given.

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Eigenvectors of few-body scattering matrices at resonance energy values

Motovilov A.K. (Bogoliubov Laboratory of Theoretical Physics, JINR, Dubna, Russia)
Kolganova E.A.

First, we discuss the explicit representations [1] for the T- and scattering matrices analytically continued on unphysical energy sheets in a multichannel problem involving only two-body channels. Then we analyze the analogous (but much more complex) explicit representations [2,3] for the analytically continued T- and S-matrices in the three-body problem unphysical sheets. In both the binary multichannel and three-body cases the representations [1,2] for the T- and S-matrices on unphysical energy sheets are explicitly written in terms of just the same matrices but taken only on the physical sheet. The representations imply that a resonance on an unphysical energy sheet is the (complex) energy value where the appropriately truncated scattering matrix on the physical sheet has eigenvalue zero. We conjecture that that the channel components of the eigenvector of the truncated scattering matrix belonging to its zero eigenvalue make sense of breakup amplitudes for the corresponding resonance state. In the case of a multi-channel problem with purely binary channels this statement has been proven in [1]. Now we extend this result to the truncated three-body scattering matrices responsible for resonances on the two-cluster three-body unphysical sheets.

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Few-body universality: from Efimov effect to super Efimov effect

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Physics is said to be universal when it emerges regardless of microscopic details. The most remarkable example is the Efimov effect, which predicts the emergence of an infinite tower of three-boson bound states in three dimensions with binding energies obeying the universal exponential scaling. In this talk, I will discuss our recent proposal for its condensed matter realization, namely, the Efimov effect in quantum magnets [1]. Also, I will discuss our recent discovery of new few-body universality, the super Efimov effect, which predicts the emergence of an infinite tower of three-fermion bound states in two dimensions with binding energies obeying the universal doubly exponential scaling [2,3].

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Integral transform methods: a critical review of kernels for different kinds of observables

Orlandini G. (University of Trento, Italy)

The Lorentz Integral transform (LIT) method has proved a very productive approach to calculate observables that require in principle the knowledge of many-body scattering states. In the LIT case the kernel is a Lorentzian function and one of its advantages consists in the possibility to use bound state methods to calculate the transform, avoiding the continuum problem. In this contribution I will critically review the use of other kernels (even wavelets), emphasizing the criteria for their applicability to different kinds of observables.

A Coulomb-like off-shell T-matrix with the correct Coulomb phase shift

Oryu S. (Tokyo University of Science)
Watanabe T. Hiratsuka Y.

By means of the two-potential theory, a Coulomb-like off-shell t-matrix is obtained by a screened Coulomb potential with a distorted wave Green's function and a Moller wave operator where the distortion is given by an auxiliary Coulomb potential which is the difference between the Coulomb and a screened Coulomb potentials. These potential are defined by a universal range: $\mathcal{R} \equiv kR$ and the Sommerfeld parameter: $\eta(k) = ZZ'$ [1,2]. The universal range appears only on several discrete range-bands, if we require the zero phase shift for the auxiliary potential. By the range-bands, a Coulomb-like off-shell t-matrix is well defined as well as the Coulomb phase shift. Furthermore, the Coulomb phase shifts of full partial waves for the systems from the $e^- - e^-$ to the heavy ions such as ^{208}Pb-^{208}Pb are automatically reproduced by using the above mentioned range-bands.

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Electroweak structure of light nuclei

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In this talk, I will review recent progress in microscopic calculations of electroweak properties of light nuclei, including electromagnetic moments, form factors and transitions in between low-lying nuclear states along with preliminary results for single- and double-beta decay rates. These calculations are based on nuclear Hamiltonians that include two- and three-nucleon realistic potentials, and one- and two-body nuclear electroweak currents. I will show that this framework successfully explains the body of available experimental data provided that many-body contributions in both the nuclear Hamiltonians and currents are accounted for.

Spatial separation and its transition in a one-dimensional system of a few fermions

Pecak D. (Institute of Physics of the Polish Academy of Sciences, Warsaw, Poland)
Sowiński T.

Properties of the ground-state of a two-component mixture of a few fermions with different mass is studied within an exact diagonalization approach. It is shown that depending on a shape of an external confinement different spatial separations between components, manifested by specific shapes of density profiles, can be obtained in the strong interaction limit. We find that the system studied undergoes a particular transition between orderings when the confinement is changed adiabatically from the uniform box to the harmonic oscillator shape. We study properties of this transition in the framework of the finite-size scaling method adopted to a few-body systems. Our findings generalize previous results on the separation induced by the mass difference between components [1].

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Measurement of polarization transfered to a proton bound in nuclei

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A1 Collaboration

Possible differences between free and bound protons may be observed in the ratio of polarization-transfer components. We report the measurement of this ratio on deuteron at low and high missing momenta. Observed increasing deviation of the measured ratio from that of a free protonas a function of the virtuality, similar to that observed in 4 He, indicates that the effect in nuclei is due to the virtuality of the knock-out proton and not due to the average nuclear density. The measured differences from calculations assuming free-proton form factors (about 10%), may indicate in-medium modifications.

NN and Nd scattering with intermediate dibaryons

Platonova M.N. (Lomonosov Moscow State University, Moscow, Russia)
Kukulin V.I.

Recent experimental progress has led to discovery of multiquark states searched for 50 years since the beginning of QCD. In particular, the first reliable confirmation of existence of six-quark (dibaryon) resonances has been found recently at COSY facility (Juelich) [1]. Since the dibaryon resonances are intimately related to the short-range NN interaction and the cross sections of dibaryon production are typically very small, they should be manifested in processes with high momentum transfers, such as meson production in NN and Nd collisions or elastic Nd scattering at large angles. Just for such processes there exist discrepancies between the experimental data and conventional theoretical models for NN and $3N$ interaction which do not include dibaryon degrees of freedom. In view of all above, study of dibaryon resonances in hadronic and nuclear processes with high momentum transfers becomes of particular importance.

New experimental and theoretical evidences of dibaryon resonances in NN system are presented in the talk. Excitation of intermediate dibaryons in the processes of one- and two-pion production in NN collisions is considered [2]. In particular, relative contributions of an intermediate Δ isobar and isovector dibaryons in the reaction $pp \to d\pi^+$ are investigated. Inclusion of dibaryon resonances is shown to considerably improve the description of experimental data for this reaction, provided the consistent parameterization of the $\pi N\Delta$ vertex in πN and NN scattering is used. Manifestation of the intermediate isoscalar and isovector dibaryon resonances in the two-pion production processes such as $pn \to d\pi^0\pi^0$ and $pn \to d\pi^+\pi^-$ is also studied. The interpretation of the near-threshold enhancement (the so-called ABC-effect) for the above two-pion production reactions in terms of the sigma-dressed isoscalar dibaryon is given. Consequences of intermediate dibaryons production in NN system for Nd elastic and inelastic scattering are also discussed.

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Effective field theory for Halo Nuclei

Platter L. (University of Tennessee, Knoxville, U.S.A. and Physics Division, Oak Ridge National Laboratory, Oak Ridge, TN , USA)

Halo nuclei are weakly bound nuclei whose degrees of freedom are a tightly bound core and a small number of valence nucleons. These systems are of experimental interest since they are important in reactions relevant to nuclear astrophysics but also since they frequently occur close to the neutron dripline. I will discuss the application of effective field theory to these weakly bound nuclei and provide a number of examples where this approach leads to predictions for important observables.

Flavor Analysis of Nucleon, Delta, and Hyperon Electromagnetic Form Factors

Plessas W. (University of Graz, Graz, Austria)
Rohrmoser M. *Choi K.-S.*

We report on a study of the flavor contents in electromagnetic form factors of baryons along a relativistic constituent-quark model. It considers baryons as three-quark systems with flavors u, d, and s and relies on an invariant mass operator composed of a linear confinement (with a strength corresponding to the string tension of quantum chromodynamics) and a hyperfine interaction (derived from Goldstone-boson exchange among constituent quarks) [1]. Covariant predictions for baryon electric and magnetic form factors are generated in the point-form of relativistic dynamics. The theory guarantees for strict Poincaré invariance and fulfills electromagnetic current conservation.

In case of the nucleons the detailed flavor contributions to the elastic electromagnetic form factors of both the proton and the neutron are reproduced in accordance with phenomenological data [2-4] for momentum transfers up to $Q^2 = 3$–4 GeV^2. In this range of momentum transfers no additional degrees of freedom beyond $\{QQQ\}$ configurations of flavors u and d are advocated and there is also no indication for quark-diquark clustering. Only, for the particular ratio of d to u flavor contributions of the Pauli form factor F_2^d/F_2^u we observe a certain inconsistency among the different phenomenological analyses [2-4].

For the Δ and the hyperons we have only some global experimental data for electric radii and magnetic moments. They are reasonably described by our quark model. Regarding the flavor contents of the electromagnetic form factors of these baryons we can only compare our results with predictions from lattice quantum chromodynamics. Wherever a comparison is possible, we find similar Q^2 dependences but sometimes different absolute magnitudes.

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Measurement of tensor asymmetry T20 in coherent π^0 photoproduction on deuteron

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The deuteron, being the simplest two-body nuclear system, attracts a special attention of experimentalists and theorists for many years. Especially interesting, but experimentally challenging, are measurements of polarization observables, which provide an access to small but important reaction amplitudes.

Coherent pion photoproduction on the deuteron $\gamma + d \rightarrow \pi^0 + d$ has been studied as a source of information on π^0 photoproduction off the neutron, on π^0 interaction with the deuteron and on structure of few-body nuclear systems. On the theoretical side the models using the three-body approach to describe the pion-deuteron interaction mechanisms (Faddeev theory, coupled $\pi NN - NN$ channels) have achieved serious progress in recent years. On the experimental side a set of measurements of differential cross section for pion photoproduction reactions on deuteron become available in last decades, while the data on polarization observables are still limited.

Here we report on a recently completed measurement of the tensor asymmetry T20 in coherent photoproduction of π^0-meson on deuteron. The measurement was done at the VEPP–3 electron storage ring using an internal polarized deuterium gas target. The recoil deuteron and photons from the decay of π^0 were detected in coincidence. The degree of tensor polarization was measured to be P_{zz} = 38% and during the experiment the sign of target polarization was reversed every 30 seconds, allowing a strong suppression of false asymmetries.

The new data provide a considerable improvement in the accuracy of measurement of tensor asymmetry in this process compared to the only measurement that was reported earlier [1].

The experimental approach and data analysis procedure will be described. Preliminary results on the tensor asymmetry T20 for a photon energy range 250-600 MeV and for CM pion angle range 90^o-140^o will be presented.

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Revival of the Phase-Amplitude Description of a Quantum-mechanical Wave Function

Rawitscher G. (University of Connecticut)

The Phase-Amplitude (Ph-A) description consists in writing the wave function as $\psi(r) = y(r)\sin(\Phi(r))$, where y is the amplitude and Φ the phase. Both functions vary slowly with the distance r, and hence should be easier to calculate than the highly oscillatory function $\psi(r)$. In 1930 W. E. Milne established a second order differential equation for $y(r)$, which being non-linear, is cumbersonme to solve with the conventional finite difference methods. In 1962 M. J. Seaton and G. Peach demonstrated an iterative solution of Milne's equation, and in 2015 and 2016 the present author improved the iterative method by making use of a modern spectral expansion procedure of $y(r)$ in terms of Chebyshev polynomials [1]. The method is very economical and fast, but one big drawback is that the iterations do not converge in the vicinity of the turning points. This situation may be remedied as follows.

By defining $w(r) = y^2(r)$, one finds that w obeys a *linear third order* differential equation. For the case of a point Coulomb potential it could be shown by analytical means [2] that the solution of this equation is equivalent to the conventional Coulomb wave function expressed in terms of confluent hypegeometrical functions. By further defining $u(r) = dw/dr$, one arrives at a new differential-integral equation

$$d^2u/dr^2 + 4(k^2 - V)u = (dV/dr)\left(\int_0^r u(r')dr' + u_0\right)$$

where k^2 is the energy and $V(r)$ the potential in the Schrödinger equation. Here u_0 is the value of u at $r = 0$, chosen such that $y(0)$ has a prescribed value, and asymptotically $y(r \to \infty) = 1$.

It is the purpose of this abstract to describe a method to solve this equation numerically, again using the spectral decomposition of $u(r)$. That method, if shown to be sufficiently general, does represent an important advance for the Ph-A description for repulsive or attractive potentials, in that it can be applied in the region including turning points.

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Beta-decay spectroscopy on 12C

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In the ^{12}C-nucleus there exist broad, resonant structures 2-4MeV above the triple alpha threshold. These resonances are not well characterised in terms of their spin and breakup-channels, even though they have been subject to theoretical interest for many years. This interest is partly caused by the possibility that some of the resonant strength is the rotational excitation of the cluster-like Hoyle-state. Furthermore, clusterised structures at 2-4MeV above the triple alpha threshold are expected to contribute significantly to the production of ^{12}C in hot, stellar environments like supernovae [1,2].

Some experimental progress has been seen recently, but the results from beta-decay spectroscopy, p- and α-scattering and (γ,3α)-experiments do not agree, neither on the positions nor the widths of the resonances [3-5].

We have performed a measurement of the beta-delayed triple-alpha breakup of 12N at the IGISOL facility in Jyvskyl. Complete kinematic information allows us to investigate the breakup mechanism of 12C, including the spin of the decaying state and the angular momentum in the breakup channel.

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Three-body calculation of the $1s$ level shift in kaonic deuterium with realistic $\bar{K}N$ potentials

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In a recent test calculation [1] we demonstrated the applicability of the Coulomb Sturmian expansion method for the exact calculation of the $1s$ level shift in three-body hadronic atoms. For the hadron-nucleon interaction we used simple one-channel potentials with constant imaginary parts to account for the absorption.

In the present work the $1s$ level shift in kaonic deuterium ($\bar{K}d$) was calculated using realistic, multichannel $\bar{K}N$ interactions. Three different potentials were used, two phenomenological ones with one- and two-pole structure for the $\Lambda(1405)$ and an enegy-dependent chiral-type. All interactions reproduce the known $\bar{K}N$ experimental data, including the recent and accurate SIDDHARTA hydrogenic $1s$ level shift. They were already used in our previous coulomb-less Faddeev calculations for the $\bar{K}NN$ system [2].

To calculate the level shift in ($\bar{K}d$) with these potentials we first reduced them to act only in the $\bar{K}NN$ particle channel in the form of an "exact optical" potential. This construction reproduces the exact upper-channel (elastic) amplitude of the multichannel interaction both on- and off- energy shell and preserves its analytical structure (poles, branch cuts, thresholds..) in the energy variable. As a consequence, the interactions are complex and strongly energy-dependent, the Riemann surface of the relevant Green's function matrix elements has a complicated multi-level structure and the sought energy eigenvalue is located on one of the unphysical sheets.

Due to these features the procedure of calculating the channel Green's function matrix elements using a convolution integral in the subsytem energy variable had to be substantially modified. As a result, the following converged - accurate to $\sim$ 1 eV - values for the complex $1s$ energy shifts ΔE in ($\bar{K}d$) were obtained for the 1-pole, 2-pole and chiral potentials (in eV): (767-464 i),(782-469 i) and (835-502 i), respectively. The exact numbers were compared with the results of previous, approximate calculations for the same potentials.

Most likely the significance of the present calculation lies not as much in these numbers, as in the first possibility to relate an important an hopefully measurable observable of the $\bar{K}NN$ system to the input $\bar{K}N$ interactions without relying upon uncontrollable approximations. The proposed method can serve as an important tool in fixing the yet uncertain properties of the basic $\bar{K}N$ interactions.

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Beta-delayed particle emission from neutron halos

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Neutron halo nuclei are situated at the neutron dripline and typically have large Q-values for β decay. Beta-delayed particle emission is therefore expected to be prominent. If the structure of a halo nucleus is well approximated by a few-body model (core + one or two neutrons) the decays where halo neutrons transform into protons are of particular interest. For two-neutron halos this gives βd decay that is observed in ^{6}He and ^{11}Li [1], but where the two-neutron correlation also enters.

The case of a one-neutron halo decaying via βp is simpler, but the decay is heavily suppressed due to the extremely small Q-value. It was therefore surprising that this decay was observed [2] from ^{11}Be with a branching ratio close to 10^{-5}, several orders of magnitude larger than previous calculations. A very simple model calculation [3] of the process could reproduce the decay strength only if a strong p-^{10}Be resonance is present within the Q-window.

Prompted by this we have looked more generally at β decay to the continuum [4] and demonstrated that decays and reactions may give different results for resonance properties. The contribution will update the experimental situation and discuss how the results may be interpreted theoretically.

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How Merkuriev splitting works

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Gradusov V.A. *Yakovlev S.L.*

Many bound state and scattering calculations [2-7] for three-body Coulomb systems have been successfully performed on the base of Merkuriev-Faddeev equations for Coulomb potential [1]. The key – and not entirely understood – ingredient in the formulation of the equations is splitting of Coulomb potential into short- and long-range parts in three-body configuration space. This splitting is a functional parameter of the equations which particular functional form is not strictly dictated by the formal requirement of asymptotic channel separation in infinite configuration space. In contrast, the choice of the functional form of the splitting for practical calculations performed in finite domains is critical for obtaining and even observing convergence of the solutions. We discuss this problem starting from the splitting in two-body configuration space. With this example we develop simple and physically intuitive conditions on the splitting function. Splitting the potential in three-body configuration space makes it possible to perform calculations in a broader range of energies and to optimize the numerical convergence.

We illustrate our discussion with calculations of scattering cross sections for all processes in the system of electron, positron and proton between the positronium formation threshold and the third excitation threshold of the Hydrogen atom.

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Continuum Discretization for Quantum Scattering and Nuclear Matter Calculations

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Kukuin V.I. Pomerantsev V.N.

Recent developments of the Wave-Packet Continuum Discretization (WPCD) method [1] are discussed. The approach is based on a finite-dimensional representation for the few-body free and channel resolvents in the stationary wave-packet bases. The solution scheme is realized on a discrete on energy and momenta representation which allows to replace few-body scattering integral equations with their matrix analogs and to construct effective interactions of composite particles as well. According to the usage of the normalized continuum states [1], one can take into account the long-range Coulomb interaction without screening within the Coulomb wave-packet formalism. The numerical scheme for solving the discretized Faddeev equations is highly parallelized and is realized by using the fast GPU technique [2].

The above discretization technique is very useful in nuclear matter calculations where it allows to reformulate an integral formalism for the reaction matrix (such as the Bethe-Goldstone-type) in terms of the effective total Hamiltonian defined in the Pauli-allowed subspace. As a result, the reaction matrix at many relative momenta and energies can be found by using the respective Hamiltonian matrix diagonalization in the stationary wave packet basis which simplifies strongly the self-energy iterations. A way for an extension of the discrete approach to the account of three-nucleon correlations in nuclear matter on the basis of the three-body Bethe–Faddeev equations is discussed.

The work is partially supported by the RFBR grant 16-02-00049 and the joint RFBR-DFG grant 16-52-12005.

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A new method for calculating the baryons mass under the phenomenological interaction potential

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In this article, the nonrelativistic quark model and a new baryon mass formula are applied to study the baryon octet and decuplet masses. Our model, like all Constituent Quark Models, contains a dominant SU(6)-invariant part accounting for the average multiplet energies, and a perturbative SU(6)-violating interaction for the splitting within the multiplets, a structure which is inspired by early Lattice QCD calculations. The spectrum of the ground state and excited light baryons has been investigated by solving the Schrdinger equation under the suitable phenomenological interaction potential. Using the Jacobi-coordinates, anzast method and generalized Gursey Radicati (GR) mass formula the three body wave equation is solved to calculate the different states of the considered baryons. A comparison between our calculations and the available experimental data shows that the position of the Roper resonances of the nucleon, the ground states and the excited multiplets up to three GeV are in general well reproduced and comparable with the experimental spectrum. Also one can conclude that; the interaction between the quark constituents of baryon resonances could be described adequately by using the combination of Killingbeck and isotonic oscillator potentials form.

Uncertainty quantification in many-body applications of chiral nuclear forces

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Chiral effective field theory (EFT) has proven to be a powerful tool to derive few-nucleon forces in a model-independent way. Within chiral EFT, one maintains a firm connection with quantum chromodynamics, while following a well-defined path to generate two- and few-nucleon forces on an equal footing. High-quality two- and three-nucleon forces have been developed up to fifth and sixth order of chiral EFT [1,2]. Naturally, the next step is the application of these forces in the many-body system–the goal of *ab initio* nuclear physics and a task of formidable complexity.

In spite of recent progress, we are still faced with serious problems. One of them concerns the proper quantification of the uncertainty in predictions of structure and reaction observables. Another issue is whether the order-by-order convergence of the chiral expansion is satisfactory [3]. I will illustrate the above problems by way of representative examples of nuclear structure issues.

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Structure of weakly-bound three-body systems in two dimension

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We calculate root-mean-square radii for a three-body system confined to two spatial dimensions and consisting of two identical bosons (A) and a distinguishable particle (B). We use zero-range two-body interactions between each of the pairs, and focus thereby directly on universal properties, where the properties of the quantum system are independent on the details of the zero-range interaction between particles (the two-body scattering length is much larger than the range of the potential). We solve the Faddeev equations in momentum space and express the mean-square radii in terms of first order derivatives of the Fourier transforms of one-body densities [1]. The strengths of the interactions are in the numerical illustrations adjusted for each set of masses to produce equal two-body bound-state energies between different pairs [2]. The mass ratio, $\mathcal{A}$, between particles B and A are varied from 0.01 to 100 providing a number of bound states decreasing from 8 to 2. Energies and mean-square radii of these states for small $\mathcal{A}$ are analyzed by use of the Born-Oppenheimer potential between the two heavy A-particles [3]. For large $\mathcal{A}$ the radii of the two remaining bound states are consistent with a slightly asymmetric three-body structure. The radii diverge when $\mathcal{A}$ approaches thresholds for binding of the three-body excited states. These divergences are linear in the inverse energy deviation of the three-body energy from the corresponding two-body threshold. The structures at these thresholds correspond to bound AB-dimers and one loosely bound A-particle.

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Parity- and time-reversal-invariance-violating nucleon-nucleon interactions in the large-N_c expansion

Schindler M. R. (University of South Carolina, Columbia, SC, USA)

Violations of discrete symmetries such as parity (P) and time reversal invariance (T) in few-nucleon systems provide interesting tests for our understanding of the Standard Model (SM) as well as sensitive probes of Beyond-the-Standard-Model (BSM) physics. Parity-violating quark-quark interactions are well understood within the SM, but their manifestation at the hadronic level involves nonperturbative QCD effects. Hadronic parity violation in few-nucleon systems can therefore serve as a unique probe of the interplay of SM weak and nonperturbative strong interactions. While the SM also contains sources of T violation, the predicted T-violating effects are much smaller than current experimental bounds on corresponding observables. The measurement of T violation, e.g., in EDMs of light nuclei or in neutron-nucleus reactions, can therefore provide a sensitive window into BSM physics. Experimental constraints on symmetry-violating interactions are currently weak (if they exist at all), and we analyze both P-violating T-conserving and P-violating T-violating nucleon-nucleon interactions in terms of the large-N_c expansion of QCD to provide additional theoretical constraints. This analysis establishes a hierarchy of terms that can be mapped onto symmetry-violating potentials, which establishes relations between couplings and helps to delineate the terms that should be most important in phenomenological applications. This presentation is based on Refs. [1,2].

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Trimer and Tetramer bound states in heteronuclear systems

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The Efimov effect in heteronuclear cold atomic systems is experimentally more easily accessible than the Efimov effect for identical atoms, because of the potentially smaller scaling factor [1]. We focus on the case of two or three heavy identical bosons and one fermion. The former case was recently observed in a mixture of ^{133}Cs and ^{6}Li atoms [2],[3].

We employ the Gaussian Expansion Method as developed by Hiyama, Kino et al. [4]. This is a variational method that uses Gaussians that are distributed geometrically over a chosen range. Supplemental calculations are performed using the Skorniakov-Ter-Martirosian equation [1].

Blume et al. [5] previously investigated the scaling properties of heteronuclear systems in the unitary limit and at the three-body breakup threshold. We have completed this picture by calculating the behaviour on the positive scattering length side of the Efimov plot, focussing on the dimer threshold. In this region, the appearance of dimer-atom-atom Efimov states is predicted and for identical bosons they have been found in theoretical calculations [6]. We investigate the feasibility of finding these dimer-atom-atom states within the confines of our method.

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Relativistic Calculation of Baryon Masses and Hadronic Decay Widths With Explicit Pionic Contributions

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Canton L. Plessas W. Schweiger W.

We have studied baryon ground and resonant states by taking explicit mesonic degrees of freedom into account. We have followed a relativistic coupled-channels (CC) approach relying on a Poincaré-invariant mass operator in matrix form. It corresponds to a bare particle b that is coupled to j further mesonic channels.

Here we report results, where the b particle is either a bare N or bare Δ coupled to πNN and $\pi N\Delta$ channels, respectively. For the baryon-pion vertices we employ coupling constants and form factors from different models in the literature [1-3]. By solving the eigenvalue equation for the mass operator we obtain the pion-dressing effects on the N ground-state mass as well as the mass and hadronic decay width of the Δ. The dressed masses become smaller than the bare ones, and a finite width of the Δ resonance is naturally generated.

The results are relevant for the construction of constituent-quark models for hadrons, which have so far not included explicit mesonic degrees of freedom. They produced covariant results for hadronic decay widths generally underestimating phenomenological data [4]. A $q\bar{q}$ toy model for mesons following a similar CC approach on a microscopic level has already shown promising results for dressed masses and finite decay widths of resonances [5].

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Deuteron Analyzing Powers for *dp* Elastic Scattering at Intermediate Energies and Three Nucleon Forces

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Wada Y. Watanabe A. Eto D. Akieda T. Kon H. Miki K. Sakamoto N. Sakai H. Sasano M. Shimizu Y. Suzuki H. Uesaka T. Yanagisawa Y. Dozono M. Kawase S. Kubota Y. Lee C.S. Yako K. Maeda Y. Kawakami S. Yamamoto T. Sakaguchi S. Wakasa T. Yasuda J. Ohkura A. Shindo Y. Tabata M. Milman E. Chebotaryov S. Okamura H. Tang T.L.

Few-nucleon scattering at intermediate energies ($E/A \sim 200$ MeV) is one attractive approach to investigate the dynamical aspects of 3NFs, such as momentum and/or spin dependences. Direct comparison between the data and the rigorous numerical calculations based on bare nuclear potentials provides information of 3NFs. So far large 3NF effects are theoretically predicted and experimentally confirmed in the cross section minimum for *dp* scattering at $\sim$ 100 MeV/nucleon. With the aim of clarifying roles of the 3NFs in nuclei the experimental programs with polarized deuterons beams at intermediate energies are in progress at RIKEN RI Beam Factory (RIBF) [1]. We have measured all deuteron analyzing powers (iT_{11}, T_{20}, T_{21}, and T_{22}) for deuteron–proton (*dp*) elastic scattering at 70–300 MeV/nucleon, typically in step of 50 MeV/nucleon.

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

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

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Time-dependent correlated Gaussian approach to the nuclear response of few-nucleon systems

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Nuclear reactions such as particle emission, β-delayed particle emission, and such caused by electromagnetic transitions provide the information on nuclear structure and reaction dynamics. For example, in the primordial nucleosynthesis, nuclei having mass number 2-7 are created by radiative captures. This process is often studied by investigating its inverse reaction; photoabsorption reaction, which occurs mainly due to E1 transitions. However, one faces difficulty to treat many-body continuum states. Here we employ the time-dependent method [1]. The method requires no explicit continuum states, and we solve the time-dependent Schr?dinger equation directly to obtain the response functions of a nuclear systems. The wave function is expanded by correlated Gaussian (CG) function [2], which can efficiently describe many-body correlations. When we solve time-dependent equation, however, the artificial reflection waves appear from the model space boundaries. Ref. [3] has discussed the explicit time-dependent basis functions to avoid this problem. Combining these ideas, we develop the explicitly time-dependent CG function and describe the response of N-nucleon systems. The photoabsorption cross sections of two- to four-nucleon systems are calculated to show the power of the time-dependent CG function.

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Neutron$-{}^{19}$C scattering: emergence of universal properties in finite range potential

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In this work we revisit the well known study of neutron-deuteron doublet scattering length extending it to the ^{20}C halo nucleus approached by two halo neutrons and a core interacting by a Yamaguchi potential. The calculation of $k \cot \delta_0$ for the low energy neutron$-{}^{19}$C scattering reveals a pole coming from the log periodic solutions originated from the Efimov physics. The results for a finite range potential present a universal feature scaling with the ratio of the three-body center-of-mass energy and the position of the pole. This results is in accordance with previous calculations performed with a zero-range potential. We observed a slight change of the position of the pole as well as the neutron$-{}^{19}$C energy where the three-body ^{20}C excited state turns into a virtual state. The analytical structure of the unitary cut is not affected by introducing neither a mass asymmetry nor a finite range potential.

Gauge-independent treatment of radiative capture in nuclear reactions: application to the theory of alpha-alpha bremsstrahlung

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

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Different properties of $\bar{K}NN$ and $\bar{K}\bar{K}N$ systems

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Three-body systems consisting of nucleons and antikaons are interesting exotic objects of different type with different properties. For example, a quasi-bound state caused by strong antikaon-nucleon attraction exists in K^-pp and K^-K^-p systems. Unfortunately, it is hard to measure binding energy and width of such a state: several experiments devoted to the K^-pp system reported very different results.

One more example is (anti)kaonic deuterium. The lowest level of this exotic atom is shifted due to presence of the strong interactions. The shift and the width of $1s$ level can be measured directly, but accurate theoretical evaluation of this observables is hard.

The talk summarizes results of theoretical works [1-3] devoted to the $\bar{K}NN$ and $\bar{K}\bar{K}N$ systems. The calculations were performed using Faddeev-type AGS equations with coupled channels.

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Experimental studies of the tetra-neutron system by using RI-beam

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We have found a candidate tetra-neutron resonant state via a double-charge exchange reaction ^{4}He(^{8}He,^{8}Be) at 190 A MeV by using the SHARAQ spectrometer at the RIBF facility in RIKEN [1]. Production mechanism with kinematical consideration for the present reaction is introduced and analysis for the obtained missing mass spectrum is presented. Nuclear forces relevant for formation of multi-neutron resonance are discussed for consistent understanding of few-body systems. Other experimental approaches for the tetra-neutron system at the RIBF are also shown.

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Modern chiral forces applied to three-nucleon electroweak processes

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The improved chiral nucleon-nucleon (NN) interaction with the semi-local regularization was derived recently [1,2] up to the fifth order of the chiral expansion. In comparison to the older version of the chiral potential [3] the regularization of the potential is now performed in coordinate space what leads to a much better control of finite-cutoff artefacts. In the two-nucleon system the new force yields a very precise description of phase shifts as well as observables up to 300 MeV and shows only tiny dependence on the regularization parameter.

In the three-nucleon (3N) sector the older version of the interaction works well at the next-to-next-to leading order (N2LO) for the nuclear structure and nucleon-deuteron (Nd) scattering [4]. However, a strong cut-off dependence is observed at N3LO in description of the ^{3}H nucleus [5] and in study Nd reactions [6,7]. The situation is even worse for the electromagnetic processes in 3N systems, where the dependence on the used regulators is sizeable already at N2LO [8,9,10].

In the present contribution the recent application [11] of the state-of-the-art NN potential [1,2], obtained within the formalism of Faddeev equations [12] in momentum space, to the 3N systems will be presented with the focus on electroweak processes. In particular, predictions for proton-deuteron radiative capture, ^{3}He photodisintegration and muon capture on the ^{3}He leading to the ^{3}H, d+n or n+n+p and a muonic neutrino in the final state, will be given. Finally, the predictions on the Gamow-Teller matrix element in the ^{3}H beta decay, obtained with the single nucleon weak current supplemented by dominant exchange currents consistent with the chiral interaction [13] will be presented for the first time. The possible use of this matrix element to fix free parameters of the 3N force will be discussed.

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Invariant variables for breakup reaction

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A large set of high precision data of $^1H(\vec{d}, pp)n$ reaction at beam energy of 130 MeV were collected with SALAD and GeWall detectors [1], [2]. The polarized deuteron beams were produced with the use of the ion sources of the AGOR (KVI Groningen, The Netherlands) and COSY (IKP FZ-Juelich, Germany) accelerators.

The $\vec{d}p$ breakup reaction is one of the simplest processes to study dynamics of three nucleons. The process is characterized by a rich kinematics of the final state what makes it selective regarding the employed model of interaction. Experiments with polarized beams (or targets) give opportunity to study a large number of observables (e.g. analyzing powers) sensitive to dynamical components, which are hidden in the unpolarized case. All studied observables (e.g. cross section, vector and tensor analyzing powers) are interesting for testing theoretical calculations based on various approaches [3 - 7] to model the interaction in few-nucleon systems.

The kinematics of breakup reaction can be described in many different ways, e.g. using particles energies and their emission angels, with Jacobi momenta or in terms of invariant variables. In this work we concentrate on the Mandelstam variables which have been rewritten in a convenient way for breakup reaction (three-nucleon in final state).

The experimental data will be transformed to the variables based on Lorentz-invariants and compared with modern theoretical calculations. The main purpose of such analysis is to check its applicability for studies of various dynamical effects. In particular, studies in terms of invariant variables can encompass and treat in a consistent way very rich data sets collected for breakup reaction at various energies.

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Dynamics of several ultra-cold particles in a double-well potential

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In nowadays experiments in ultra-cold physics it is possible to study dynamical properties of a few quantum particles confined in nontrivial potentials. Typically these experiments are described on theoretical level with simplified models based on mean-field description or Hubbard-like models with limited number of modes. In my talk I will present two examples showing that in the case of strongly interacting particles these approaches may lead to completely incorrect predictions.

1. In the case of two ultra-cold BOSONS confined in a one-dimensional double-well potential we compare the exact dynamics governed by a full two-body Hamiltonian with the dynamics obtained in a two-mode model approximation. We show that for sufficiently large interactions the two-mode model breaks down and higher single-particle states have to be taken into account to describe the dynamical properties of the system correctly. The fundamental difference between the exact and two-mode descriptions emerges when inter-particle correlations are considered. For example, the evolution of the probability that both bosons are found in opposite wells of the potential crucially depends on couplings to higher orbitals of an external potential [1].

2. In the case of a few ultra-cold FERMIONS confined in a double-well potential we show that the dynamics, which is governed by single-particle tunnelings for vanishing interactions, is completely different for strong interactions. Depending on the details of the configuration, for sufficiently strong interactions (repulsions or attractions) the particle flow through the barrier can be accelerated or slowed down. This effect cannot be explained with the single-particle picture. It is clarified with a direct inspection of the spectrum of the few-body Hamiltonian [2].

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Experimental studies of few-nucleon systems at intermediate energies

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Systems of three nucleons (3N) can be treated as a testing ground for modern approaches to describe nuclear interaction. At medium energies, observables for 3N systems are sensitive to subtle effects of the dynamics beyond the pairwise nucleon-nucleon force, so-called 3N-force (3NF). For years the quest for 3NF has been motivating precise measurements of observables in systems composed of 3 nucleons, particularly in the sector of elastic nucleon-deuteron scattering [1]. Recently, a database for the deuteron breakup reaction has also been significantly enriched with precise data, collected with detection systems covering large parts of the phase space [1,2]. Breakup of a deuteron in collision with a proton leads to the final state of three free nucleons, with variety of possible kinematic configurations, revealing locally enhanced sensitivity to particular aspects of the interaction dynamics, like 3NF, Coulomb force between protons, or relativistic effects. This feature makes the breakup reaction a very versatile tool for validation of the theoretical description.

Reactions involving 4 nucleons pose immense challenges as regards exact theoretical calculations for such systems. Nonetheless, they attract attention due to expected enhanced sensitivity to certain aspects of the nuclear dynamics, manifesting themselves in various channels and configurations.

The most important results of recent experimental studies of 3N and 4N systems at medium energies will be discussed. A brief survey of ongoing and planned projects will also be given.

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Ground state properties of weakly bound few-body systems

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Vranješ Markić L. *Boronat J.*

The results of the recent research in quantum systems will be presented. Ground state properties of weakly bound systems consisting of few particles are explored with a special emphasis on a universality of quantum halo states - weakly bound systems with a radius extending well into the classically forbidden region.

The focus of the study are clusters consisting of T↓, D↓, ^{3}He, ^{4}He and alkali atoms. The study of realistic systems is supplemented by model calculations in order to analyze how low-energy properties depend on the interaction potential. The use of variational and diffusion Monte Carlo methods enabled very precise calculation of both size and binding energy of the trimers and tetramers.

Using dimensionless measures of the binding energy and cluster size, studied atomic clusters are compared to other known halos in different fields of physics. Characteristic scaling lengths, which make size-energy ratio to be universal, are selected.

As the scaled binding energy decreases, tango type trimers separate from Borromean type [1]. Research is extended to tetramers. Furthermore, the structural properties of different trimers are compared with recently published experimental results [2,3] obtained by Coulomb explosion imaging of diffracted clusters.

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Few-Body Effects in Neutron Star Matter

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Nuclear reactions and processes stimulated by huge pressure in the overdense matter of a neutron star are considered in the frame of their mutual influences. These forced reverse reactions and nonlinear interactions as well as few-body effects play the important role in the forming of the unusual states that are impossible in ordinary conditions. The neutron resonances of three-body type arise in certain layers of crystalline structure in neutron star envelopes [1] and lead to local oscillations of density, which change the micro profile of pulsar impulses.

The primary chemical composition of neutron star determines the ways of matter transformation in the layers of neutron star crusts. It is shown that apart from an electron capture by nucleus the reactions with emission of neutrons, alpha particles and formations of excited nuclei take place in deep layers of inner crust.

The nonlinear interactions of excited nuclei result in high harmonic generations and reactions with gammas, which are able to punch out nucleons and alpha particles from the nuclei. So, the inner crust layers are enriched with free neutrons and alpha particles. The calculations demonstrate crucial distinction between the processes of nuclides transformation in the case of Fe and Si groups of elements.

The special experiments are proposed to detect the neutron resonances of few-body type in the low energy region [2]. Our calculations are carried out for those neutron resonances that appear in the crystal with ^{113}Cd isotopes and demonstrated the absence of three-body resonances in the crystals with ^{112}Cd isotopes.

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Many-body effects in three-body systems: a case of (d,p) reactions

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Johnson R.C. Waldecker S.J.

It has been recently shown [1] that projecting a many-body wave function into a three-body channel results in a three-body model with complex nonlocal energy-dependent three-body optical potential which is not equal to the sum of pairwise two-body optical potentials describing elastic scattering in the two-body subsystems. The two terms of this potentials that can be interpreted as two-body potentials in a three-body system still depend on the position of and interaction with the third body. Other terms describe complicated multiple scattering effects that include excitation of internal degrees of freedom of the constituents of the system. Nevertheless, in the case of A(d,p)B reactions, which are affected by only those components of the three-body wave function A+p+n in which p-n separation is small, an A-n (A-p) optical potenial can be obtained by averaging over the position of p (n). This results in an adiabatic model for deuteron channel that contains nonlocal energy-dependent optical potentials, describing elastic scattering data, which should be evaluated at a different nucleon energy than that widely used. Our new numerical calculations with energy-dependent N-A optical potentials, taken from nonlocal dispersive optical model [2] designed to forge the link between nuclear structure and reactions, have shown that many-body effects in three-body systems are much more important than previously thought.

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On-shell transition in the SRG framework with a chiral interaction

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Arriola E.R. Szpigel S.

In the framework of similarity renormalization group (SRG) [1] we use a chiral nucleon-nucleon interaction at N3LO [2] in the 1S0 channel in order to investigate the on-shell transition during the SRG flow towards the infrared limit [3-5]. Our analysis is based on the Frobenius norm of the effective interactions at different similarity cutoffs [6]:

$$\phi = ||V_\lambda|| = \sqrt{TrV_\lambda^2}\ .$$

Choosing $\beta = \frac{d\phi}{d\lambda}$ as the order parameter, we observe a typical behaviour of a crossover transition. The pseudo-critical similarity cutoff λ_c can be located by the maximum of $\frac{d\beta}{d\lambda}$. This scale depends on the number of points used to represent the momentum space and is about $\lambda_c = 0.9$ fm^{-1} for $N = 30$ points.

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Faraday waves in coldatom systems with two- and three-body interactions

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Gammal A. Abdullaev F.Kh.

By following some previous works on the role of three-body interactions in Bose-Einstein condensates (BEC), we consider ultracold atomic system with two- and three-body interactions periodically varying in time. Typically, in dilute BEC systems, three-body effects are quite small in comparison with two-body effects. However, a relevant role of a even small repulsive three-body interaction in condensates was shown in [1], when considering attractive two-body interactions. In such a case, the existing critical maximum number of atoms for stability can be considerably extended. More recently, an interesting scheme to reach a condensate with almost pure three-body effects was suggested in [2], by periodical variations in time of the two-body interaction. Therefore, we study two models of time-dependent three-body interactions, with quadratic and quartic dependence on the two-body atomic scattering length a_s [3]. We verify that parametric instabilities in the condensate leads to the generation of Faraday waves (FW), with wavelengths depending on the background scattering length, as well as on the frequency and amplitude of the modulations of a_s. Such results can open new experimental possibilities to tune the period of Faraday patterns by varying not only the frequency of modulations and background scattering length, but also through the amplitude of the modulations.

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Three nucleon scattering in a "three dimensional" approach

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Golak J. Skibiński R. Witała H.

Recent results published in [1] hint that the traditional partial wave approach used to describe three nucleon scattering does not produce convergent results for certain kinematical situations. In this talk I will introduce the so-called "three dimenional" approach to few nucleon calculations where, instead of resorting to partial wave decomposition, the three dimensional degrees of freedom of the nucleons are utilized directly. Practical calculations using this approach are possible, to a large extent, due to the possibility of writing the relavent operators in their most general form where their matrix elements in momentum space are a linear combination of scalar functions and spin - isospin operators [2]. Constructing this general operator form is a difficult task but it significantly limits the computational complexity of the calculations. Currently operator forms exist e.g. for the two-nucleon force, the two-nucleon transition operator and for certain types of three-nucleon forces [3]. I will describe a new procedure that can be used to construct this general form for few nucleon potentials. Additionally, special emphesis will be put on the applications and benefits of this new "three dimenional" formalism in the description of three-nucleon scattering.

The project was financed from the resources of the National Science Center (Poland) under grants No. DEC-2013/11/N/ST2/03733 and DEC-2013/10/M/ST2/00420.

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Trion and biexciton in monolayer transition metal dichalcogenides

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Kezerashvili R.Ya.

Today as a potential semiconductor counterpart to gapless graphene, one of the most promising materials is a class of direct bandgap monolayers of transition metal dichalcogenides (TMDCs) such as WS_2, WSe_2, MoS_2, $MoSe_2$. Optical excitation of TMDC monolayer generates electron-hole pairs, excitons ($X = eh$), held together via Coulomb interactions. In the presence of residual free electrons and holes, excitons interact with the surrounding charges, ultimately binding to form trions ($X^- = eeh, X^+ = ehh$) that are charged excitons, and neutral biexcitons ($X_2 = eehh$). One of the most remarkable features of 2D TMDC monolayers is a strong Coulomb interaction between charge carriers (electrons and holes) that leads to the formation of multi-carrier bound states of excitons, trions and biexcitons. The week dielectric screening and reduced dimensionality allowing the formation of trions and biexcitons with binding energy few tens of meV.

We study the trion and biexciton in TMDC monolayers within the framework nonrelativistic potential model using the method of hyperspherical harmonics (HH). For solution of three- and four-body Schredinger equations, we expand the wave functions of three- and four bound particles in terms of the antisymmetrized hyperspherical harmonics, and obtain the corresponding hyperradial equations that are solved numerically. In our calculations we use the 2D screened electrostatic interaction potential [1]. This potential differs substantially from the usual $1/r$ Coulomb potential, exhibiting nonlocal macroscopic screening which arises in 2D systems. We evaluate the trion and biexciton binding energies for a range of values of the screening length assuming different electron and hole effective masses. The convergences of binding energy calculations for the ground state of the trion and biexciton are studied.

We study solutions of hyperradial equations in the lowest approximation for the grand angular momentum to examine two regimes: a long range and a short range cases when the interparticle distance is much greater and much less than the screening length. For these cases, we find the analytical expressions for the energy and wave function for the trion and biexciton states.

The comparison of our results with experimental data and results obtained using the path integral Monte Carlo approach [2] and the stochastic variational method [3] is presented.

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Contribution of the Δ-isobar mechanism to the reaction $pp \to \{pp\}_s\pi^0$ in the resonance region

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The resonance structure observed in the total cross section of the reaction $pp \to d\pi^+$ with the maximum at about 600 MeV was explained by the $\Delta(1232)$-isobar excitation in the intermediate state [1]. Recently new analysis was performed [2] showing, however, that the pure Δ-mechanism is not sufficient to explain the absolute value of the total cross section of the reaction $pp \to d\pi^+$ and therefore dibaryon contributions were considered in [2]. In this situation it is important to study another channel of this reaction, $pp \to \{pp\}_s\pi^0$, at similar kinematics conditions but with formation of the diproton $\{pp\}_s$ in the final state with small excitation energy $E_{pp} < 3$ MeV providing a dominance of the $^1S_0$ state. Due to difference of of the spin S and isospin T of the deuteron $(S = 1, T = 0)$ and diproton $(S = 0, T = 1)$ the reaction $pp \to \{pp\}_s\pi^0$ provides an independent test for the models of the reaction $pp \to d\pi^+$.

According to [3], the approach [1] completely fails to describe the data on the reaction $pp \to \{pp\}_s\pi^0$ obtained by ANKE@COSY [4]. A simpler model based on the triangle diagram of the one-pion exchange with the subprocess $\pi N \to \pi N$ turned out to be more successful [5]. In this work we study the reaction $pp \to \{pp\}_s\pi^0$ using one-loop diagrams with the subprocess $\pi N \to \Delta \to p\pi^0$. The parameters for the coupling constants and vertex form factors which were used to explain the COSY data on the reaction $dp \to \{pp\}_s N\pi$ [6], are applied here. The calculated energy dependence of the differential cross section at zero angle of the pion is in qualitative agreement in shape with the data at energy 350-800 MeV. However, its absolute value is by factor of 4-5 below the data if the off-shell behaviour of the vertex $\pi N\Delta$ form factor is taken into account. When the off-shell effects are in part neglected, the data is still underestimated by $\sim 30\%$. A similar underestimation is obtained here using the vertex form factors from Ref.[2].

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Applications of the stochastic variational method in few-body problems

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We will review some of the most recent applications of the Stochastic Variational Method (SVM):

(1) SVM is used to show that the effective mass model correctly estimates the binding energies of excitons and trions but fails to predict the experimental binding energy of the biexciton. Using high-accuracy variational calculations, it is demonstrated that the biexciton binding energy in transition metal dichalcogenides is smaller than the trion binding energy, contradicting experimental findings [1],[2].

(2) The energies and physical properties of three-electron systems are studied using an explicitly correlated Gaussian basis optimized by the stochastic variational method. The stability of the system as a function of the nuclear charge is analyzed. The role of the Coulomb and magnetic interactions in shaping the structure of these systems is discussed [3],[4].

(3) We have extended the explicitly correlated Gaussian basis approach to solving time-dependent problems. The method gives an accurate fully quantum mechanical description of ionization of small atoms and molecules.

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Three-nucleon force effects in $p - {}^3$H and $n - {}^3$He scattering

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Kievsky A. *Marcucci L. E.*

We present new results for $p - {}^3$H and $n - {}^3$He scattering for energies below the trinucleons breakup threshold (i.e. below the opening of $d - d$ channel). The calculations are performed solving the four-body quantum mechanical problem using the Kohn variational principle and the hyperspherical harmonics (HH) technique. These calculations are rather complex since the two reaction channels are coupled and involve both $T = 0$ and $T = 1$ states. So far, only a few other accurate calculations has been performed for these processes [1].

Clearly, these four-body reactions are a particularly interesting "theoretical laboratory" to test the accuracy of our present knowledge of the nucleon–nucleon (NN) and three nucleon (3N) interactions. Moreover, they are also of interest for astrophysics, energy production, and studies of fundamental symmetries. For these reasons, we have extended our HH technique [2] to treat these processes.

The calculations are carried out considering NN and 3N interactions derived from chiral effective field theory, and taking fully into account of the Coulomb repulsion between the protons. From these calculations we can extract information on energies and widths of the lowest excited states of ^{4}He and compute several elastic and transfer observables. The obtained results are compared with the available experimental data. In particular we have studied the effects of the inclusion of the 3N interaction. We have found that this has a significative impact on the observables, in particular close to the $n - {}^3$He threshold [3]. We report also on the results of a bechmark performed for these reactions using the HH, the Alt–Grassberger–Sandhas, and Faddeev-Yakubovsky methods [4].

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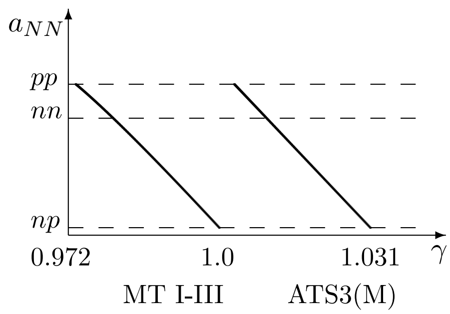
S-wave approach for nnp and ppn systems with phenomenological correction for singlet NN potentials

Vlahovic B. (North Carolina Central University, Durham, NC)
Suslov V.M. Filikhin I.

Three-nucleon systems are considered assuming the neutrons and protons to be distinguishable particles. The configuration space Faddeev equations within the s-wave approach are applied to study bound state and scattering problems. The phenomenological Malfliet-Tjon MT I-III and Afnan-Tang ATS3 NN potentials are used. We modified the potentials by scaling strength parameters to define nn, pp and np singlet components. The scaling parameters γ are fixed to reproduce two-body experimental scattering lengths. The relation between the scattering lengths and γ for MT I-III and modified ATS3 potentials is shown in the figure below. The experimental values of the singlet NN scattering lengths [1] are shown by dashed lines (pp, nn, np). We calculated the ground state energies of ^{3}H and ^{3}He nuclei. Performed is also numerical evaluation for the charge symmetry breaking energy. The relations between the nn, pp and np singlet potentials are proposed. The nd and pd breakup scattering at E_{lab} =4.0 and 14.1 MeV are studied within the same model. Calculations of phase shifts and inelasticities as well as the breakup amplitudes are performed. We compare the results obtained within this model and those calculated using the isospin formalism [2].



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Strongly interacting one-dimensional systems in a trap

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Strong interparticle coupling in one-dimensional geometries leads to an unusual duality between impenetrable bosons and ideal fermions [1], often called the Fermi-Bose mapping. This duality allows one to describe the strongly-interacting regime and some modern experimental setups [2,3] in a relatively simple manner.

Here we present an extension of this mapping to systems under external confinement. In particular, we show that the Fermi-Bose mapping can be used to determine the spectral and structural properties of trapped systems. We note that the calculated properties also characterize spin chain systems. As a consequence, strongly interacting trapped systems realize Heisenberg Hamiltonians with non-homogeneous couplings. To illustrate our findings we apply the formalism to an impurity problem, where one distinguishable particle is immersed in a sea of identical atoms.

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Absence of observable Efimov resonances in ultracold KRb mixtures

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The two body interaction of ultracold atoms can be changed by several orders of magnitude by addressing magnetic Feshbach resonances. Employing this feature they recently became a driving force in few-body physics due to the observation of the Efimov effect. While initially observed in equal mass systems, even richer few-body physics is expected in the mass-imbalanced case. Previous experiments with ultracold mixtures of potassium and rubidium showed an unexpected non-universal behavior of Efimov resonances across isotope combinations. I will present our measurements of the scattering length dependent three-body recombination coefficient in ultracold heteronuclear mixtures of ^{39}K-^{87}Rb and ^{41}K-^{87}Rb. In contrast, we do not observe any signatures of Efimov resonances in either mixture. Our results show good agreement with our theoretical model for the scattering dependent three-body recombination coefficient and reestablishes universality of the three-body parameter across isotopic mixtures.

Study of charge symmetry breaking via the gamma-ray spectroscopy of ${}^{4}_{\Lambda}$He and ${}^{4}_{\Lambda}$H

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J-PARC E13,E63 collaboration

The charge symmetry breaking (CSB) effect reported in the few body A=4 mirror hypernuclei is one of the hot topics in strangeness nuclear physics. Precise gamma-ray spectroscopy with an energy resolution of a few keV is a powerful tool to investigate such an effect. In fact, a gamma-ray spectroscopy study of ${}^{4}_{\Lambda}$He was performed at the J-PARC K1.8 beam line (J-PARC E13) for this purpose. ${}^{4}_{\Lambda}$He hypernuclei were produced by the (K^-, π^-) reaction with a 1.5 GeV/c kaon beam using a liquid ^{4}He target. Gamma rays were measured with a newly developed Ge detector array, Hyperball-J. The excitation energy of first excited state of ${}^{4}_{\Lambda}$He(1^+) was successfully determined to be 1.406±0.004 MeV. By comparing to that of the mirror hypernucleus (${}^{4}_{\Lambda}$H) from previous old studies, we conformed the existence of CSB effect and its spin dependence. Our next step is a more precise and conclusive measurement of the excitation energy of ${}^{4}_{\Lambda}$H(1^+) to experimentally establish the fewest-body mirror hypernuclei system. We are planing gamma-ray spectroscopy of ${}^{4}_{\Lambda}$H at the J-PARC K1.1 beam line (J-PARC E63) via the ^{7}Li(K^-, π^-) reaction.

The results of the gamma-ray spectroscopy of ${}^{4}_{\Lambda}$He and an outline of the J-PARC E63 experiment will be given in this contribution.

Ferromagnetism of a repulsive Fermi gas: ongoing and future experiments in Florence

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Valtolina G. Scazza F. Amico A. Burchianti A. Recati A. Enss T. Inguscio M. Roati G.

Itinerant ferromagnetism represents one of the most spectacular manifestations of interactions within many-body fermion systems. In contrast to weak-coupling phenomena, it requires strong repulsion to develop, making a quantitative description of ferromagnetic materials notoriously difficult. In this frame, it is still debated whether the simplest case envisioned by Stoner of a homogeneous Fermi gas with short-range repulsive interactions can exhibit ferromagnetism at all.

Here, I will discuss two experimental routes to tackle such an intriguing problem with ultracold Fermi gases.

I will first describe a recent experiment in which we create an artificial ferromagnetic state by segregating degenerate spin mixtures of 6Li atoms into two initially disconnected reservoirs. Starting from such a configuration, we characterize the behavior of the gas as a function of the interspecies interactions and temperature through two distinct but interconnected measurements of spin dynamics. First, we observe the softening of the spin-dipole mode, unambiguously connected to the diverging magnetic susceptibility approaching the ferromagnetic transition. Second, we investigate the diffusion dynamics of the two spin domains, whose temporary halt outlines the metastable character of the ferromagnetic state. Notwithstanding the limited lifetime of the repulsive Fermi gas due to the competing pairing instability, our findings allow us to draw in the temperature-interaction plane the critical boundaries for the ferromagnetic phase to exist, at least in a metastable sense. Intriguingly, our findings point to the existence of repulsive Fermi polarons, which nicely link the features of the many-body system herein investigated to the microscopic properties of few-body fermion systems.

I will then outline the exciting possibility to realize long-lived Fermi gases at strong repulsion offered by a novel mixture of Lithium and Chromium atoms. Indeed, the peculiar Cr-Li mass ratio enables an extraordinary suppression of atom recombination into paired states in the regime of strong interspecies repulsion, making such a system a clean benchmark for the study of the para-to-ferro-magnetic phase transition in ultracold gases.

Also in this case, I will outline how interesting many-body features of Cr-Li systems naturally arise from the unique three-body properties of such atomic mixture

Study of the Few Nucleon Systems at CLAS

Zachariou N. (University of Edinburgh)

The study of few nucleon systems with electromagnetic probes is an essential component of the scientific program carried out at the Thomas Jefferson Laboratory. Here we present measurements of exclusive reactions on light nuclei using real photon beams with energies up to 3 GeV and the CEBAF Large Acceptance Spectrometer (CLAS), a nearly 4π magnetic spectrometer, in order to study the properties of strongly interacting matter and the transition from hadronic (i.e in terms of nucleons and mesons) to partonic (in terms of quark and gluons) degrees of freedom in nuclear interactions. We will discuss the progress made in understanding the relevant degrees of freedom using polarisation observables and unpolarised cross sections of deuteron and ^{3}He photodisintegration in the few-GeV photon-energy region. Recent high-statistics experiments with the CLAS detector have provided us with sufficient counting rates to study the effects of initial- and final-state interactions in reactions off the deuteron. Such data allow us to extract a large set of polarisation observables for final-state interactions in hyperon photoproduction and to study the properties of the hyperon-nucleon interaction. Initial-state effects are studied by mapping the dependence of experimental observables on the spectator-nucleon momentum. We will present recent results for polarisation observables for quasi-free $K^+\Lambda$ off the bound proton in a deuteron as well as for final-state interactions in the reaction $\gamma d \to K^+\Lambda n$, and will discuss their impact on hyperon-nucleon studies.

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Aarhus general information

Banks

Numerous banks are situated in the city center. Bank opening hours: Monday-Friday 09:30-16:00, Thursday 09:30-18:00. Closed Saturdays and Sundays

Currency exchange

Forex is located close to the main train station in the city center. Address: Banegårdspladsen 20, 8000 Aarhus C, Phone: (+45) 86 80 03 40 Opening hours: Monday-Friday 09:00-18.00, Saturday 10:00-15:00

Credit card / cash points

Out of banking hours, cash points accepting major credit cards are conveniently located all around the city.

Travel / Flights

To search for local travel within Denmark see www.rejseplanen.dk (available in English).
For information on flights in/out of Aarhus airport: www.aar.dk
For information on fights in/out of Billund airport: www.bll.dk

Bus times to Aarhus and Billund airports can be found at the information desk.

Dining out in Aarhus

Most restaurants in Aarhus are open from 11:30-24:00. However, hot meals are generally not served after 22:00. Service charges are included in the price; tipping is not required.

Shopping

Shops in Aarhus are usually open Monday to Friday from 9:30 17:30 (Saturday 09:30 16:00). Supermarkets and department stores are open until 20:00. On Sundays some shops are open. Most shops accept all major credit cards, however in some shops the use of a foreign credit card will add a transaction fee of 3.75% of the purchase amount.

Voltage

Electricity in Denmark is 220V AC. Plugs are European standard with two round pins.

Emergency phone numbers

Emergency phone (police, re, ambulance) (+45) 112
Falck rescue services (+45) 70 10 20 30
Police (+45) 87 31 14 48
Casualty dept. of Aarhus Hospital (+45) 87 11 31 31
Doctor, out of hours (+45) 70 11 31 31


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7 RADISSON BLU SCANDINAVIA HOTEL / SCANDINAVIAN CONGRESS CENTER
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