INTERNATIONAL WORKSHOP ON

FEW-BODY SYSTEMS

(FBS-Dubna-2012)

Bogoliubov Laboratory of Theoretical Physics
JOINT INSTITUTE FOR NUCLEAR RESEARCH
Dubna, Russia, June 27 – 29, 2012

PROGRAM AND ABSTRACTS

Dubna
2012

INTERNATIONAL WORKSHOP ON

FEW-BODY SYSTEMS

(FBS-Dubna-2012)

BLTP, JINR, Dubna, Russia, June 27 – 29, 2012

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INTERNATIONAL WORKSHOP ON
FEW-BODY SYSTEMS
(FBS-Dubna-2012)
BLTP, JINR, Dubna, Russia, June 27 – 29, 2012

Overview

The International Workshop on Few-Body Systems, FBS-Dubna 2012, will be held on June 27 – 29, 2012, at the Bogoliubov Laboratory of Theoretical Physics, JINR, Dubna, Russia. The workshop program covers various topics in physics of few-body systems including scattering theory, Coulombic few-body problems, few-body resonances, Efimov effect, Borromean binding, etc.

Few-body systems theory is dedicated to various quantum systems that might be considered consisting of several (say two, three, or four) elementary constituents. Depending on a particular situation and the energy range under consideration, the role of such constituents may be played by quarks, mesons, individual nucleons, nuclei or even by atoms and molecules. Smallness of the number of constituents in a system allows one to develop mathematically rigorous, exact and faithful approaches to its treatment, that do not require further simplifying physical assumptions or approximations. Due to their universality, the approaches based on the theory of few-body systems pave the way to successful solving various problems in nuclear physics, in physics of atoms and molecules, in quantum chemistry etc.

The purpose of the workshop is to bring together experts and young researchers working on few-body problems of nuclear physics, astrophysics, and physics of atomic and molecular collisions, for presenting their new results, identifying hot topics, and reporting on progress in methods and approaches.

Program of the workshop includes the following topics:

- Scattering theory for quantum systems of several particles;
- Recent progress in theory of Coulombic few-body systems;
- Universal properties of few-body systems at ultra-low energies, Efimov and Thomas effects, Borromean binding, halo systems;
- Numerical approaches to solving few-body bound-state, resonance and scattering problems.

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Sessions of the workshop will take place at the **Conference Hall** of the Bogoliubov Laboratory of Theoretical Physics. The workshop schedule is as follows.

Workshop Schedule[1]

	27.06 We	28.06 Th		29.06 Fr
9.00-9.50	Registration			
09.50	Opening			
Chair	*Belyaev*	*Blokhintsev*		*Kartavtsev*
10.00	Pen'kov	Rubtsova		Efros
10.30	Melezhik	Kukulin		Fedotov
11.00	Bidasyuk	Efremov		Lekala
11.30 *11.50*	*Coffee break*	*Coffee break*		*Coffee break*
Chair	*Yakovlev*	*Sandhas*		*Popov*
11.50	Kartavtsev	Kolganova		Blokhintsev
12.20	Motovilov	Vinitsky		Orlov
12.50	Gusev	Kouzakov		Pupyshev
13.20 *15.00*	*Lunch*	*Lunch*		*Lunch*
Chair	*Motovilov*	*Pen'kov*		*Orlov*
15.00	Yakovlev	Sandhas		Solov'ev
15.30	Levin	Shlyk		Pons
16.00	Popov	Shevchenko		Grozdanov
16.30	Mikhailov	Revai		Belyaev
17.00 *17.20*	*Coffee break*	*Coffee break*		Closing
Chair	*Kolganova*	*Pupyshev*		
17.20	Grinyuk	17.20	Egorova	
17.50	Ershov	17.40	Zarubin	
18.20	Grigorenko	18.00	Cerkaski	
		18.20	Machavariani	
		18.40	Lyuboshitz	
19.00	*Welcome Party*			

[1] Status of June 21, 2012

INTERNATIONAL WORKSHOP ON

FEW-BODY SYSTEMS

(FBS-Dubna-2012)

BLTP, JINR, Dubna, Russia, June 27 – 29, 2012

Abstracts

of contributed presentations

Rate of the $p+p+e \to d+\nu$ reaction at the center of Sun conditions

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Rate of the $p+p+e \to d+\nu$ process in the Sun and neutrino current are calculated. Initial state is considered in the framework of a three-body approach.

Near-threshold behavior of three-particle systems in s- and p-states

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The recent experimental observations of the Efimov effect stimulated new interest to theoretical investigation of this universal phenomenon. The appearance conditions of this effect is not easy to study both analytically and numerically. Especially in systems with higher angular momentum and systems of more particles there is still no final understanding how this effect can develop. Efimov himself stated that effect should exist in systems with higher angular momenta only in molecular regime, i.e. masses of two particles are much larger then mass of the third one, but no definite statement concerning the infinite or finite number of bound states were made.

In the present work a general three-particle problem with short-range interaction is studied in near-threshold states with different angular momenta. The considered system consist of two equal particles (both bosons and fermions are considered) and one particle of different nature. Using two types of particles with considerably different masses it is possible to tune the structure of spectrum in order to simplify Efimov spectra observation. Main numerical results are presented in a form of threshold diagrams displaying the regions where three-body bound states exist depending on two-body parameters and mass ratio. These threshold diagrams were obtained numerically by high-precision variational calculations and supported by explicit analytical expression in different asymptotic regions.

Different effects that appear on the threshold diagrams are studied both analytically and numerically. The special attention is paid to the occurrence conditions of the Efimov effect in three-particle p-states and in s-states with two resonating pairs of particles. We show that infinite series of bound states is universally possible (for any shape of short-range potential and any mass ratio) only in case of three particles in s-state and all three pairs in resonance. In other cases, typically associated with Efimov effect the infinite series do not exist. This can be explained using the fact that a singular kernel of the integral Faddeev equations

does not always lead to the infinite discrete spectrum. Even in the absence of infinite Efimov series one can observe the universal nonmonotonic behavior of energy thresholds, which is typically associated with Efimov effect. This effect of "trap" can be observed and explained in connection with avoided crossing of energy levels of different nature. We also provide some generalization of the universal properties of thresholds to four-particle system in *s*-states. We define occurrence conditions of "trap" effect and avoided crossings.

Analytic continuation of effective range expansion as a method to obtain bound state characteristics. Application to ^{6}Li

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Asymptotic normalization coefficients (ANCs) are important nuclear characteristics. They determine cross sections of radiative capture processes at astrophysical energies [1]. Their knowledge is necessary for solving the inverse scattering problem. The ^{6}Li nucleus in the $\alpha + d$ channel is one of the most interesting systems for which it is important to know ANCs. The ANC values for this system determine the cross section of the radiative capture $^4\mathrm{He}(d,\gamma)^6\mathrm{Li}$, which is the only process of ^{6}Li formation in the big bang model. The available data on the values of the ANCs C_l for the $^6\mathrm{Li} \to \alpha + d$ channel are characterized by a large spread (l = 0, 2 is the channel orbital angular momentum).

In the present work, the C_l values are found by analytic continuation in energy of the effective range expansion for $d\alpha$ scattering to the pole corresponding to the bound ^{6}Li state. Both one- and two-channel [2] versions of the effective range expansion are employed. Several sets of scattering phases are used as an input. The calculations are performed with and without the preassigned (fixed) value of the ^{6}Li binding energy ε. It follows from the numerical results obtained that the absolute values of C_l increase with increasing ε as well as with taking account of the Coulomb interaction. Account of the channel coupling affects only slightly the C_0 value. On the other hand, account of that coupling is absolutely necessary to get the reliable C_2 value. The ways of allowing for two- and three-body inelastic threshold phenomena within the effective range expansion formalism are discussed. The need for more accurate low-energy $d\alpha$ scattering data and the corresponding phase-shift analysis is emphasized.

1. A. M. Mukhamedzhanov and R. E. Tribble, Phys. Rev. C **52** (1999), 3418.
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Correlation effects in two-body systems in a magnetic field

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Can a mesoscopic system with a few particles moving in one-body potential exhibit a quantum phase transition (i.e. a phase transition driven by quantum fluctuations) due to the two-body interaction? The related question is, if such a transition occurs, what are the concomitant structural changes? Two-electron quantum dot (QD) being a mesoscopic system may provide answers on the above questions, since predictions made within theoretical models for two-electron QDs can be succesfully verified by thorough experimental analysis [1,2].

Using a three-dimensional parabolic approximation for confining potential, two-body systems in a perpendicular magnetic field are studied for various strengths of a general two-body interaction $U_M = \alpha_M / r^M$ ($\alpha_M > 0$, $M > 0$). We found the onset of shape-phase transitions in three-dimensional systems at a certain choice of the magnetic field strength and the width of the system. In particular, for the Coulomb interaction the ground state of two-electron QDs can be localized only in the lateral plane even for very strong magnetic fields. In contrast, for excited states the electron density distribution may evolve from the lateral to the vertical orientation along the direction of the applied magnetic field. The specific requirements for such transitions are discussed in terms of classical and quantum correlations. The analytical results obtained in the harmonic approximation are in a good agreement with available experimental data and numerical results for two-electron QDs [1].

1. R. G. Nazmitdinov and N. S. Simonović, *Finite-thickness effects in ground-state transitions of two-electron quantum dots*, Phys. Rev. B **76** (2007), 193306.
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Novel resonant states in three-body problem

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We consider the bound states of the three-body system consisting of a light particle and two heavy ones when the heavy-light short range interaction potential has a resonance

corresponding to the non-zero orbital moment. Within the Born-Oppenheimer approach we suggest the novel method to find the effective potential between the heavy particles by self-consistent scattering of light particle by two heavy ones. In the case of the exact resonance in the p-wave scattering the effective potential is shown to be attractive and long-range, namely it decreases as the third power of inter-atomic distance. Moreover, the range and power of this potential, as well as the number of the bound states are determined mainly by the mass ratio of the heavy and light particles and the parameters of the heavy-light short range potential.

Some relativistic aspects of few-body dynamics in electrodisintegration of trinucleons

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Inclusive response functions for electrodisintegration of trinucleons in the quasielastic peak region are accurately calculated. The non-relativistic Hamiltonian that includes realistic $NN + NNN$ forces has been employed. The results compare well with experiment at not high momentum transfers q. However, the comparison deteriorates progressively as q increases turning to a sharp disagreement at $q = 0.7$ GeV/c. This can be attributed to the fact that relativistic effects in nuclear dynamics were not accounted for.

Approaches to implicitly account for these effects are considered. These approaches involve the use of a subsidiary reference frame different from the laboratory one. They also involve a modification of the non-relativistic calculation such that momenta of fast fragments in the reaction final states take their correct relativistic values.

When the relativistic features are accounted for a very good agreement between theory and experiment is met.

Three-body correlations in ^{6}Be studied in knockout and charge exchange reactions

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The recent progress in research with radioactive ion beams (RIB) leads to increase of interest to nuclear systems close to the driplines and even beyond. Many of these systems have

three-body decay modes. This is mainly $2p$ decay mode if the proton dripline systems are considered. From theoretical point of view this means studies of processes in the Coulombic three-body continuum which is especially difficult for theoretical treatment. Effective and precise treatment of experimental data here are not possible without development of appropriate theoretical tools. Different required techniques and approaches are illustrated by the examples of works made in collaboration with experimentalists from world leading RIB facilities: (i) Correlations in the two protons decay of ^{6}Be in knock out reaction (2009, MSU, USA), (ii) investigation of excitation states and discovery of the novel IVSDM mode in ^{6}Be in charge exchange reaction (2009, FLNR, Dubna).

New method for a solution of coupled radial Schrödinger equations: Applications to halo-nuclei

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A modified variable phase method for numerical solution of coupled radial Schrodinger equations, which maintains linear independence for different sets of solution vectors, is suggested. The modification involves rearrangement of coupled equations to avoid usual numerical instabilities associated with components of the wave function in their classically forbidden regions. The modified method is applied to nuclear structure calculations of halo nuclei within the hyperspherical harmonics approach.

Transformations of the three-body pseudo-vector ($L^P = 1^+$) hyper-spherical harmonics

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The relations of the hyper-spherical harmonics expressed in different variables are widely used in practical calculations. Two kinds of the hyper-spherical variables are of special importance, one set is connected with Jacobi coordinates and another, which is connected with the momenta of inertia. In this report, the simple explicit expressions via the Clebsh-Gordan coefficients are derived for the transformations of the pseudo-vector ($L^P = 1^+$)

hyper-spherical harmonics in these sets of variables. Similar expressions for the transformations of the scalar ($L^P = 0^+$) hyper-spherical harmonics are known for a long time [1,2]. The presented expressions for both $L^P = 1^+$ and $L^P = 0^+$ cases are significantly simpler than general ones obtained in [3].

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Studies of few-body dynamics in dripline nuclei at FLNR

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The nuclear driplines are nowadays achieved experimentally for the light nuclear systems and there is an important trend in the modern research with radioactive ion beams to study the systems close and even beyond the driplines. Many of these systems demonstrate unusual properties which can be attributed to different forms of irreducible few-body dynamics, like three-body nucleon haloes, true three-body decays (e.g. two-proton radioactivity as a special case), soft excitation modes, etc.

In the recent years there was a successful line of research at Flerov Laboratory of Nuclear Reactions dealing with light dripline systems. Novel results related to studies of few-body phenomena were obtained for such isotopes as ^{5}H, ^{7}H, ^{8}He, ^{10}He, ^{6}Be, ^{17}Ne, and ^{26}S. The major results of these studies are presented and discussed from theoretical point of view. We focus on continuum properties of three-body systems, studies of specific correlations, and practicalities of connection between theory and experiment.

Structure properties of the four-cluster nuclei ^{10}Be and ^{10}C

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In the framework of the four-particle approximation (two α-clusters plus two nucleons), we study the structure functions of ^{10}Be and ^{10}C nuclei. New versions of the $\alpha\alpha$-interaction

are proposed. With the use of our models of $\alpha\alpha$-, nn-, pp-, $n\alpha$-, and $p\alpha$-interactions, we obtain an accurate description of the corresponding S-phase shifts of elastic scattering at low energies simultaneously with a precise description of the energies and radii of ^{10}Be and ^{10}C nuclei. General properties of the four-particle wave functions are studied, and two dominant configurations present in the nuclei are revealed. A detailed study of characteristic features of the structure functions of these nuclei is carried out. We analyze the density and charge distributions, form-factors, pair correlation functions [1]. We also obtain and explain the momentum distributions of α-particles, and of the extra nucleons.

The structure functions of the four-cluster nuclei ^{10}Be and ^{10}C are compared with those of the three-cluster halo nuclei ^{6}He and ^{6}Li.

The bound states of the ^{10}Be and ^{10}C nuclei within four-particle model are studied in the framework of a variational method with Gaussian bases providing enough precision in the four-body calculations.

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Low-energy $H^+ + H_2$ reactive collisions: Role of permutation symmetry in mean-potential statistical model

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Complex-forming, reactive $H^+ + H_2$ system is studied in the interval of collision energies: $(0.001 - 0.5)$ eV. We use statistical theory based on a mean isotropic potential deduced from a full potential energy surface.The reaction probabilities incorporate the full permutation symmetry of the protons. We compare our results with other statistical models and full quantum mechanical approaches that take account of this symmetry either correctly, approximately or erroneously.

Resonant tunneling of the few bound particles through repulsive barriers

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A model of quantum tunneling of the few bound particles interacted by potential of oscillator type on the short-range repulsive barrier potentials is presented. We consider a

model of system of few one-dimensional spinless particles with discrete spectrum by the transverse symmetric variables of relative motion of particles in center-mass-system and continuous spectrum by a longitudinal variable of motion of center-mass-system. A multichannel scattering problem for the Schrödinger equation with the few short-range repulsive barriers is formulated. This problem is reduced to the boundary value problem for a set of close-coupling second order differential equations with respect to the longitudinal variable on whole axis, by using expansion of wave function over the oscillator basis of the few bound particles. We analyze effect of quantum transparency consisting in nonmonotonical dependence of transmission coefficient at resonance tunneling of the few bound particles throughout repulsive potential barriers.

This is a joint work with Sergue Vinitsky, Pavel Krassovitskiy, Ochbadrakh Chuluunbaatar, and Luongle Hai.

Translationally invariant calculations of form factors, densities and momentum distributions in finite nuclei with short–range correlations included

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The approach elaborated in [1] to calculate the density matrices of finite nuclei has been applied in studying a combined effect of center–of–mass motion and short–range nucleon-nucleon correlations on the nucleon density and momentum distributions in light nuclei. Unlike a common practice, suitable for infinite or externally bound systems, these distributions are determined as expectation values of appropriate intrinsic operators that depend on the relative coordinates and momenta (Jacobi variables) and act on intrinsic ground–state wave functions. The latter are constructed in the so-called fixed center–of–mass approximation, starting with mean–field Slater determinants modified by some correlator (e.g., after Jastrow or Villars). We use and develop the formalism based upon the Cartesian or boson representation, in which the coordinate and momentum operators are linear combinations of the creation a and annihilation $a^{\dagger}$ operators for oscillatory quanta in the three different space directions. Each of the relevant multiplicative operators can then be reduced to the form: one exponential of the set $\{a\}$ times another exponential of the set $\{a\}$. In the course of such a normal–ordering procedure we get the own "Tassie–Barker" factors for each distribution and point out other model-independent results. Our numerical calculations of the charge form factors , densities and momentum distributions will be shown for nuclei ^{4}He and ^{16}O.

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Recent investigations of the two-component three-fermion system in the universal limit of zero-range interactions

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Overview of the recent results for the ultra-cold two-component three-fermion system is presented. Significant attention is paid to the isotopic and angular-momentum dependencies of the bound-state energies and low-energy scattering data found by the authors [1–3] and other researchers [4,5] in the universal limit of the zero-range interaction. Correspondingly, a comparison with similar results in 1D [6] and 2D [7] is discussed. Furthermore, qualitatively discussed are the calculations of the non-universal (potential-dependent) properties [8,9], the relation of them to the zero-range-interaction model results, and the crossover of different types of the three-body bound states [10].

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2. O. I. Kartavtsev and A. V. Malykh, Pis'ma ZhETF **86** (2007), 713.
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4. S. Endo, P. Naidon, and M. Ueda, Few-Body Syst. **51** (2011), 207.
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The ^{4}He trimer as an Efimov system

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We review the results which demonstrate the Efimov nature of the ^{4}He three-atomic system.

This is a joint work with Alexander K. Motovilov and Werner Sandhas.

A puzzle of the $C^{6+}+He \to C^{6+}+He^{+}+e$ experiment

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The basic theory of the ionization processes in collisions of fast ionic projectiles with atomic systems at small momentum transfer is well established (see, for instance, the text-books [1,2]). The emergence of the cold-target-recoil-ion-momentum spectroscopy (COLTRIM) [3] made it possible to measure fully differential cross sections for the ionizing ion-atom collisions with high precision, thus providing a new, very stringent test of the theory. In this context, theoretical interpretation of the experimental results [4] on singly ionizing 100-Mev/u C^{6+}+He collisions can be regarded as unsatisfactory. So far none of the published theoretical treatments, ranging from first [5] and second Born approximations [6] to three-body distorted-wave [7] and impact-parameter coupled-pseudostate models [8], has been able to obtain reasonable agreement with the measured angular distribution of the ejected electron in the plane perpendicular to the momentum-transfer direction. At the same time, all the approaches more or less adequately reproduce the measured angular distribution of the ejected electron in the scattering plane.

We present a theoretical analysis of the "C^{6+} puzzle". In particular, we discuss relativistic, second-Born, and distorted-wave effects on differential cross sections. It is shown that neither of them can explain the discrepancy between theory and experiment. We find, however, that a finite momentum resolution due to a velocity spread in a supersonic helium jet can be responsible for the observed disagreement. This finding supports conclusions of an earlier work [9], though in [10] they were claimed to be inconsistent with experimental conditions of [4].

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New way in description of few-body scattering

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In the talk, we discuss a new purely discrete way in treatment of few-body scattering. The way includes a few key steps which being taken together leads to tremendous facilitation and acceleration for all few-body calculations. In their turn, this crucial improvement of all scattering calculations makes it possible to solve now such highly uneasy problems which are completely beyond of ability of the conventional approaches.

For this purpose, we transform the conventional scattering integral equations into fully discrete matrix form with regular matrix elements using the lattice-like basis in momentum space. Then we solve the resulted few-body matrix equations using an ultra-fast graphical processor unit (GPU-computing). Such GPU calculations for our new lattice form of scattering equations take only a few minutes of PC computing time to calculate both elastic and inelastic scattering and also three-nucleon breakup with fully realistic *NN*-potentials.

Threshold effects in two- and three-body problems on lattices

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The existence of eigenvalues for the discrete Schrödinger operators associated to the Hamiltonians of systems of two and three quantum-mechanical particles on lattices interacting via short-range pair potentials will be showed and dependence of their number on the total quasi-momentum will be discussed.

The double-Λ hypernucleus ${}^{11}_{\Lambda\Lambda}$Be

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The ground state energy of the double-Λ hypernucleus ${}^{11}_{\Lambda\Lambda}$Be is calculated within the framework of the five-body model $\alpha\alpha n\Lambda\Lambda$. The five-body system is described using the Faddeev-formalism for the unequal mass clusters involved and the potential harmonics expansion of the corresponding amplitudes. The resulting coupled differential equations depend only on the inter-cluster interactions, $\Lambda\Lambda$, Λn, $\Lambda\alpha$, $n\alpha$, and $\alpha\alpha$, which are fairly well known from previous investigations of hypernuclei. The results obtained are in excellent agreement with the recent KEK-E373 experiment as well as with the theoretical results obtained within the Gaussian expansion method by Hiyama *et al.* The $\Lambda\Lambda nn$ double hypernucleus is also discussed.

The system of three three-dimensional charged quantum particles: Asymptotic behavior of the continuous spectrum eigenfunctions at infinity

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To our knowledge there are no complete results expressed in terms of eigenfunctions (even not strictly proved mathematically) related to the system of three or more charged quantum particles. For the system of the three such identical particles we suggest the asymptotic formula describing the behavior of eigenfunctions at infinity in configuration space.

Low-energy elastic scattering of a polarized neutron on a polarized deuteron

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The spin structure of the amplitude of S-wave elastic scattering of slow neutrons on deuterons is analyzed . The operators of projection onto the quartet state (total spin $J = 3/2$)

and doublet state (total spin $J = 1/2$) of the *nd* system and the scattering amplitudes, corresponding to these states, are introduced. It is shown that in the low-energy limit the dependence of the effective cross section of *nd*-scattering upon the neutron and deuteron polarization vectors is determined by only two scattering amplitudes (the quartet and doublet ones), the contributions of which are summed up incoherently. The expression for the correlation tensor of the final *nd* system at low-energy scattering of unpolarized neutrons on unpolarized deuterons is derived as well. The question about relation between the quartet length of *nd*-scattering and triplet length of neutron scattering on a proton is discussed.

Two-body and three-body field theoretical equations with and without quark-gluon degrees of freedom

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The new relativistic two-body and three-body equations for the amplitude of the coupled $NN \Longleftrightarrow NN\pi$ and $Nd \Longleftrightarrow 3N)$ reactions are considered within the standard field-theoretical *S*-matrix approach in the time-ordered three-dimensional (3D) form. Therefore, the corresponding relativistic equations are 3D from the beginning and the considered formulation is free of the ambiguities which appear due to the 3D reduction of the 4D Bethe-Salpeter equations. The solutions of the considered equations satisfy automatically the unitarity and causality conditions and other first principles of the theory even after the truncation over the multiparticle ($n > 3$) intermediate states. The form of these three-body equations does not depend on the choice of the Lagrangian and it is the same for the formulations with and without quark degrees of freedom. The effective potential of the suggested equations is defined by the vertex functions with two on-mass shell particles. It is emphasized that these INPUT vertex functions can be constructed from the experimental data.

Unlike to the well known Faddeev equations, the suggested three-body equations have the form of the three-body Lippmann-Schwinger-type equations with the connected potential. Nevertheless, after simple modification one can rewrite the suggested equations in the form of the Faddeev equations for the disconnected and connected parts of the three-body potential. The corresponding microscopic potential contains the contributions from the pure three-body (contact and overlapping) forces and from the particle creation (annihilation) mechanism. The complete set of the three-body forces, appearing in the considered field-theoretical approach with and without quark-gluon degrees of freedom is analyzed.

Low-dimensional few-body physics in atomic traps

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In recent years, low-dimensional quantum systems have become experimentally accessible showing impressive developments in the field of ultracold atoms and molecules [1,2]. This has stimulated the necessity of detailed and comprehensive investigations of collisional processes in the confined geometry of atomic traps. Here the free-space scattering theory is no longer valid and the development of the low-dimensional theory including the influence of the confinement is needed. The restricted geometry leads to a quantization of the atomic motion for the confined degrees of freedom. Another effect of the two-body problem in a trap is the confinement-induced nonseparability of the center-of-mass (CM) and the relative motions.

In our works we have developed a computational method [3-5] for pair collisions in tight atomic waveguides and have found several novel effects in its application: the confinement-induced resonances (CIRs) in multimode regimes including effects of transverse excitations and deexcitations [4], the so-called dual CIR yielding a complete suppression of quantum scattering [3], and resonant molecule formation with a transfer of energy to CM excitation while forming molecules [5]. A recent result is the computation of multi-channel effects responsible for the CIRs splitting [6] observed experimentally in [7].

A possible extension of the theory will also be discussed in order to include the effects of the trap anharmonicity [8,9] and a tensorial structure of the Feshbach resonances [10] responsible for the CIRs. These effects can lead to a novel and rich physics.

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The derivation method for the break-up amplitude in the few-particle system with the pure Coulomb interaction

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The derivation method for the full break-up amplitude in the few-particle system with the pure Coulomb interaction is developed. This method is based on the investigation of the singularities which take place in the many-body Lippmann-Schwinger equation interactions (Born series) when the complex energy Z approaches the energy shell. It is shown that the summation of the Born series enables one to isolate explicitly the Lippmann-Schwinger solution Coulomb singularity. As a result the break-up channel amplitude is represented in the form of the modified (nonsingular on energy shell) Born series. The partial summation procedure of these series which leads to the distorted-wave second Born approximation for the amplitude under investigation is elaborated.

This is a joint work with V. L. Shablov and Y. V. Popov.

A priori bounds on variation of the spectrum and spectral subspaces of few-body Hamiltonians

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We apply the results of [1–5] on variation of the spectrum and spectral subspaces of a Hermitian operator under a perturbation to few-body Hamiltonians. In particular, we give bounds on the shift of binding energies and variation of the corresponding eigensubspaces of a few-body Schrödinger operator if an extra interaction or an external field is added, provided that positions of the initial binding energies are known. It should be underlined that our results are not perturbative in the sense of the conventional (series) perturbation theory. Moreover, most of the bounds we give are sharp.

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The effective-range theory application to study the nuclear vertex constants for bound and resonant states of the lightest nuclei up to ^{8}Be

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The effective-range theory taking into account the Coulomb interaction has been developed and applied to computing the nuclear vertex constants for a decay (fuse) $AB + C$ and for relating the asymptotic normalization coefficients of the radial wave functions for a nucleus A. We study the ^{3}He s-wave bound state and the resonant s-wave states of ^{2}He, ^{3}He, ^{8}Be, the p-wave states of ^{5}He and ^{5}Li, and the d-wave state of ^{8}Be. Experimental phase shifts and pole positions are used as input data.

Differential equations for the recombination amplitude in three bosons system with zero-range pair potentials

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Differential equations in the momentum space for the $3 \to 2$ recombination processes of three bosons with pair forces of zero-range radius have been derived.

Self-consistent Bohmian description of strong field-driven electron dynamics

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Drawing from the Bohmian formulation of the time-dependent Schrödinger equation, we present a self-consistent hydrodynamical method to describe electron dynamics in strong

field light-matter interactions. Prototypical implementation is made for one-dimensional H atom embedded in short and intense laser pulses. The method provides very accurate electron densities and yields quantum trajectories that shed light on the electron dynamics, beyond the strong-field approximation.

Square-integrable bases in the many-body Coulomb scattering problem

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A method, well known in nuclear physics as the resonating group method, is applied in atomic physics for the case of the long-range Coulomb potential. Its most established version is the so-called convergent close-coupling (CCC) method [1]. In CCC, a square-integrable Laguerre basis is employed for expansion of radial wave functions. The finite system of algebraic equations in the box must be supplemented by boundary conditions. In the case of single ionization, the asymptotic solution of the many-body Schrödinger equation is more or less known. In the case of double ionization, it is not. As a result, the continuum wave function of one ejected electron is described by a set of pseudostates. This leads to certain problems in comparisons between theory and experiment [2].

This disadvantage can be partly removed. Applying an additional integration of the Green's function in the integral Lippmann-Schwinger (LS) equation, we are able to consider both outgoing electrons on equal footing, as the Coulomb waves [3]. This approach was utilized in evaluation of the fully differential cross sections (5DCS) for the $(e,3e)$ processes in helium [4]. The calculations are performed in the case of a coplanar geometry where the incident electron is fast and both ejected electrons are slow. The obtained results are in satisfactory agreement with all the experimental data of Lahmam-Bennani et al. [2,5], without any need for renormalizing the data. However, a detailed analysis of the calculations shows that the full convergence in terms of the basis size is not reached. The latter is due to the fact that the free term in the LS does not have the correct asymptotic behavior, and its integral term is formally divergent. So, the results must depend on the size of the box.

It is worth mentioning that there are attempts to build bases alternative to the Laguerre one, but in such a case the basis functions are not square-integrable and are fully numerical [6]. And they again do not solve the problem of the correct asymptotical behavior of the double-continuum wave function.

The latter problem can be solved within the parabolic Sturmian basis [7], because in this case the free term of the corresponding integral LS equation is a well known 3C function which obeys the correct global Coulomb asymptotic behavior. However, the interaction in this particular case is represented by differential operators which compactness is questionable.

In conclusion, a mathematically correct proof that square-integrable bases can be applied in many-body Coulomb scattering theory is lacking, but their practical applications are widely used. Review of this problem is presented in [8].

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Elastic scattering of a quantum particle by a central potential

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The one-dimensional Schrödinger scattering problem with a central potential is studied. The linear version of the variable phase approach is used to obtain the low-energy asymptotics of regular and irregular solutions of this problem.

Signature of the $\Lambda(1405)$ resonance in neutron spectra from the $K^- + d$ reaction

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Neutron spectra from the reaction $K^- + d \to \pi + \Sigma + n$ were calculated in the energy range $E_{K^-}^{\rm cm} = 0 - 50$ MeV using coupled channel Faddeev equations for the description of the $\bar{K}NN - \pi\Sigma N$ three-body system. The aim was to trace the signature of the $\Lambda(1405)$ resonance in the spectra. We found, that while in the direct spectra kinematic effects mask completely the peak corresponding to the resonance, the deviation spectrum method [Esmaili, Akaishi, and Yamazaki, Phys. Rev. C **83** (2011), 055207] is able to eliminate kinematics and produce clear evidence of the resonance. The dependence of the obtained spectra on the incident kaon energy is discussed.

New treatment of the multi-channel continuum via the discrete spectral shift formalism

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The new method for the solution of multi-channel scattering problems in discretized L_2 representation without solving the scattering equations is given. The technique allows to construct the discrete analog of the spectral shift function (SSF) for the total and free Hamiltonians which is the object of the general spectral theory of the perturbations. The main advantage of this discrete version of the SSF formalism is that it can be directly generalized to the multi-channel case. Here the set of different discrete SSFs corresponding to different spectral branches could be defined, in contrast to the conventional theory in continuum. Moreover, each such disretized spectral shift function is directly interrelated to the corresponding eigenchannel phase shift similarly to one-channel case. Finally, each element of the multi-channel S-matrix can be found at many energies simultaneously from the one-fold diagonalization of the Hamiltonian matrix in the multi-channel L_2 basis. As an illustration, numerical results for several multi-channel scattering problems in nuclear and atomic physics are presented.

The AGS equations

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Starting from the basic concepts of two-body collision theory, in particular the definition of transition operators and the corresponding integral equations, we recall that an analogous procedure leads quite naturally to their three-body analogue, the AGS (Alt-Grassberger-Sandhas) equations. We show that these relations did and still do provide an adequate tool for treating three-nucleon processes, Coulomb corrections, and photodesintegration processes. The extension to four-body systems is also sketched.

Antikaonic three-body systems

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We calculated the 1s level shifts and widths of kaonic deuterium, corresponding to accurate results on near-threshold antikaon - deuteron scattering. The Lippmann-Schwinger eigenvalue equation with a strong $K^- - d$ and Coulomb potentials was solved. The two-body

$K^- - d$ potentials reproduce the near-threshold elastic amplitudes of $K^- d$ scattering obtained from the three-body Alt-Grassberger-Sandhas equations with the coupled channels using four versions of the $\bar{K}N - \pi\Sigma$ potentials. Both new $\bar{K}N - \pi\Sigma$ potentials reproducing the very recent SIDDHARTA data on kaonic hydrogen and our older potentials reproducing KEK data have one- or two-pole versions of the $\Lambda(1405)$ resonance and reproduce experimental data on $K^- p$ scattering.

Low energy φ-meson-deuteron scattering in frame of the AGS equations

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This work is devoted to low energy scattering of a φ-mesons by deuterons. AGS equations with Van-der-Waals φ-meson-nucleon and Malfliet-Tjon nucleon-nucleon potentials as input are used. To simplify the problem local potentials are replaced by Bateman separable potentials of the order of $N = 6$. The order and the type of approximation was chosen to reproduce scattering lengths of the two-body input.

Discrete representation for ionization process in three-body problem

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A complete set of Gaussian wave packets is proposed for description of the ionization channel.

Mechanisms of the $dp \to pp_s\,\Delta$ reaction with formation of the $^1S_0$ diproton and the Δ isobar

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The COSY data on the well known charge exchange reaction $dp \to pp_s n$ at small transferred momenta are supplemented recently by reaction $dp \to pp_s X$ at beam energy $1 - 2$

GeV , where the invariant mass of the X system M_x corresponds to the mass of the $\Delta(1232)$-isobar. Measurements with the polarized deuteron beam could give an important information on the spin structure of the $NN \to N\Delta$ subprocess at small transferred momenta. In order to get this information, the main mechanisms of this reaction have to established. Here we discuss the mechanism with Δ-isobar excitation (i) in the target and in (ii) the projectile. We show that the first mechanism allows to explain the data at larger M_x. The second mechanism is found to be much less important.

Resonant scattering for charged particles produced by confining environment

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Resonance scattering problem of charged particles via quasistationary states imbedded in the continuum produced by confining environment is considered. The reduction of the problem for two charged ions to a boundary-value problem is given together with the asymptotic behavior of the solution and the results of R-matrix calculations. Nonmonotonic dependence of physical parameters on collision energy and/or confining environment due to resonance transmission and total reflection effects is confirmed that can increase the rate of recombination processes.

This is a joint work with A. A. Gusev, O. Chuluunbaatar, V. L. Derbov, and P. M. Krassovitskiy.

Zero-range potential for charged particles

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The pairwise zero range potential is constructed for particles interacting via the Coulomb potential. The singular part of the asymptote of the wave function at the origin which is caused by the common effect of the zero range potential singularity and of the Coulomb potential is explicitly calculated by using the Lippmann-Schwinger type integral equation. The singular pseudo potential is constructed from the requirement that it enforces the solution to the Coulomb Schrödinger equation to possess the calculated asymptotic behavior at the origin. This pseudo potential is then used for constructing a model of the imaginary absorbing potential for the positron electron system. This potential allows to treat the annihilation process in positron electron collisions on the basis of the non relativistic

Schrödinger equation. The functional form of the pseudo potential constructed in this paper is analogous to the well known Fermi-Breit-Huang pseudo potential. The generalization of the optical theorem on the case of the imaginary absorbing potential in presence of the Coulomb force is given in terms of the partial wave series.

"Tomography" of cluster structure of light nuclei via relativistic dissociation

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Capabilities of relativistic nuclear physics for development of physics of nuclear clusters are presented. Stacks of pellicles of nuclear track emulsion continue to stay an effective means of exploratory research, in particular, allowing studying of cluster dissociation of great variety of light relativistic nuclei in the same type of experiments. Despite the fact that the value and capabilities of the relativistic approach to the study of nuclear clustering has been recognized by quite a long time, electronic experiments have not been able to get closer to a wholesome analysis of relativistic fragment ensembles. The continued pause in the investigation of "fine" structure of relativistic fragmentation has led to resumption of regular exposures of nuclear emulsions in beams of light nuclei obtained for the first time at the JINR Nuclotron. To date, the analysis of peripheral interactions of the relativistic isotopes of beryllium, boron, carbon and nitrogen, including radioactive ones, with nuclei of the emulsion composition, is performed, what allows presenting the clustering pattern for the whole family of light nuclei.

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