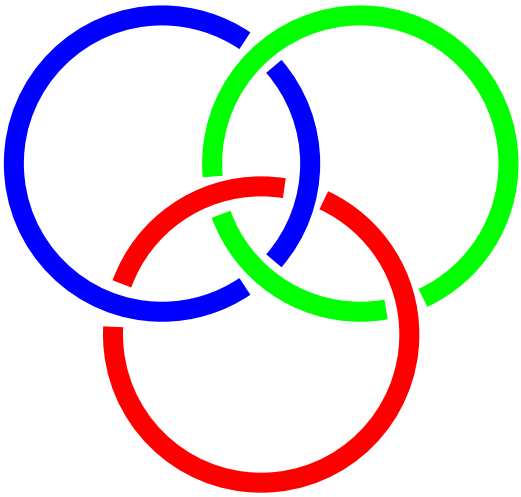
Critical Stability Abstracts



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Three-body decays of many-body resonances

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We discuss the three-body decay mechanisms of many-body resonances. Sequential decays proceed via two-body configurations after emission of the third particle. In direct decay all three particles leave simultaneously their interaction regions. The intermediate paths within the interaction regions are not observables and only accessible through models. The momentum distributions carry, apart from polarization, all possible information about decay modes and resonance structure. We use complex-scaled hyperspherical adiabatic expansion method to describe the three-body systems. The cases we use as examples (12C, 9Be and 6Be) present their own intriguing problems and they are moreover requested for astrophysical applications. When possible we compare our computed energy distributions with the experimental ones.

Binding in some few-body systems containing antimatter

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The field generated by a fixed proton and antiproton a distance R apart is a particular example of a dipole field. The existence or otherwise of bound states of an electron (or a positron) in such a field was originally studied by Fermi and Teller and Wightman [1-3] in the late forties. They showed that if $R > 0.639a_0$, a bound state of the system existed but if $R < 0.639a_0$, no bound states existed. This result was confirmed in the mid-sixties by several authors, including Mittleman and Myerscough [4], Coulson and Walmsley [5] and Byers Brown and Roberts [6]. Crawford [7] obtained the interesting result that if $R > 0.639a_0$, a countable infinity of bound states exists.

It is of interest to consider what happens if an electron and a positron are both present in the dipole field. This system corresponds to $\mathrm{H} + \bar{\mathrm{H}}$ with the positions of the nuclei fixed, as in the Born-Oppenheimer approximation. Armour et al. [8] were able to show that an upper bound to the R value below which no bound state of this system exists is $0.8a_0$. They did this using the Rayleigh-Ritz variational method and a basis set in prolate spheroidal coordinates similar to Kołos et al. [9], but with the addition of a function to represent very weakly bound positronium. More recently, Strasburger [10] has reduced this upper bound to $0.744a_0$, using a basis set made up of explicitly correlated Gaussian functions.

As far as I am aware, no lower bound has been obtained for the above R value. A question of interest is whether a bound state of the the system containing the electron and the positron exists for $R < 0.639a_0$, the critical value for each particle on its own in the presence of the nuclei.

To investigate this, I assume that for a given value of R, there exists a bound state, ϕ, of the system containing the electron and the positron, i.e.

$$\hat{H}_f \phi = E\phi, \tag{1}$$

where $\hat{H}_f$ is the Hamiltonian of the system and is of the form

$$\hat{H}_f = -\frac{1}{4}\nabla^2_{\boldsymbol{\rho}} - \nabla^2_{\mathbf{r}_{12}} + V - \frac{1}{r_{12}}\ . \tag{2}$$

$\boldsymbol{\rho}$ is the position vector of the centre of mass of the positronium w.r.t. the mid-point of the internuclear axis and $\mathbf{r}_{12}$ is the position vector of the positron (particle 2) w.r.t. the electron (particle 1).

$$V = -\frac{1}{r_{p_1}} + \frac{1}{r_{\bar{p}_1}} + \frac{1}{r_{p_2}} - \frac{1}{r_{\bar{p}_2}} \tag{3}$$

is the dipole potential due to the nuclei. E satisfies the condition

$$E = -\frac{1}{4} - \epsilon \quad (\epsilon > 0) \tag{4}$$

$-\frac{1}{4}$ a.u. is the energy of positronium in its ground state at rest at infinity.

If C is any well-behaved function, it follows from equation (1) that

$$\hat{H}_{fc}\phi_c = E\phi_c, \tag{5}$$

where $\hat{H}_{fc} = C\hat{H}_f C^{-1}$ and $\phi_c = C\phi$.

It is convenient to take

$$C = exp\left[\frac{ar_{12}}{1+\delta r_{12}}\right] \tag{6}$$

where a and δ are positive constants. Note that as $C^\dagger \neq C^{-1}$, $\hat{H}_{fc}$ is a non-Hermitian operator.

I then consider the expectation value,

$$\frac{\left\langle \phi_c \left| \hat{H}_{fc} \right| \phi_c \right\rangle}{\langle \phi_c | \phi_c \rangle} \tag{7}$$

It can be shown that

$$\frac{\left\langle \phi_c \left| \hat{H}_{dip} \right| \phi_c \right\rangle}{\langle \phi_c | \phi_c \rangle} \leqslant -\frac{1}{4} + a^2 + \frac{\left\langle \phi_c \left| \frac{1}{r_{12}} \right| \phi_c \right\rangle}{\langle \phi_c | \phi_c \rangle} - \epsilon \quad (\epsilon > 0) \tag{8}$$

where

$$\hat{H}_{dip} = -\frac{1}{4}\nabla^2_{\boldsymbol{\rho}} - \nabla^2_{\mathbf{r}_{12}} + V \tag{9}$$

is the Hamiltonian for a non-interacting electron and positron in the dipole field of the nuclei. For this Hamiltonian, the bound states of each particle are the same as for the electron (positron) dipole system described at the start of this abstract.

Equation (8) will be used to try to obtain information about the relationship between the bound states of the system containing only one of the particles and the system containing both the electron and the positron with the interaction between them included.

As δ approaches zero, ϕ_c remains square-integrable and the factor C it contains reduces the effect of the Coulomb attraction between the electron and the positron. The extent of this reduction and the value of the right-hand side in the inequality (8) are dependent on the choice of a.

The implications of letting δ approach zero in (8) for a given value of a will be explored. As far as possible, any conclusions drawn will be checked against the exact results for the single particle in the dipole field obtained by Wallis et al. [11] and Jonsell [12] and the very accurate variational results for the two particle interacting system obtained by Strasburger [10].

Some consideration will also be given to the system in which the Coulomb attraction between the particles is taken to be of the form $-\dfrac{\gamma}{r_{12}}$ $(\gamma \geqslant 0)$.

If time permits, I will describe results of a preliminary investigation of the increase in the mass of the positron that would be necessary for it to form a bound state with a hydrogen molecule. The aim is to simulate conditions under which very large positron annihilation rates have been observed in low-energy positron scattering by some larger molecules. These very high rates are thought to be due to positron capture into vibrational Feshbach resonances of infrared-active modes [13].

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Scattering states of three-body systems with the Hyperspherical Adiabatic method

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In this work we use the Hyperspherical Adiabatic (HA) method [1] in combination with the Khon variational principle to calculate scattering observables for a three-body system. The convenience of such an approach relies on the properties of the adiabatic basis, which is known to reproduce asymptotically (that is, at large values of the hyperradius) all the possible products of the scattering process in a multi-body system [2].

The HA method is based on the parametrization of the system internal degrees of freedom by means of hyperspherical coordinates. At small values of the hyperradius the adiabatic basis elements are calculated by means of an expansion in Hyperspherical Harmonics, whereas at large hyperradius an accurate description of the basis is obtained following the procedure indicated by Nielsen and co-workers [3]. The system wavefunction is then expanded onto a basis made of a product of hyperradial functions times the adiabatic basis, and an extra term which describes asymptotically the possible "2+1" states of the system. Finally, the coefficients of the expansion as well as the elements of the elastic S-matrix are obtained by means of the Kohn variational principle [4].

We will present numerical implementations of the method to the study of different three-body systems, restricting our applications to cases of total orbital angular momentum $L = 0$. In particular, we have chosen a three-nucleon system with semi-realistic potentials, such as a simple gaussian well, and MT s-wave projected interactions, in order to reproduce benchmark calculations available in the literature. We have also applied the method to the study of molecules made of identical atoms, such as the Helium trimer.

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New nuclear three-body clusters ϕNN

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Solving Faddeev differential equations, binding energies of three-body systems of the type ϕNN are calculated. Due to the strong attraction between ϕ-meson and nucleon, suggested in [1] and [2], bound states appear in systems $\phi + np$ (singlet and triplet), $\phi + nn$ and $\phi + pp$. This indicates on the principal possibility of the formation of new nuclear clusters with increased number of nucleons.

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Boundary-condition-determined wave functions, and their nodal structure, for few-electron atomic systems

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Highly compact wave functions with a clear physical meaning for the He atom and He-like isoelectronic ions for $Z = 1 - 10$ are written as a symmetrized product of $\exp[(ar + br^2)/(1 + r)]$ electron-nucleus terms and an electron-electron Jastrow factor to satisfy the correct asymptotic behavior both at short and large interparticle distances. Some parameters are chosen to satisfy exactly the cusp-conditions, while the others are optimized by variational Monte Carlo calculations. The wave function energy is within 2 millihartrees from the non relativistic limit in the entire Z range, improving previously published work on similar compact wave functions. We tested the validity of the coalescence wave function approximation. The Z-dependence of the optimized parameters allows us to write a general form of the wave function, using Z as an explicit parameter and four parameters independent from Z. We checked the validity of this wave function on the case $Z = 30$.

For more than two electrons we investigate the nodal structures of atomic wave functions based on a product of spatial orbitals, namely Restricted, Unrestricted and Generalized Valence Bond wave functions. While the wave functions are different, their nodal structures are shown to be equivalent. This result is verified by fixed node-diffusion Monte Carlo simulations for atoms up to Ne. For 3 and 4 electrons we investigate the shape of the nodal structure while the nuclear charge approaches its critical value.

Relativistic Hydrogen in Strong Magnetic Fields

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We study the bound states of relativistic hydrogen-like atoms coupled to strong homogeneous magnetic fields, under the assumption of an infinitely heavy nucleus. Working in the adiabatic approximation in which the electron is confined to the lowest Landau level, we show that the discrete spectrum is always non-empty and that, as the field strength increases, its eigenvalues successively descend into the lower part, $(-\infty, -m_e c^2]$, of the continuous spectrum (m_e being the electron mass). This phenomenon is roughly periodical in $\log B$. The question of the correct physical interpretation of this phenomenon will be posed. This talk is based on joint work with Philippe Briet and Pierre Duclos (Centre de Physique Théorique, Marseille, Luminy and Université du Sud Toulon-Var).

Feshbach resonances in ultracold atomic gases

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Critical Stability, Erice, October 2008

A low energy effective theory based on a microscopic multi-channel description of the atom-atom interaction is derived for the scattering of alkali atoms in different hyperfine states [1]. This theory describes all scattering properties, including medium effects, in terms of the singlet and triplet scattering lengths and the range of the atom-atom potential and provides a link between a microscopic description of Feshbach scattering and more phenomenological approaches based on the treatment of the Feshbach molecule as a point boson. It permits the calculation of medium effects on the resonance coming from the occupation of closed channel states. The examination of such effects are demonstrated to be of particular relevance to an experimentally important Feshbach resonance for ^{40}K atoms. We then discuss the case of a single impurity interacting resonantly with a gas of fermions and show how it changes from being essentially a quasi-particle excitation to a molecular excitation with increasing coupling strength [2].

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Challenges and achievements in the ab-initio three- and four-body scattering calculations: the Coulomb force

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There is a long history of theoretical prescriptions for the solution of the Coulomb problem in three-nucleon continuum. Most of them employ configuration-space framework [1, 2, 3]. In contrast, we solve momentum-space integral equations. The method we use for the inclusion of the Coulomb interaction is based on the ideas proposed in Ref. [4] for two charged particle scattering and extended in Ref. [5] for three-particle scattering, but differs significantly from those earlier works in the practical realization. The Coulomb potential is screened, standard scattering theory for short-range potentials is used, and the renormalization procedure is applied to recover the unscreened limit. In our method [6] the Coulomb potential is screened in a novel way that allows successful application of the numerical techniques developed previously for solving three-nucleon equations without Coulomb and avoids approximations on the nuclear interaction and the treatment of screened Coulomb used in Ref. [5]. The outcome of our method are fully converged calculations for observables of proton-deuteron (pd) elastic scattering and breakup, pd radiative capture, and electromagnetic disintegration of ^{3}He nuclei; the results for pd elastic scattering agree well with the ones obtained using configuration-space techniques [7]. The method has been extended successfully to four-nucleon scattering [8] and to three-body nuclear reactions [9, 10] involving ^{4}He, ^{11}Be or ^{12}C nuclei.

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Few-body Physics in Ultracold Gases: The Role of Efimov Physics

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In this talk, I will discuss general properties of few-body collisions and their influence on ultracold quantum gases in the regime where interatomic interactions are strongly affected by a Feshbach resonance. Since the early days of the achievement of Bose-Einstein condensation, it has been recognized that few-body processes are of crucial importance in determining the stability of condensates.

Nevertheless, ultracold gases also offer an outstanding opportunity to explore one of the most counterintuitive quantum phenomena that manifest in a "simple" few-particle system: the Efimov effect. In fact, the first strong experimental evidence of Efimov physics was recently found in ultracold quantum gases as a giant loss of atoms causing the gas to become highly unstable.

Nowadays, we know that Efimov physics affects three-body processes in experiments on ultracold quantum gases, and it now serves as a "guide" in the difficult task of achieving atomic and molecular stability. In this talk, I will outline some of my recent work on Efimov physics and also discuss some of its implications for the many-body behavior of ultracold quantum gases.

Can one bind three electrons with a single proton?

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Of course not for an ideal H^{--} atom. But with the help of an intense homogenous magnetic field B, the question deserves to be reconsidered. It is known (see e.g. [BD]) that as $B \to \infty$ and in the clamped nucleus approximation, this ion is described by a one dimensional Hamiltonian

$$H := \sum_{i=1}^{3} -\frac{\Delta_i}{2} - Z\delta(x_i) + \sum_{i<j} \delta(x_i - x_j) \quad \text{acting in} \quad L^2(\mathbb{R}^3)$$

where $Z = 1$ is the charge of the nucleus, and δ stands for the well known "delta" point interaction. We shall present an extension of the "skeleton method", see [CDR1, CDR2], to the three degree of freedom case. This is a tool, that we learn from [R], which reduces the spectral study of H to the study of the kernel a system of linear integral operators acting on the support of the delta interactions. Finally we shall present the critical value of Z for which H has a bound state.

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The physics of long-range atom-surface interactions and its applications

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The long range interaction between atoms and material surfaces or nanobodies is a case study of a pure quantum system interacting with macroscopic or mesoscopic systems. This field is of increasing importance owing to the fast development of nanoscience and nanotechnologies. The confinement of atoms inside a nano-size space strongly alters the internal properties of the atomic system and its response to external excitation, e.g. light irradiation. In addition to surface-induced energy level shifts and spontaneous emission enhancement/inhibition, there is atom symmetry break due to the anisotropy of the surface near-field, inducing energy level mixing, population transfer, or selective surface-enhancement of forbidden lines [1] The dramatic influence of surface-guided waves (like morphology-dependent resonances of nanobodies, or surface polariton modes of dispersive materials) on atom-surface van der Waals interactions has also been considered. Experimentally there are two distinct approaches to the investigation of the properties of atoms in interaction with surfaces and nanostructures. High resolution laser spectroscopy at gas-dielectric interfaces (like reflection spectroscopy, or transmission spectroscopy of sub-micrometer vapour cells) allows one to monitor the properties of selected radiative atomic states in a confined environment. Resonant coupling between excited atoms and surface polaritons has led to the first observation of repulsive van der Waals surface forces, as well as the dramatic modification of decay channels and branching ratios of excited states [2]. The influence of thermal surface excitations is now under scrutiny [3]. On the other hand, high resolution momentum spectroscopy with atomic beams gives access to the monitoring of long-lived states interacting with surfaces and nanobodies. Beam-surface diffraction experiment, and transmission of velocity-selected metastable beams trough nano-slits or nano-gratings, has allowed one to study surface-induced symmetry break, and inelastic atom diffraction produced by energy level mixing [4]. Implications in cavity QED, as well as applications to atom optics and interferometry at the nanoscale [5] will be discussed. The conditions of existence of long-range, weakly bound atom-surface complex will be considered.

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The driven Schrödinger approach to quantum scattering calculations

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Quantum scattering calculations on two and three-body systems with Coulomb interaction using the driven Schrödinger equation combined with the exterior complex scaling are discussed. Results for two-body scattering are reported, and the generalization to three-body scattering is considered.

Poincaré Invariant Three-Body Scattering

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Traditionally three-nucleon calculations are carried out by solving Faddeev equations in a partial wave truncated basis, working either in momentum or in coordinate space. In Ref. [1] the Faddeev equations were solved directly as function of vector variables for scattering at intermediate energies. The key advantage of this formulation lies in its applicability at higher energies, where special relativity is expected to become relevant. We investigate relativistic three-boson scattering in the framework of Poincaré invariant quantum mechanics [2]. The main points are the construction of unitary irreducible representations of the Poincaré group, both for noninteracting and interacting particles. The application to three-body scattering is based on the Faddeev scheme, which is reformulated relativistically. The usage of Poincaré-Jacobi momenta leads to various algebraic modifications of corresponding standard nonrelativistic expressions. Due to its dependence on the total momentum, the two-body off-shell t-operator entering the Faddeev equation acquires additional momentum dependence beyond the usual energy shift which is characteristic in nonrelativistic calculations. We handle this by using a first resolvent method [3] and thus can exactly solve for the relativistic two-body operator embedded in the three-body system [4].

Comparison of the relativistic and non-relativistic calculations lead to observations the should be also relevant for realistic interactions [5, 6]. This comparison does not involve a non-relativistic limit, instead relativistic and non-relativistic three-body calculations with interactions fitted to the same two-body data are compared. All of the differences result from the different ways in which the two-body dynamics appears in the three-body problem.

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On the determination of the parameters of quantum resonances: theory and experiment

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Determination of the parameters of a resonance (the energy and the width) from experimental data is not an unambiguous procedure, in particular for broad resonances. Also theoretically, different approaches often result in somewhat different resonance parameters.

In an attempt to clarify the situation we perform an investigation, using a simple model with a resonance (a particle in a potential well) as an example, where we simulate experimental determination of resonance parameters, using the usual R-matrix method, and then compare these "experimental" parameters with those calculated using different theoretical approaches.

The results tend to show that for narrow resonances that the different methods are in good agreement for narrow resonances but begin to disagree with the resonance width increasing. We argue that this disagreement is actually not due to one method being "more precise" than another one, but due to inherent impossibility of defining the resonance parameters as physical observables.

Few-body physics with ultracold Cs atoms and molecules

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Ultracold atomic gases are versatile systems to study few-body physics because of full control over the external and internal degrees of freedom. The scattering properties can be controlled because of the magnetic tunability of the two-body scattering length in the proximity of a Feshbach resonance and weakly bound dimers can be produced. Here, we experimentally explore three- and four-body physics by studying ultracold (30-250 nK) atom-dimer and dimer-dimer collisions with Cs Feshbach molecules in various molecular states and Cs atoms in different hyperfine states. An atom-dimer resonance is observed and interpreted as being induced by a trimer state, possibly an Efimov state [1]. A strong magnetic field dependence of the relaxation rate is also observed in a atom-dimer mixture made of non-identical bosons. Dimer-dimer inelastic collisions have been studied in a pure, trapped sample of Feshbach dimers in the quantum halo regime. We identify a pronounced loss minimum with varying scattering length along with a further suppression of loss with decreasing temperature [2]. These observations provide insight into the physics of a few-body quantum system that consists of four identical bosons at large values of the two-body scattering length.

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The ab initio no-core shell model

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Critical Stability, Erice, October 2008

The ab initio no-core shell model (NCSM) is a well-established theoretical framework aimed at an exact description of nuclear structure starting from high precision interactions between the nucleons [1, 2]. The principal foundation of the method is the use of effective interactions appropriate for the large, but finite, harmonic-oscillator model spaces employed in the calculations. These effective interactions are derived from the underlying realistic inter-nucleon potentials by a unitary transformation in a way that guarantees convergence to the exact solution as the basis size increases. We will exemplify the performance of the NCSM within nuclear physics by showing recent results from studies of p-shell nuclei. We will also demonstrate the recent adaption of the effective-interaction approach to the many-boson problem [3]. Finally, we will outline an extension of the NCSM formalism to achieve an ab initio description of open quantum systems and nuclear reactions by employing techniques from the Resonating Group Method (RGM) [4].

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Virtual states, halos and resonances in three-body atomic and nuclear systems

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Critical Stability, Erice, October 2008

A bi-dimensional map in the parameter space can be defined in the Efimov limit by the critical conditions for an excited state in three-body systems with two-identical particles. The scattering lengths of the two-body subsystems and one three-body scale define the parametric space. The border of the map encloses a region where excited states do exist (see ref. [1]). In this parameter space crossing the critical boundary, when at least one subsystem is bound, implies that an excited state becomes a virtual one [2] and a continuum resonance in the Borromean case. We show that these qualitative features are independent of mass ratios.

The Borromean case of a three-boson continuum resonance was recently evidenced [3] in an experiment with trapped ultracold cesium gas near a Feshbach resonance. It is hoped that mixtures of different mass atoms in traps with tunable interactions allows to check the transition from Borromean to non-Borromean situations where a continuum resonance becomes bound and turns to a virtual state by changing the sign of the scattering length. In the nuclear context, one example is ^{20}C modeled as $\mathrm{n}-\mathrm{n}-{}^{18}\mathrm{C}$ system with a s-wave short-range interaction between the pairs. Using a zero-range interaction we show that this system presents a virtual state that turns into an excited state when the ^{19}C binding is decreased [2]. Close to this condition, we also discuss the low-energy neutron–^{19}C elastic scattering. The s-wave phase-shift presents a zero corresponding to a pole of $k\,\cot\delta$ in the complex plane. The pole is sensitive to the position of the excited bound or virtual state. We also discuss these results in the context of ultracold atomic systems of different species with tunable interactions.

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Few-Body Approaches and Problems in Hypernuclei

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Critical Stability, Erice, October 2008

It takes two nucleons to bind a Lambda hyperon, and perhaps as many as three nucleons to bind two Λ hyperons. In my talk I will review few-body calculations which are relevant for deciphering the onset of binding in Λ hypernuclei and in $\Lambda - \Lambda$ hypernuclei. I will also discuss the onset of binding for Ξ hyperons, stabilizing them against the free-space conversion $\Xi + \mathrm{N} \to \Lambda + \Lambda$, which may require a core of two protons, two neutrons and two Lambda hyperons. The physics implications on the stability of strange hadronic matter will be discussed.

Few-body reactions in nuclear astrophysics

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Critical Stability, Erice, October 2008

Stellar nucleosynthesis reactions are responsible for the abundances of the different elements in the Universe. These reactions happen at very low relative energies between the nuclei involved, and the calculation of the corresponding production rates is one of major issues in Nuclear Astrophysics. These reactions can be of different nature (radiative capture, rearrangement processes...) and very often can be described as few-body processes. In this talk we describe how to compute the production rates for three-body radiative capture reactions, using the $\alpha + n + n \rightarrow {}^6\mathrm{He} + \gamma$ process as an example.

The calculation includes sequential processes (where an intermediate 5He resonance is populated) as well as direct capture of the two neutrons by the alpha particle. This production rate is compared to the estimated one for the four-body recombination process, $\alpha+n+n+n \rightarrow {}^6\mathrm{He}+n$, which compete with the radiative two-neutron capture as a source of 6He. For rearrangement reactions, where the initial nuclei can recombine themselves to produce different final products, we propose the use of the adiabatic approximation as an efficient procedure to distinguish between the different reaction channels, being at the same time possible to compute the transition probabilities at the required very low relative energies.

The Hyperspherical Harmonic method for a A-body system without permutation symmetry

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Critical Stability, Erice, October 2008

The Hyperspherical Harmonic (HH) method has been widely used in nuclear physics to describe nuclei with $A = 3, 4$ [1]. The extension to larger systems is hampered by the large degeneracy of the HH basis. The construction of specifically anti-symmetric states reduces the dimensionality of the basis but encounters technical and numerical difficulties. The coefficients of anti-symmetric basis elements, constructed as a linear combination of HH basis elements times appropriate spin-isospin vectors, are the more difficult to obtain the larger the number of basis elements and/or the number of particles considered; however, once the basis has been anti-symmetrized, the solution of the Schrödinger equation becomes much easies because the potential energy matrix elements can be calculated efficiently. In the present talk we would like to discuss the possibility of using the HH method without resorting to the construction of anti-symmetrized basis states. The obvious disadvantage of the proposed approach is in the very large basis that one needs to handle, which has to be balanced with the simplicity of avoiding the initial construction of anti-symmetric basis states; the physical basis states, having the desired symmetry, are automatically generated in the diagonalization of the Hamiltonian. Preliminary results for the discrete states of $A = 3, 4$ systems will be shown using a simple nucleon-nucleon potential.

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Theoretical investigation of the spectra of rotating trimers by means of a variational quantum method based in distributed Gaussian functions

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Critical Stability, Erice, October 2008

We have recently developed an approximate method to study the rovibrational spectra of molecular trimers, based in the use of distributed Gaussian functions (DGFs) to describe the interparticle distances [1, 2]. The main assumption is to consider that rotation and vibration can be treated separately. The purely vibrational problem for a zero total angular momentum, $J = 0$, is solved by means of an exact variational quantum approach which employs a set of triangular arrangements formed by the combination of DGFs for the R_1, R_2 and R_3 coordinates [3]. The eigenstates of the $J = 0$ case constitute the radial basis set to solve the rotational Hamiltonian.

The method has been applied for the Ar^3 system and the comparison with results from exact hyperspherical coordinate calculations [1, 4] reveals the validity of the approximation to describe the bound states for large values of the total angular momentum.

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Highly excited bound states and near-threshold resonances in ozone isotope effect

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The three-body recombination reaction,

$$O_2 + O + M \rightarrow O_3 + M \tag{1}$$

is one of the central reactions of the Chapman cycle controlling the stability of the stratospheric ozone (O_3) layer. This reaction, in which O_3 is initially formed at dissociation threshold, is also responsible for large enrichments of heavy isotopomers of ozone. The enrichments, which seem unrelated to the natural abundances of oxygen isotopes and therefore are called 'surprising', are observed both in the field measurements and in the lab [1]. Despite numerous studies in the past few years, the isotope fractionations are still far from being satisfactorily explained and several essential questions remain to be solved [2].

In this talk I plan to discuss recent quantum mechanical studies of two unusual isotope dependences in reaction (1):

- Isotope Effect 1 (IE-1), the dependence of the recombination rate on the difference of zero-point energies of the two fragmentation channels to which excited ozone can dissociate, i.e. X + YZ ← XYZ* → XY + Z, where X, Y, and Z stand for the three isotopes of oxygen;
- Isotope Effect 2 (IE-2), the symmetry dependence of the recombination rate: the rate is smaller for symmetric molecules (e.g. XYX) than for non-symmetric ones (e.g. XXY).

Both isotope effects, IE-1 and IE-2, will be analyzed using the full-blown quantum mechanical calculations of near-threshold resonance spectra as well as the cross-sections for collisional stabilization of ozone at dissociation threshold. It will be shown that the distributions of resonance widths in the rotating molecule *and* the peculiar topology of ozone interaction potential are able to explain most of the observed isotope dependences.

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Behavior of Wave Functions near the Thresholds

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Critical Stability, Erice, October 2008

In this talk I shall discuss the behavior of a wave function of an N-particle system, whose energy is close to that of the dissociation threshold. It is widely known that close to the dissociation threshold the wave functions might become very diffuse forming the so-called halo. The physical examples are numerous, for instance, Rydberg or Efimov states in atomic and molecular physics, halo nuclei in nuclear physics, etc. Yet, when a long-range repulsion between the dissociation fragments is being present, there acts a super-size blocking, i.e. the wave functions do not become diffuse and eventually a bound state at the threshold can be formed. I discuss the connection between bound states at the threshold and super-size blocking and sketch the derivation of conditions on pair potentials, which guarantee the formation of bound states exactly at the threshold. Under minor assumptions this proves that negative atomic ions have a bound state at the threshold when the charge of the nucleus is critical.

A Mathematical Theory for Vibrational Levels Associated with Hydrogen Bonds

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Critical Stability, Erice, October 2008

We propose an alternative to the usual time–independent Born–Oppenheimer approximation that is specifically designed to describe molecules with Hydrogen bonds. In our approach, the masses of the Hydrogen nuclei are scaled differently from those of the heavier nuclei, and we employ a specialized form for the electron energy level surface. Consequently, anharmonic effects play a role in the leading order calculations of vibrational levels.

Multiple scattering of light in cold atoms: from light localisation to plasma physics

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Critical Stability, Erice, October 2008

Cold atoms have emerged as ideal quantum system to study coherent transport properties of light. First experiments have established that dilute samples with large optical thickness allow studying weak localization of light.

The present goal of this research is to study coherent transport of photons in dense samples. Anderson localization of light or superradiance are among the most interesting situation currently studied.

The transition from coherent to incoherent transport is also studied, leading to investigations on anomalous diffusion (Levy flights) or random lasing (in the presence of strong pumping).

Many of these aspects will be discussed and illustrated with recent experimental observations.

Consistent α-cluster description of the Hoyle state in ^{12}C

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Critical Stability, Erice, October 2008

During the recent years, there is a continuous interest to the experimental and theoretical study of the ^{12}C nucleus [1, 2, 3, 4]. In this respect, of special importance is the description of the Hoyle state, which was predicted more then 50 years ago merely from the abundance of elements in the universe. Whereas the Hoyle state is fairly well studied experimentally, e. g., its extremely small width Γ and Hoyle to ground-state transition density (in particular, the monopole transition matrix element M_{12} and the transition radius A_{tr}) were measured, the theoretical description of a comparable accuracy meets essential difficulties. For the astrophysical applications, the challenging problems is a consistent description of the near-threshold 0_2^+ (Hoyle) state, whose properties are extremely sensitive to parameters in the α-cluster model. On the other hand, the choice of the effective two-body and three-body potentials is of general interest and their parameters have to be adjusted to fit the ^{12}C observables.

Previous calculations [5, 6] revealed that the α-cluster model, even with a simplest local α-α potentials, provides a surprisingly good description of the ground and excited states of the ^{12}C nucleus. The aim of this reportis to present the calculations of the lowest 0^+ states of ^{12}C with the α-α potentials, which are chosen to describe the s-, d-, g-wave α-α elastic-scattering phase shifts up to energy $E_{cm} < 12$ MeV and the experimental energy and width of the α-α resonance (the ground state of ^{8}Be). The effective three-body potential of a Woods-Saxon form is taken, which parameters are chosen to fix the ground and excited 0^+ state energies and the ground-state's root-mean-square radius at their experimental values.

The main result is the amazing descriptive ability of the above-described α-cluster model. The calculations reveal that for a number of the α-α potentials both the width of the Hoyle state Γ and the structural parameters M_{12} and A_{tr} are in excellent agreement with the experimental data as shown in Fig. 1. There is enough room for further improvement of the model; it is discussed that description of the electromagnetic and (α, α) reactions could be useful to impose additional restrictions on the effective potentials.

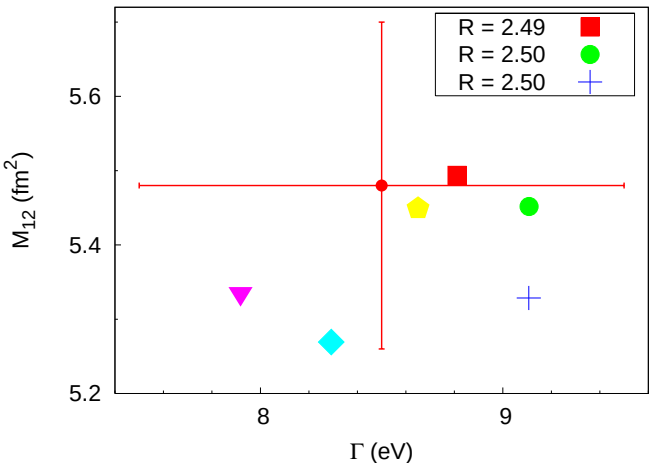

Figure 1: Monopole transition matrix element M_{12} vs width Γ dependence for few two-body potentials. The point with error-bars shows the experimental data. Corresponding values of the excited state root-mean-square radius $R^{(1)}$ is shown in the inset.

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Three-body force effects in few-nucleon systems

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Critical Stability, Erice, October 2008

Different models for a realistic nucleon-nucleon (NN) interaction are constructed by fitting the available NN data. These models contain a certain number of parameters which are fixed in order to obtain an almost perfect description of the data below 350 MeV. It is well known that these models produce a systematic underbinding in the three- and four nucleon systems. Accordingly different models of three-nucleon interactions (TNI) have been developed. In this talk we would like to analyze the equivalence of the different models in the descrition of the few-nucleon dynamics in the low energy region.

Scattering processes in a framework of Faddeev approach

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Critical Stability, Erice, October 2008

Method of scattering calculations on three-body systems using differential Faddeev equations is discussed. An algorithm for calculating three-body resonances is considered and applied to the study of Helium trimer.

How to model p-scattering using point interactions and related three-body problems

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Critical Stability, Erice, October 2008

It is well-known that the celebrated Fermi delta potential model [1, 2] leads to non-trivial scattering in the s-channel only. We propose a new family of point interaction models which may be used to describe particles with non-trivial interaction also in the p-channel while preserving exact solvability and point character of the interaction [3]. These models are given by self-adjoint operators and their spectral and scattering properies are studied in detail. The developed method is applied to the system of three quantum particles and we discuss the possibillity that this operator is semibounded (in contrast to the Landau Hamiltonian studied by Minlos-Faddeev in the sixties [4]).

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Multiparticle interactions of zero-range potentials

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For two particles it is often convenient to replace local or non-local potentials by zero-range interactions. Since they are zero-range, these interactions can often be replaced by boundary conditions at a point where the separation between two particles vanishes. In either case, zero-range potentials are useful when the details of the interaction at small distances are not critical for the dynamics. The description of Bose condensates is an example where zero-range interactions are basic to theories of the condensed aggregates. These theories employ the model interactions to obtain a mean field description of large numbers of particles. On a more fundamental level, zero-range interactions are employed to model the interactions of three particles, where they have been used to study the properties of loosely-bound Efimov states. Owning to their success in these areas they have been generalized to allow for multichannel interactions, interactions for states with non-! zero angular momentum and energy dependent zero-range potentials. Properties of these generalized potentials and their applications will be illustrated for the interaction of three particles at vanishingly small kinetic energy.

Light nuclei in the continuum

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Critical Stability, Erice, October 2008

The development of light, neutron-rich beams has opened in the last decade new perspectives for the study of many-neutron systems. Breakup experiments at GANIL will be described, using beams of $^{6-8}$He, ^{11}Li, ^{14}Be and ^{15}B at several tens of MeV/N. Our approach is based on the detection in coincidence of the breakup fragment and the neutrons in order to investigate the different correlations in the final state of these very neutron-rich systems.

Several particular cases will be discussed: fragment-n correlations in ^{7}He, ^{10}Li and ^{9}He; $2n$ correlations in ^{6}He, ^{11}Li and ^{14}Be; and three-body and $4n$ correlations in ^{8}He and ^{14}Be.

Welcome address

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Critical Stability, Erice, October 2008

This welcome address will briefly present the Ettora Majorana Centre for Scientific Culture of Erice, and stress the importance of quantum few-body systems at the edge of stability.

Efimov Effect in 2-Neutron Halo Nuclei

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Critical Stability, Erice, October 2008

The 2-neutron halo nuclei near the neutron drip line are the ideal candidates for studying the Efimov effect in atomic nuclei. In this talk we will present our work to investigate the occurrence of Efimov states in 2-neutron halo nuclei, like, ^{14}Be, ^{19}B, ^{22}C, and ^{20}C. We will also present the result of our calculations to study the evolution of the bound Efimov states into resonances with increasing two body (neutron-core) binding energy. Finally, we will tie up the emergence of the asymmetric resonances with the Fano phenomenon and discuss its implication for the possible experimental observation of Efimov states in atomic nuclei.

Microscopic Description of Few-Body Systems in the Fermionic Molecular Dynamics Approach

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Critical Stability, Erice, October 2008

The Fermionic Molecular Dynamics (FMD) [1] is a microscopic model for the description of nuclei in the p- and sd-shell. Many-body basis states are Slater determinants of Gaussian wave packets localized in phase space. The wave packet basis is very flexible and includes the harmonic oscillator shell model basis as well as Brink-type cluster states as limiting cases. The width of the wave packets is a variational parameter and allows to describe loosely bound halo nuclei. The intrinsic Slater determinants are projected on parity, angular momentum and total linear momentum to restore the symmetries of the Hamiltonian.

We discuss the spectrum of ^{12}C with a special emphasis on the structure of the first excited 0^+ state, the famous Hoyle state. In the FMD approach the Hoyle state is found to be dominated by dilute alpha-cluster configurations, a picture that is confirmed by electron scattering data for the transition from the ground into the Hoyle state [2] The FMD wave function can also be decomposed into $N\hbar\Omega$ shell model configurations illustrating the highly coherent nature of the Hoyle state.

As another application we present recent results for neon isotopes [3]. The low lying states of ^{17}Ne and ^{18}Ne can be understood essentially as systems of a ^{15}O or ^{16}O core and two protons in weakly bound s- or d-orbits. In FMD calculations we find in ^{17}Ne a large admixture of spatially extended s^2 configurations explaining the large experimental charge radius. Higher lying excited states of ^{18}Ne have ^{14}O–^{4}He cluster nature. Clustering becomes even more important in the heavier isotopes $^{19-22}$Ne. For example the parity doublets in ^{19}Ne are related to the coexistence of ^{16}O–^{3}He and ^{15}O–^{4}He cluster configurations.

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Two-boson correlations in various one-dimensional traps

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Critical Stability, Erice, October 2008

A one-dimensional system of two trapped bosons which interact through a contact potential is studied using the optimized configuration interaction method. The rapid convergence of the method is demonstrated for a series of trapping potentials of convex and non-convex shapes. The energy spectra, as well as natural orbitals and their occupation numbers are determined in function of the interboson interaction strength. Various correlation characteristics are discussed in dependence both on the shape of the confining potential and on the sign and strength of the interaction. Entanglement properties are examined particularly carefully. In all the cases studied, a special attention is paid to the demonstration of the fermionization effects when the interaction becomes strong enough.

Universality in low-energy few-body systems and leading corrections

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The zero range model with proper renormalization is a powerful too calculate a variety of interesting low-energy observables in nuclear and atomic physics. In the three-body sector this approach reveals many interesting features (such as approximate discrete scale invariance) of systems with large scattering length.

In my talk I will discuss the zero-range in the more general context of effective field theories and address recent results for three-body recombination of identical bosons. Furthermore, I will explain how finite range effects modify such leading order results and show how the "leading order" discrete scale invariance constrains the impact of such effects.

Interaction Blockade and Vortices in Atom Traps

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Critical Stability, Erice, October 2008

Many analogies exist between nanostructured quantum systems such as quantum dots, and trapped ultra-cold atom gases. The newly emerging "atomtronics" makes phenomena such as Bose-Einstein condensation accessible for the micro- and nano-design of future quantum devices. In this talk, we shall discuss how effects similar to Coulomb blockade in quantum dots may occur in systems of ultracold, trapped atoms [1-3]. We furthermore comment on vortices in single- and multi-component systems and point out the analogies between bosonic and fermionic quantum gases set rotating [4-5].

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Proof of stability of tetraquarks in a minimal-path model of linear confinement

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The quark–antiquark confining potential, $V_2(r) = r$ (in appropriate units) is generalised to baryons as $V_3 = \min(d_1 + d_2 + d_3)$, where d_i is the distance of the $i^{\rm th}$ quark to a junction whose location is adjusted to minimise the interaction. See Fig. 1, left. Hence estimating V_3 involves solving the famous Fermat–Torricelli problem.

The extension to the tetraquark problem, initiated by several authors, has been recently revisited in Refs. [1, 2]. It consists of the minimum of $(r_{13}+r_{24})$ and $(r_{14}+r_{23})$ on one side, which is the so-called flip-flop potential (Fig. 1, centre), and on the other side, $(d_{15}+d_{25}+d_{56}+d_{63}+d_{64})$, with the junction points $\mathbf{r}_5$ and $\mathbf{r}_6$ optimised. This latter term is a Steiner minimal tree (see Fig. 1, right) and it should be computed carefully and efficiently.

This intricate four-body potential, inspired by the flux-tube limit of QCD, has been applied to solve the tetraquark problem for configurations $(Q, \bar{Q}, q, \bar{q})$ and $(Q, Q, \bar{q}, \bar{q})$ with two different masses M and m.

From a careful variational calculation, it is found that the tetraquark ground-state is slightly bound for $M = m$, and, while the hidden-flavour state becomes unbound when M/m increases, the state with two units of heavy flavour becomes more stable. See the contribution by A. Valcarce and J. Vijande to this Workshop.

A subtle property of minimal Steiner tree with four terminals gives a rigorous upper bound for the above four-body potential, and the four-body problem is exactly solvable with this upper bound. It is demonstrated that the flavour-exotic tetraquark is stable in the limit of large mass ratio M/m.

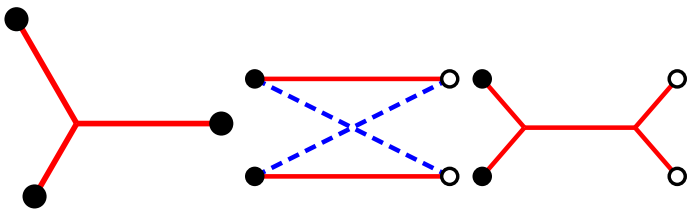

Figure 1: Y-shape confinement for baryons, and the flip-flop and the Steiner tree terms for tetraquarks.

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A journey through exotica in hadronic physics

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The fascination with the exotic transcends all disciplines. Hadronic, or strong interaction physics has not been immune from it. Time and again it has come up with ideas of exotic hadrons. Time and again they turn out to be mirages. But then, once in a while, the exotic materializes, and all the past failures pale into the excitement of those discoveries. I will present a tour through some of these ups and downs of exotica in hadronic physics.

Four–quark stability

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In order to discuss the stability of four–quark states against dissociation into two isolated mesons we shall present in this talk an exact method to study four-quark systems based on the hyperspherical harmonics formalism. We shall apply it to several physical systems of interest containing two heavy and two light quarks using different non–relativistic quark-quark potentials. Our conclusions mark the boundaries for the possible existence of compact, non-molecular, four-quark bound states. While $QQ\bar{n}\bar{n}$ states may be stable in nature, the stability of $Q\bar{Q}n\bar{n}$ states would imply the existence of quark correlations not taken into account by simple quark dynamical models. The possible role played by confining interactions not factorizable into simple two-body components will be discussed.

Spin solvent effects in doped helium clusters: A microscopic manifestation of superfluidity

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Doing a parallelism of nuclei/electrons with dopant/helium atoms, a quantum chemistry approach is used to perform spectral simulations of molecular species embedded in helium clusters of variable size.

To account for the spin characteristics of the solvent, Hartree or Hartree-Fock methodology is applied to obtain energies and structural properties of the aggregates. In this frame, one considers the distortion induced on the molecular dopant by the surrounding helium atoms. As a consequence of the different spin multiplicity, inherent to the boson/fermion nature of the helium environment, selection rules for Raman [1] or infrared [2] spectra depending on the polar/non polar character of the dopant, predict completely different profiles in these diverse scenarios.

This finding agrees with, e.g. the experimental infrared spectra of oxygen carbon sulfide, OCS, in helium nanodroplets [3]. Below the critical transition temperature of ^{4}He, 2.12 K, the boson profile is close to the gas phase spectrum of the dopant. So, the later seems to be freely rotating inside the droplet, a microscopic manifestation of superfluidity. In turn, even at lower temperatures (but above 0.003 K, the superfluid transition temperature of ^{3}He), the corresponding fermion spectrum shows an unstructured broad shape resembling the case of heavy molecules immersed in liquids. This peculiar behavior is illustrated through simulated spectra of the iodine chlorine (ICl) molecule, a species which mimics to the quasi-linear OCS molecule.

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Four-body nuclear systems

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The study of the four nucleon (4N) system is interesting from a number of different perspectives. First of all, many reactions involving four nucleons, are of extreme astrophysical interest, as they play important roles in solar models or in big-bang nucleosynthesis. Moreover, 4N systems have become increasingly important as testing grounds for models of the nuclear force, being the $A = 4$ system the simplest system that presents the complexity - thresholds and resonances - that characterize nuclear systems.

The theoretical description of $A = 4$ systems still constitutes a challenging problem from the standpoint of nuclear few-body theory. Only recently, with the near-constant increase in computing power and the development of new numerical methods, the study of the bound and scattering states has reached a satisfactory level of accuracy. In this contribution, the application of the hyperspherical harmonics method to study these systems will be discussed. The calculations have been performed using realistic models for nucleon-nucleon and three-nucleon forces. The results will be compared with the most recent calculations performed by means of the Faddeev-Yakubovsky approach and the experimental data.

Solving the Coulomb scattering problem without using Coulomb functions

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In order to solve the scattering problem using the Schrödinger equation one has to define properly the behavior of the solution at infinity. However for many body scattering the asymptotic form of the wave function is rather complicated especially in the case of coulomb interaction. Therefore the method which allows solving the problem without using asymptotic form of the solution at infinity could be an advantage.

The wave function which solves the scattering problem has to satisfy the Schrdinger equation, to be zero at the origin while at infinity it has to be the sum of incoming and outgoing waves. If we subtract the incoming wave from the solution, then the result function will satisfy the driven Schrödinger equation. It will be zero at the origin but at infinity it will have the form of pure outgoing wave. Such boundary condition at infinity is very convenient for application of complex scaling method, which reduces the outgoing wave to exponentially decreasing function. This means that we can use zero boundary condition at infinity, when solving this problem.

The method works only for exponentially decreasing potentials [1]. If the potential decreases slower, than the divergence occurs. Rescigno et al. showed in [2] that the method can be made converging for potentials decreasing faster than the coulomb one. One needs to truncate the potential in rather far point R, and then apply the exterior complex scaling with rotating point R. It is well known that the truncation of a coulomb potential gives a mistake for any truncation radius. Thus the Coulomb problem requires a special consideration.

In the present work we suggest the method which reduces the scattering problem to the system with zero boundary conditions and still works in the case of pure (unscreened) coulomb interaction. Another preference of the method for many body scattering is that we do not need the coulomb wave function to subtract the phase shift from the solution.

We prove the method analytically and then test it numerically.

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Theory of Classical and Quantum Reaction Dynamics in Multidimensional Systems

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Transition state theory – invented by Wigner, Eyring and Polanyi in the 1930's – is one of the fundamental concepts to compute chemical reaction rates. In classical mechanics reaction type dynamics is induced by saddle-centre-...-centre equilibrium points ('saddles' for short). The main idea underlying transition state theory is to compute the reaction rate from the flux through a dividing surface placed near the saddle, dividing phase space into a reactants region and a products region. In order not to overestimate the reaction rate, the dividing surface needs to have the property that it is crossed exactly once by all reactive trajectories and not crossed at all by nonreactive trajectories. The construction of such a dividing surface for systems with more than two degrees of freedom was a major problem in transition state theory. We will study in detail the phase space structures governing the dynamics near a saddle and provide an algorithm based on a normal form to compute these phase space structures. In addition to a dividing surface with the desired properties we will determine the phase space conduits which trajectories must follow in order to react. These are given by the stable and unstable manifolds of a normally hyperbolic invariant manifold (NHIM) which can be shown to exist near the saddle and also forms the main building block for the construction of the dividing surface. The NHIM is the mathematical formulation of the so called activated complex – a kind of supermolecule poised between reactants and products. Furthermore, we will study the signatures of these phase space structures in the quantum mechanics of reactions. These consist of a quantisation of the increase of the cumulative reaction probability (the quantum analogue of the classical flux) as a function of the energy and of quantum resonances associated with the activated complex. We will see that similar to the classical case the cumulative reaction probability (and also the quantum resonances) can be computed from an efficient algorithm based on a quantum normal form.

Experimental low energy antiproton physics

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Experiments with low-energy antiprotons are currently performed at the antiproton Decelerator (AD) of CERN. The main focus of the three experimental collaboration is the study of fundamental symmetries, especially CPT invariance, using antiprotonic atoms and antihydrogen. The ASACUSA collaboration focusses on precision spectroscopy of antiprotonic helium, an exotic three-body system consisting of a helium nucleus, an electron and an antiproton. The antiproton occupies metastable states which allows precision determination of its mass and magnetic moment [1] by comparison to three-body QED calculations.

Anthydrogen, the simplest neutral antimatter atom, promises CPT tests of highest precision by comparison to hydrogen, which is one of the best studied atoms. The ATRAP and ALPHA collaborations aim at producing and trapping antihydrogen in a neutral-atom trap and to measure the 1S-2S two-photon transition [2] to a precision similar to the one achieved for hydrogen (relative precision $\sim 10^{-14}$). ASACUSA is preparing an experiment to measure the ground-state hyperfine structure of antihydrogen [3], the corresponding quantity for hydrogen being measured to relative precision of $\sim 10^{-12}$ in the hydrogen maser.

The AD delivers only pulsed beam which makes experiments of nuclear or particle physics type difficult. This restriction will not apply at the planned FLAIR facility [4] at FAIR, Darmstadt, where the availability of continuous antiproton beams at energies 100 times lower than at the AD will enable measurements not currently possible anywhere in the world. This talk will give an overview on current and planned experiments with low-energy antiprotons.

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Variational calculations of K-few-N states

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Deeply bound KNN, KNNN and KNNNN states are discussed. The effective force exerted by the K meson on the nucleons is calculated with static nucleons. Next the binding energies are obtained by solving the Schrödinger equation or by variational calculations. The dominant attraction comes from the S-wave $\Lambda(1405)$ and an additional contribution is due to $\Sigma(1385)$. The latter state is formed at the nuclear peripheries and absorbs a sizable piece of the binding energy. It also generates new branches of quasi-bound states.

The lowest binding energies based on the phenomenological KN input fall into the 40-80 MeV range for KNN, 90-150 MeV for KNNN and 120-220 MeV for Kα systems. The uncertainties are due to unknown KN interactions in the distant subthreshold energy region. Comparison with other calculations [1],[2],[3], is made.

A simple physical picture emerges from this approach. The mesons are strongly correlated to slowly moving nucleons. The correlations are of the $\Lambda(1405)$ type at large densities, and of the $\Sigma(1385)$ type in the peripheries. Each K,N pair has a good chance to stay also in the Σ, π form. The structure is rather loose as sizable fractions of the binding energies are hidden in the short ranged correlations.

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