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Peculiar Corners of Hilbert Space where Strange States Lie

One of the exciting opportunities presented by experimental capabilities at ultracold temperatures is the possibility of forming and probing highly quantum mechanical types of states that would normally be too weakly bound or too unstable to survive in a warmer environment. Two of the most prominent types of states that have been receiving extensive attention in recent years are (1) Efimov trimers formed from three ground state atoms, and the closely related tetramers which inherit many aspects of the Efimov trimer wavefunction; (2) Ultra-long-range Rydberg molecules, where simply by virtue of the Rydberg electron colliding over and over with a far distant ground state atom, sufficient binding can be achieved to keep the pair of atoms bound at very large internuclear distances. This invited talk will review the theory of both of these groups of states and discuss recent experimental and theoretical advances.

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Non-Equilibrium dynamics with ultracold few-body systems

Abstract: In the past few years, the progress made by the field of utracold atoms has increasingly been translated into promising prospects for controlling atomic behavior. The present day ability to control interatomic interactions in an ultracold quantum gas enables the prediction and realization of a complex array of quantum phenomena that interconnect a number of different physics subfields. The rich and fundamental nature of few-body correlations represent opportunities for exploring novel phases of matter and offers a path for understanding strongly correlated collective phenomena. In this talk we will discuss non-equilibrium dynamics in few-body systems, and more specifically on how out-of-equilibrium an isolated quantum systems evolves into an equilibrium state. We use the hyperspherical adiabatic representation in order to explore such phenomena and propose different ways in which the system can be led to a non-equilibrium state and discuss relevant observables accessible to ultracold quantum gases experiments.

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Josephson-type atom-number oscillations in tunable spin-orbit coupled BEC with time-dependent Raman frequency

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The atom-number internal Josephson oscillations, in tunable spin-orbit coupled (SOC) Bose-Einstein condensates (BEC) with Raman frequency varying in time, are studied for attractive two-body interactions, considering parametric resonances which can emerge due to the time-oscillating Raman frequency. In the high-frequency limit, the system is described by a coupled averaged Gross-Pitaevskii formalism with renormalized SOC and modified phase-dependent nonlinearities. For this modified system in the case of attractive nonlinearities we found stationary bright solitons and striped solitonic solutions. The control of internal Josephson oscillations of the atomic population between components under the time modulated SOC is investigated. The theoretical predictions are proved by the numerical simulations of the full coupled GP system of equations with SOC.

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Dimensional effects in Efimov physics

Efimov physics is drastically affected by the change of spatial dimensions. Efimov states occur in a tridimensional environment, but disappear in two and one dimensions. Nowadays, the effective dimension of the system can be continuously changed in ultracold traps by compressing the atomic clouds in one or two directions. In this talk, I will show some recent theoretical advances related to the effect of dimensionality in the Efimov phenomenon. I will start with a very ideal case with no physical scales, passing to a system with finite energies in the Born-Oppenheimer approximation and finishing with a general system. The connection between the general and ideal cases allows the calculation of the effective spatial dimension where the system is embedded."

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On the Existente of Rydberg Nuclear Molecules

Present nuclear detection techniques prevents us from determining if the analogue of a Rydberg molecule exists for the nuclear case. But nothing in nature disallows their existence. As in the atomic case, Rydberg nuclear molecules would be a laboratory for new aspects and applications of nuclear physics. We propose that Rydberg nuclear molecules, which represent the exotic, halo nuclei version, such as 11Be+11Be, of the well known quasimolecules observed in stable nuclei such as 12C+12C, might be common structures that could manifest their existence along the dripline. A study of possible candidates and the expected structure of such exotic clustering of two halo nuclei: the Rydberg nuclear molecules, is made on the basis of three different methods. It is shown that such cluster structures might be stable and unexpectedly common.

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Recent topics of quantum hydrodynamics and turbulence

Quantum condensed systems such as superfluid helium and atomic Bose-Einstein condensates (BECs) have order parameters. Hydrodynamics and turbulence of these systems are severely restricted by the order parameters. The typical example is quantized vortex; any rotational motion of superfluid is sustained only by quantized vortices. Quantum hydrodynamics and turbulence [1] have been long studied in superfluid helium since 1950's, and recently in atomic Bose-Einstein condensates (BECs) too. In this presentation, I would review the characteristics and motivation of this field, and discuss the recent novel topics.

1. **Novel studies of counterflow in superfluid helium**

Hydrodynamics of superfluid ^{4}He is well described by the two-fluid model. The most characteristic phenomenon of the two-fluid model is thermal counterflow, which has been studied for more than a half century. However, the three-dimensional coupled dynamic of the two-fluid model is seldom addressed. The recent visualization experiments show that the profile of the normal fluid flow is seriously modified by the development of superfluid turbulence [2]. We studied numerically the three-dimensional coupled dynamics of the two-fluid model and found that the profile of the normal fluid flow is changed by the mutual friction with the vortex tangle [3] (Fig.1). Another topic is vortex tangle caused by spherically symmetric thermal counterflow. We study the development of the inhomogeneous vortex tangle [3].

2. **Hydrodynamics and turbulence of atomic BECs**

Most experiments of atomic BECs have been performed for systems trapped by a harmonic potential. The recent realization of the box potential has made this system more attractive. Navon et al. observed the clear statistical law of quantum turbulence in a BEC trapped by a box potential [5]. As the continuation, we study the cascade flux and succeed in obtaining the information from the particles lost from the potential. Using a time periodic force, we inject energy at a large lengthscale and generate a cascade. The adjustable trap depth provides a high-momentum cutoff which realises a synthetic dissipation scale (Fig.2). The observations are consistent with the numerical simulation of the Gross-Pitaevskii model [6]. Another topic is two-component

BECs. We found that the vortices belonging to different components are phase-separated by the intervortex interaction [7].

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Universal Non-Equilibrium Dynamics in a Disordered Rydberg Spin System*

Out of equilibrium spin systems with disorder can show extremely slow dynamics as known, e.g., for spin glasses, where the magnetization relaxes slowly over several orders of magnitude in time. To investigate such dynamics in the presence of quantum fluctuations we implement an isolated disordered spin system composed of long-range interacting Rydberg atoms which can be described by a Heisenberg XXZ spin model[1]. We present an experiment which disentangles the role of fluctuations stemming from disorder and quantum fluctuations. The spin system is represented by two atomic Rydberg states in a “frozen” gas of ultracold atoms under the influence of dipolar interactions ranging over macroscopic distances. We find strong deviation from the mean field prediction of the magnetization. Instead, the magnetization relaxes with a universal non-exponential decay much slower than the timescale associated with the exchange coupling strength. Such dynamics, which bears similarities to spin glasses, is in good agreement with a discrete truncated Wigner approximation revealing that the evolution is determined by the build-up of entanglement driven by quantum fluctuations. We will also discuss the spin dynamics under the presence of an external field.

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Nonequilibrium Quantum Dynamics of Ultracold Bosonic and Fermionic Mixtures

We discuss several prototype situations of the nonequilibrium quantum dynamics of ultracold single species and mixtures ranging from the correlated quantum dynamics in optical lattices to beyond mean-field behaviour of solitons and collisionally coupled correlated species. Firstly we demonstrate[1] in a 'bottom-up approach' the correlated many-particle effects in the collective breathing dynamics for few- to many-boson systems in a harmonic trap. Many-body processes in black and grey matter-wave solitons are explored thereby demonstrating that quantum fluctuati- ons limit the lifetime of the soliton contrast, which increases with increasing soliton velocity[2]. For atomic ensembles in optical lattices we explore the interaction quench induced multimode dynamics leading to the emergence of density-wave tunneling, breathing and cradle-like proces- ses. An avoided-crossing in the respective frequency spectrum provides to a beating dynamics for selective modes[3,4]. A particular far from equilibrium system is then studied at hand of the correlated quantum dynamics of a single atom collisionally coupled to a finite bosonic reservoir[5]. The presentation provides also some selective aspects of our recent investigations on atom-ion hybrid systems [6-8] using the same methodology. First the ground state properties of ultracold trapped bosons with an immersed ionic impurity are discussed. Subsequently the capture dyna- mics of ultracold atoms in the presence of the impurity ion is explored. An outlook is provided on our most recent exporations of quenches across phase boundaries for mixtures[9] — and impurity dynamics and Bose- as well as Fermi polaron physics in the ultracold regime[10]. Our methodo- logical approach, the multi-layer multi-configuration time-dependent Hartree method for bosons and fermions represents a powerful ab initio method for the investigation of the correlated non- equilibrium quantum dynamics of single and multi-species bosonic systems in traps and optical lattices[11,12,13].

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Production, Characterization and Perspectives of Turbulence in trapped atomic superfluid

Quantum turbulence in trapped Bose-Einstein condensate is a far from equilibrium state, obtained by injection of energy through rotations. The generation of vortices and their reaction makes the system to evolve to be turbulent. In recent years we have worked with a BEC of Rubidium atoms excited by potential disturbances producing evidences for the turbulent regime. Once in this situation, the momentum distribution **n(*r*)** has been obtained using a time-of-flight technique. The presence of power law dependence, for a determined range of momentum, can be associated with the presence of energy cascade, typical property of turbulence. The distribution was also obtained using power spectrum techniques. Based on the obtained behavior of **n(*r*)**, as the quantity of injected energy was varied, we have proposed possible types of turbulence present in the sample. Besides **n(*r*)**, many other characteristics were determined in order to identify aspects of the turbulence. Expansion behavior for the turbulent clouds allows understanding the disfferent aspect of it. Perspectives for new investigation in turbulent BEC will be discussed.

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