ExtreMe Matter Institute EMMI Workshop

Book of Abstracts

Invited Presentations

From N+1 to N+N: exploring itinerant ferromagnetism with repulsive Fermi mixtures

Matteo Zaccanti (LENS Florence)

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

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

I will first report on two recent experiments employing degenerate mixtures of 6Li atoms repulsively interacting at a broad scattering resonance, carried out both in the impurity limit and with non-polarized samples. Radio-frequency spectroscopy and study of spin dynamics allow us to unveil the ferromagnetic behavior of these systems and to investigate the competition between ferromagnetic and pairing instabilities of such a metastable repulsive Fermi liquid.

I will then discuss the possibility to realize long-lived repulsive Fermi gases with a novel mixture of Lithium and Chromium atoms, whose unique few-body properties enable an extraordinary suppression of atom recombination into paired states in the regime of strong interspecies repulsion.

One, Two, Three, Many: Few-Body Losses in Many-Body Ensembles

Frédéric Chevy (Ecole Normale Supérieure Paris)

In this talk, I wil discuss the stability of Bose-Fermi dual superfluids. I will show that in the weak-coupling limit, the three-body loss-rate is proportionnal to Tan's contact and can be used as a quantitative probe of pair correlations of the Fermi gas.

When scanning the BEC to BCS crossover describing the fermionic gas, the loss-rate interpolates between three-body losses in the weakly attractive limit, and effective two-body boson-dimer processes in the strongly attractive regime. At unitarity, we observe an anomalous loss-rate scaling as the 4/3 power of the fermion density.

Observation of quantum-limited spin transport in a strongly interacting 2D Fermi gas

Joseph Thywissen (University of Toronto)

We measure the transport properties of two-dimensional ultracold Fermi gases during transverse demagnetization in a magnetic field gradient. Using a phase-coherent spin-echo sequence, we are able to distinguish bare spin diffusion from the Leggett-Rice effect, in which demagnetization is slowed by the precession of spin current around the local magnetization. When the two-dimensional scattering length is tuned to be comparable to the inverse Fermi wave vector, we find that the bare transverse spin diffusivity reaches a minimum of 1.7(6) hbar/m, where m is the bare particle mass. The rate of demagnetization is also reflected in the growth rate of the s-wave contact, observed using time-resolved spectroscopy. The contact rises to 0.28(3) kF^2 per particle, which quantifies how scaling symmetry is broken by near-resonant interactions, unlike in unitary three-dimensional systems. Our observations support the conjecture that in systems with strong scattering, the local relaxation rate is bounded from above by kBT/hbar.

Kondo effect and its transport measurement with ultracold atoms

Yusuke Nishida (Tokyo Institute of Technology)

We propose a simple but novel scheme to realize and measure the Kondo effect with ultracold atoms [1,2]. Our system consists of imbalanced Fermi seas of two components of fermions and an impurity atom of different species which is confined by an isotropic potential. We first apply a \pi/2 pulse to transform two components of fermions into two superposition states. Their interactions with the impurity atom then cause a "transport" of fermions from majority to minority superposition states, whose numbers can be measured after applying another 3\pi/2 pulse. In particular, when the interaction of one component of fermions with the impurity atom is tuned close to a confinement-induced p-wave or higher partial-wave resonance, the orbital degeneracy leads to the Kondo effect where the resulting conductance is shown to exhibit the universal logarithmic growth by lowering the temperature. The proposed transport measurement will thus provide a clear evidence of the orbital Kondo effect accessible in ultracold atom experiments and pave the way for developing new insights into Kondo physics.

[1] Y. Nishida, "SU(3) orbital Kondo effect with ultracold atoms,"

Phys. Rev. Lett. 111, 135301 (2013) [arXiv:1308.3208].

[2] Y. Nishida, "Transport measurement of the orbital Kondo effect with ultracold atoms,"

Phys. Rev. A 93, 011606(R) (2016) [arXiv:1508.07098].

Dipolar quantum droplets

Igor Ferrier-Barbut (University of Stuttgart)

Recently we have observed that despite what was expected from mean-field predictions, a three-dimensional dipolar Bose-Einstein condensate under an overall attractive interaction does not collapse, but condenses into a liquid phase. This phase is stabilized from mean-field collapse by beyond mean-field terms that are arising from quantum fluctuations in the ground state. I will present our results characterizing this liquid phase and the phase transition, both in the trapped, and un-trapped case.

Exploring dipolar physics with ultracold atomic gases of Erbium

Lauriane Chomaz (University Innsbruck)

Due to their large magnetic moment and exotic electronic configuration, atoms of the lanthanide family such as dysprosium and erbium are an ideal platform for exploring the competition between inter-particle interactions of different origins and different behaviors. Recently, a novel phase of dilute droplet have been reported when changing the ratio of the contact and dipole-dipole interactions and setting the mean-field interactions to attractive in an ultracold bosonic dysprosium gas. This has been attributed to the distinct non-vanishing beyond-mean-field effects when canceling the mean interaction in presence of DDI and is thus expected to be general to dipolar gases. Here, we report on the investigation of dilute droplet physics in a bosonic erbium gas. By precise control of the s-wave scattering length a, we quantitatively probe the Bose-Einstein condensate (BEC)-to-droplet phase diagram and the rich underlying dynamics. In a prolate geometry, we observe a crossover from a BEC to a dense macro-droplet of 10^4 atoms, and characterize the special properties of this state. By this mean we quantitatively demonstrate the stabilizing role of the quantum fluctuations.

Ultra dilute Low-Dimensional Liquids

Grigory E. Astrakharchik (Universitat Politécnica de Catalunya)

We calculate the energy of one- and two-dimensional weakly interacting Bose-Bose mixtures analytically in the Bogoliubov approximation and by using the diffusion Monte Carlo technique. We show that in the case of attractive inter- and repulsive intraspecies interactions the energy per particle has a minimum at a finite density corresponding to a liquid state. We derive the Gross-Pitaevskii equation to describe droplets of such liquids and solve it analytically in the one-dimensional case.

The heteronuclear Efimov scenario in an ultracold Bose-Fermi mixture with large mass imbalance

Matthias Weidemüller (University of Heidelberg)

A Bose-Fermi mixture of Cs-133 and Li-6 atoms is an ideal system for the investigation of the heteronuclear Efimov scenario, since its large mass imbalance results in a drastically reduced scaling factor between consecutive three-body states. Additionally, the existence of two independent interaction parameters, one between the unlike species, and one between the same species, enables few-body phenomena that have no counterexamples in the homonuclear case [1]. Here we present our recent measurements and analysis of three-body recombination spectra in an ultracold Li-Cs-Cs system. Two broad Li-Cs Feshbach resonances are used for tuning the interparticle interactions [2], while each of them is characterized with a different sign and magnitude of the intraparticle interactions. For negative Cs-Cs scattering length a series of three consecutive Efimov resonances is observed. The excited states are found to be in good agreement with the universal zero-range theory at finite temperature [3], while the ground state deviates [4,6]. For repulsive Cs-Cs interaction the ground state transforms into the Li+Cs2 scattering channel and the corresponding three-body resonance is missing. Both, the modified scaling factor via short-range effects and the absence of the ground-state resonance, are in qualitative agreement with the spinless van der Waals theory [5,6].

Work performed in collaboration with J. Ulmanis, S. Häfner, R. Pires, E.D. Kuhnle (Heidelberg University), C.H. Greene (Purdue University), Y. Wang (Kansas State University), F. Werner (Laboratoire Kastler Brossel), D.S. Petrov (Université Paris Sud).

[1] J. Ulmanis et al., National Science Review 3, 174 (2016).

[2] J. Ulmanis et al., New J. Phys 17, 055009 (2015).

[3] D.S. Petrov and F. Werner, Phys. Rev. A 92, 022704 (2015).

[4] J. Ulmanis et al., Phys. Rev. A 93, 022707 (2016).

[5] J. Ulmanis et al., Phys. Rev. Lett. 117, 153201 (2016).

[6] S. Häfner et al., arXiv:1701.08007.

Five-body Efimov effect and universal pentamer in fermionic mixtures

Dmitry Petrov (University Paris-Sud)

We show that four heavy fermions interacting resonantly with a lighter atom (4 + 1 system) become Efimovian at mass ratio 13.279(2), which is smaller than the corresponding 2 + 1 and 3 + 1 thresholds. We thus predict the five-body Efimov effect for this system in the regime where any of its subsystem is non-Efimovian. For smaller mass ratios we show the existence and calculate the energy of a universal 4 + 1 pentamer state, which continues the series of the 2 + 1 trimer predicted by Kartavtsev and Malykh and 3 + 1 tetramer discovered by Blume. We also show that the effective-range correction for the light-heavy interaction has a strong effect on all these states and larger effective ranges increase their tendency to bind.

Orbital interactions in mixed confinement

Simon Fölling (LMU/MPQ Munich)

As an earth-alkaline-like atom, fermionic ytterbium features a metastable excited orbital state, connected to the ground state orbital via an ultra-narrow clock transition. The zero angular momentum states additionally feature a strong decoupling of nuclear spin and electronic state.

The particular isotope Yb-173 features a near-resonant molecular bound state, leading to a Feshbach resonance between the two orbital states. We trap both atomic orbitals in optical lattices with varying dimensionality, and state-dependent confinement. We investigate the resulting two- and few-body physics in this resonantly interacting system, which governs the effective interactions in the many-body system.

Cold atom systems with spin-orbit coupling

Doerte Blume (Washington State University)

The realization of spin-orbit coupled cold atom systems opens the door for studying scenarios typically encountered in condensed matter systems with unprecedented control. This work considers two- and three-atom systems in the presence of single-particle spin-orbit coupling and discusses possible implications for many-body systems. Specifically, a generalized scattering framework for two particles interacting through a short-range two-body potential in the presence of isotropic or Weyl spin-orbit coupling will be introduced and results near free-space p-wave resonances will be presented. Moreover, it will be discussed how the presence of an equal mixture of Rashba and Dresselhaus spin-orbit coupling modifies the three-body energy spectruThe realization of spin-orbit coupled cold atom systems opens the door for studying scenarios typically encountered in condensed matter systems with unprecedented control. This work considers two- and three-atom systems in the presence of single-particle spin-orbit coupling and discusses possible implications for many-body systems. Specifically, a generalized scattering framework for two particles interacting through a short-range two-body potential in the presence of isotropic or Weyl spin-orbit coupling will be introduced and results near free-space p-wave resonances will be presented. Moreover, it will be discussed how the presence of an equal mixture of Rashba and Dresselhaus spin-orbit coupling modifies the three-body energy spectrum.

Observation of the Bose polaron and fundamental fluctuations in Bose-Einstein condensates

Jan Aarlt (Aarhus University)

The behavior of a mobile impurity particle interacting with a quantum-mechanical medium is of fundamental importance in physics. Due to the great flexibility of atomic gases, this scenario was previously realized experimentally in pure fermionic systems, however there had not been a realization in a bosonic environment.

Our investigation of the Bose polaron is based on the realization of 39K Bose-Einstein condensates (BECs) in the vicinity of three Feshbach resonances. These resonances allow for the condensation of

39K and enable tuning of the scattering length between atoms in the (F=1,m_F=-1) and (1,0) states. We measure the energy of an impurity interacting with the BEC by performing radio frequency spectroscopy between these states. Our results are in good agreement with theories that incorporate three-body correlations, both in the weak-coupling limits and across unitarity.

In the second part of the talk I will discuss current experiments towards the observation of fundamental fluctuations in interacting BECs. By using non-destructive measurements and feedback within an experimental sequence we achieve run to run stability of the final atom number at the shot noise limit in thermal ensembles. This is the basis for our current investigation of fluctuations in BECs.

The Bose polaron problem: a quantum Monte-Carlo study

Stefano Giorgini (University of Trento)

I will review some recent results on the problem of a single impurity coupled to a Bose gas at zero temperature obtained using quantum Monte Carlo methods. The use of such non-perturbative theoretical tools allows one to reliably investigate configurations where the strength of the interaction between the impurity and the bath ranges from the weak to the strong coupling regime. Results on the binding energy and the effective mass of the impurity are discussed as a function of both the coupling constant between the impurity and the bath and within the bath. Calculations are performed in three spatial dimensions for different values of the mass ratio which are relevant to recent experiments at JILA and in Aarhus as well as in one spatial dimension where the coupling strength within the bath can be made so large that the bosons behave as a gas of non-interacting fermions (Tonks-Girardeau regime). In particular, in 1D one finds that the effective mass of the impurity increases to very large values when the impurity gets strongly coupled to an otherwise weakly repulsive bath. This heavy impurity hardly moves within the medium, thereby realizing the "self-localization" regime of the Landau-Pekar polaron.

Visualizing Efimov physics in Bose polarons

Xiaoling Cui (Institute of Physics, Beijing)

Bose polaron is generally considered to be a promising many-body system to host the novel Efimov correlations. Nevertheless, no signature of Efimov physics has been reported in the existing Bose polaron experiments up to date. In this talk, I will show that the Efimov physics can be directly observed in Bose polarons with large mass imbalance. Taking the ^{6}Li(impurity)-^{133}Cs(bosons) system as an example, our calculation shows two visible Efimov branches in the spectral response of ^{6}Li atoms, as well as the spectral broadening due to their hybridizations with the attractive branch. Moreover, the Bose polaron in this case features much narrower spectral widths, as compared to those with small mass imbalance, suggesting well-behaved quasi-particles with reduced atom loss. Finally, if time permits, I will enumerate a few other polaron systems where the three-body correlations can take the dominated effect.

Experimental many-body physics using arrays of individual Rydberg atoms

Antoine Browaeys (Institut d'optique Palaiseau)

This talk will present our on-going effort to control the dipole-dipole interaction between cold Rydberg atoms in order to implement spin Hamiltonians that may be useful for quantum simulation of condensed matter problems. In our experiment, we trap individual atoms in two-dimensional arrays of optical tweezers [Nogrette, Phys. Rev. X 4, 021034 (2014)] separated by few micrometers and excite them to Rydberg states using lasers. The arrays are produced by a spatial light modulator, which shapes the dipole trap beam. We can create almost arbitrary, two-dimensional geometries of the arrays with near unit filling [Barredo, Science 354, 1021 (2016)].

The talk will present our demonstration of the coherent energy exchange in small chains of Rydberg atoms resulting from their dipole-dipole interaction [Barredo, Phys. Rev. Lett. 114, 113002 (2015)]. This exchange interaction realizes the XY spin model. We have also implemented the quantum Ising model [Labuhn, Nature 534, 667 (2016)]. The spin ½ Hamiltonian is mapped onto a system of Rydberg atoms excited by lasers and interacting by the van der Waals Rydberg interaction. We study various configurations such as one-dimensional chains of atoms with periodic boundary conditions, rings, or two-dimensional arrays containing up to 30 atoms. We measure the dynamics of the excitation for various strengths of the interactions between atoms. We compare the data with numerical simulations of this many-body system and found excellent agreement for some of the configurations.

This good control of an ensemble of interacting Rydberg atoms thus demonstrates a new promising platform for quantum simulation using neutral atoms, which is complementary to the other platforms based on ions, magnetic atoms or dipolar molecules.

State transfer in small spin chains

Artem Volosniev (TU Darmstadt)

"How a quantum state can be transmitted?" is the question that arises in one's mind when one thinks, for example, about quantum computing, see, e.g., Ref.~[1,2]. We study this problem in a Heisenberg spin-chain Hamiltonian [3,4], and show that if one is given the opportunity to tune the spin-spin interactions, then one can design chains that enjoy perfect state transfer. We illustrate this statement by analyzing dynamics in a simple yet non-trivial four-body system. We also discuss a possible proof-of-concept realization of this system with a one-dimensional gas of strongly-interacting cold atoms, in which the effective spin-spin interactions are determined by the shape of the trapping potential.

Coherently coupled Bose gases: from many- to few-body physics

Alessio Recati (University of Trento)

In this talk I review some basic concepts of zero temperature coherently driven Bose gases and I present some recent developments. In particular: (i) the possibility of string breaking and pair vortex creation at the mean-field level is reported; (ii) the beyond mean-field corrections (Belyaev and LHY) are presented with emphasis on symmetry breaking and few-body physics; (iii) in the last part the effect of a deep optical lattice on the ferromagnetic phase transition and on the two-body spectrum is discussed.

Impurities strongly interacting with a Fermi sea

Rudolf Grimm (IQOQI Innsbruck, Austrian Academy of Science, Innsbruck, Austria)

Impurity atoms immersed in a Fermi sea show a wealth of exciting phenomena when the interaction is tuned via a Feshbach resonance. We report on experiments with fermionic or bosonic potassium atoms in a large, deeply degenerate Fermi sea of Li-6. In the case of fermionic impurities (K-40), we focus on the low-concentration limit and apply a Ramsey technique to study the fast response of the impurities to sudden changes of the interaction strength [Cetina et al., Science 354, 96 (2016)]. For near-resonant conditions, we observe the formation dynamics of quasiparticles (Fermi polarons) in real time and, in the resonance case, an interference between the repulsive and the attractive quasiparticle branch. For bosons (K-41) in the Fermi sea, a small condensate is formed, which then acts as a mesoscopic impurity. For strongly repulsive conditions we find phase separation, such that the condensate is in the center of the Fermi sea and compressed by the fermion pressure. We show that three-body recombination can be used for probing the spatial overlap at the interface between the two species. We also study collective modes of the BEC in the Fermi gas across the transition to the phase-separated state, demonstrating dramatic changes of the collective mode frequencies.

Poster Presentations

Probing a Quantum Gas: Species-Selective Manipulation of Impurities using Multiple Radiofrequency Dressed Potentials

Adam Barker, University of Oxford

(Bentine, Elliot; Harte, Tiffany; Luksch, Kathrin; Mur-Petit, Jordi; Yuen, Ben; Foot, Christopher)

Ultracold atoms can be magnetically-confined by adiabatic potentials formed by radio-frequency (RF) dressing of the atomic energy eigenstates. Extending this approach to multiple frequencies can generate versatile trapping surfaces, such as a double-well potential. We will investigate the dynamics of a Bose-Einstein condensate (BEC) using a second atomic species as an impurity probe. This approach relies on the ability to manipulate both species independently, which can be achieved using several dressing frequencies. This creates trapping surfaces which are specific to the Lande gF-factor of each species, such as a double-well for impurity atoms (Rb-85), which can be immersed in a single-well trapped BEC (Rb-87) [1]. Tunnelling of impurity atoms across the double-well can be correlated to excitations within the BEC, which permits non-destructive probing of condensate dynamics [2]. Resolving small numbers of impurity atoms will be achieved using fluorescence imaging in a near-detuned optical lattice. An optical dipole trap sculpted by a 2D acousto-optic deflector provides further engineering of the trapping potentials, allowing additional control over the geometry and dimensionality of the trapped gases. [1] E.Bentine, T.L. Harte, K. Luksch, A. Barker, J. Mur-Petit, B. Yuen and C. J. Foot, arXiv: 1701:05819 (2017); [2] D. Hangleiter, M. T. Mitchison, T. H. Johnson, M. Bruderer, M. B. Plenio, D. Jaksch, Phys. Rev. A 91, 013611 (2015)

A path-integral approach to composite, rotating impurities

Giacomo Bighin, Institute of Science and Technology Austria

(Lemeshko, Mikhail)

The study of composite, rotating impurities interacting with a quantum many-body environment is extremely important for the description of several experimental settings: cold molecules in a Bose-Einstein condensate or embedded in helium nanodroplets, electronic excitations in a BEC or in a solid. In all these cases the vibrational and rotational degrees of freedom create an involved energy level structure, with a continuous exchange of angular momentum with the surrounding environment.

The recently-introduced angulon quasiparticle [1-2] formalizes the concept of a composite, rotating impurity interacting with a bosonic environment and greatly simplifies the many-body problem by reformulating it in terms of quasiparticles. Very recently a strong evidence was provided that molecules embedded in superfluid helium nanodroplets form angulons [3].

Nonetheless, current state-of-the-art theories of angular momentum redistribution in many-body environment rely on a perturbative expansion, valid either in the weak- or in the strong-coupling regime. We introduce an alternative approach to the angulon problem making use of the path integral formalism, extending Feynman's treatment for the polaron to the case of composite impurity. A clear advantage is that the bath degrees of freedom and the interaction can be integrated out exactly, resulting in an effective, single-particle description for the angulon in which the many-body character of the original problem is encoded in an interaction term. This alternative, effective treatment for the angulon is, in principle, valid at arbitrary coupling and at arbitrary temperature. The results obtained will be compared with existing state-of-the-art theories for composite impurities and with experimental data from the rotational spectrum of molecules embedded in helium nanodroplets.

References:

[1] R. Schmidt and M. Lemeshko, Phys. Rev. Lett. 114, 203001 (2015).

[2] R. Schmidt and M. Lemeshko, Phys. Rev. X 6, 011012 (2016).

[3] M. Lemeshko, Phys. Rev. Lett., in press (2017), arXiv:1610.01604

Mixed dimensional Bose-Fermi systems

Georg Bruun, Aarhus University, Physics and Astronomy

(Wu, Zhigang; Chevy, Frederic; Suchet, Daniel)

We present a mixed dimensional atomic gas system to unambiguously detect and systematically probe mediated interactions. In our scheme, fermionic atoms are confined in two parallel planes and interact via exchange of elementary excitations in a background of three-dimensional BEC. This interaction gives rise to a frequency shift of the out-of-phase dipole oscillations of the two clouds, which we calculate using a a strong coupling theory. The shift is shown to be easily measurable for strong interactions.

We then show how the mediated interaction interaction between fermions within the same plane gives rise to topological pairing. The pairing is analysed with retardation effects fully taken into account. This is further combined with Berezinskii-Kosterlitz-Thouless (BKT) theory to obtain reliable results for the superfluid critical temperature. We show that both the strength and the range of the induced interaction can be tuned experimentally, which can be used to make the critical temperature approach the maximum value allowed by general BKT theory. Moreover, this is achieved while keeping the Fermi-Bose interaction weak so that three-body losses are small. Our results show that realising a topological superfluid with atomic Fermi-Bose mixtures is within experimental reach.

Fermi polarons in transition metal dichalcogenide monolayers

Ovidiu Cotlet, EHT Zurich

(Demler, Eugene; Imamoglu, Atac)

We present a theoretical study of Fermi polaron polaritons in monolayer transition metal dichalcogenides [1].

Lately, the Fermi polaron has received considerable attention in cold atom systems, where it results from the interaction of an impurity with a fermionic bath. We show that a similar theoretical framework can be used to understand the interaction of excitons with conduction band electrons in transition metal dichalcogenides monolayers. We show that, by embedding the monolayer into a cavity, the emerging quasi particles, which we call Fermi polaron polaritons, can also be understood using the tools developed for understanding Fermi polarons in cold atoms. Truncating the Hilbert space to a single electron hole pair, the many-body problem can be solved analytically and the theoretical predictions agree quantitatively with the experimental results.

In contrast to cold atom experiments, in this solid state realization, we have access to both absorption and emission data, which reveal complimentary information about the many body physics. In absorption, the experimental data can be understood by treating the total momentum as an integral of motion. However, in emission, the system first relaxes to the lowest energy energy state (which, at large Fermi energies, is at a finite momentum) and then it can decay through radiative recombination.

Using a Chevy ansatz, we also investigate the response of the Fermi polaron polariton to an external low frequency electric field. Although this quasi particle is charge neutral we show that one can associate to it an effective charge. This is because the hole in the Fermi sea, which has a positive charge, has a negative mass: therefore it will move in the same direction as the electron under the influence of the electric field. We also analyze the effect of disorder on this quasi particle. An interesting question is to what extent the ultra small mass of polaron polaritons influence transport properties.

[1] M. Sidler, et. al. Nat. Phys. 2016, doi:10.1038/nphys3949

Spin Localization of a Fermi Polaron in a Quasirandom Optical Lattice

Callum Duncan, Heriot-Watt University

(Loft, Niels J S; Öhberg, Patrik; Zinner, Nikolaj T; Valiente, Manuel)

Recently, the topics of many-body localization (MBL) and one-dimensional strongly interacting few-body systems have received a lot of interest. These two topics have been largely developed separately. However, the generality of the latter as far as external potentials are concerned - including random and quasirandom potentials - and their shared spatial dimensionality, makes it an interesting way of dealing with MBL in the strongly interacting regime. Utilising tools developed for few-body systems we look to gain insight into the localization properties of the spin in a Fermi gas with strong interactions. We observe a delocalized–localized transition over a range of fillings of a quasirandom lattice. We find this transition to be of a different nature for low and high fillings, due to the diluteness of the system for low fillings.

Virial expansion coefficients in two-component unitary Fermi and Bose gases

Shimpei Endo, Monash University, School of Physics & Astronomy

(Castin, Yvan)

Equation of states of the unitary gases has been studied actively and measured precisely in recent cold-atom experiments . While various many-body theories have been applied to understand these strongly correlated many-body systems, one can also challenge them from a few-body approach. One prime example is the virial exlansion, which provides us with accurate thermodynacs at high temperature. Indeed, coefficients in the virial expansion can be obtained once we have accurate few-body solutions. By exactly solving 3-body and 4-body problems, we calculate 3rd and 4th virial coefficients of the unitary Fermi gases at equal masses based on a contour integral method. Our results are in good agreement with those observed in cold atom experiments and other theoretical studies. The contour integral method can also be applied to systems where the Efimov effect occurs. We calculate 3rd virial expansion coefficients for both two-component unitary Fermi and Bose gases for variable mass ratios and three-body parameters.

Towards the determination of Bose polaron properties at non-zero temperatures

Nils Günther, Icfo Institute of photonic sciences

(Massignan, Pietro; Tarruell, Leticia; Lewenstein, Maciej; Bruun, Georg)

In the framework of Many-Body Field Theory, an extended ladder approximation is used to compute the self energy of the Bose polaron, a single impurity interacting with a dilute Bose-Einstein Condensate (BEC) by means of a broad interspecies Feshbach resonance. At zero temperature, we compute the ground state energy, the effective mass, the residue and the contact of the polaron all across the resonance. We also present our preliminary results towards the determination of the self-energy at non-zero temperature. We expect that the polaron properties will display non trivial and in particular a non monotonic temperature dependence, because the temperature enters the calculation not only through the occupation number of the ground state, but also in the speed of sound of the elementary excitations of the BEC.

A quantum gas of fermionic ytterbium-173 with tunable interaction

Moritz Höfer, Max-Planck-Institut für Quantenoptik

(Riegger, Luis; Darkwah Oppong, Nelson; Bloch, Immanuel; Fölling, Simon)

The alkaline-earth-like element ytterbium features a strong decoupling between the nuclear and the electronic spin degree of freedom as well as a metastable excited state. Owing to the vanishing angular momentum in both the ^{1}S$_0$ ground state and ^{3}P$_0$ metastable state, no magnetic Feshbach resonances are expected. The interaction between these two orbitals can be described by a coupled two-channel model. The isotope ^{173}Yb exhibits a shallow bound state below the continuum in one of the two interorbital interaction channels, causing a Feshbach resonance between the two orbitals. We demonstrate the tunability of the interorbital scattering length by cross-thermalization measurements. The two- and many-body interactions are probed by high-resolution clock-line spectroscopy in a three-dimensional lattice as well as in the quasi-2D regime. Furthermore, the different AC polarizabilities of both orbitals allow for the creation of state-dependent (nuclear spin-independent) optical potentials. A state-dependent lattice represents the building block for the implementation of the two-orbital Kondo-lattice model. In this regime of mixed confinement, we spectroscopically explore the interorbital interaction.

Probing mesoscopic transport with cold atoms

Dominik Husmann, ETH Zürich

(Lebrat, Martin; Häusler, Samuel; Krinner, Sebastian; Brantut, Jean-Philippe; Corman, Laura; Esslinger, Tilman)

Quantum point contacts (QPCs) featuring quantization of conductance are fundamental components for mesoscopic nanostructures. Here we study the evolution of quantized conductance with interaction strength across the BEC-BCS crossover in ultracold fermions. Our system is a two-terminal setup of two Lithium 6 clouds in the two different hyperfine states, connected by an optically tailored QPC. To measure spin and particle conductance we can impose independently a spin or particle imbalance between the reservoirs, creating a restoring drive. With increasing attractive interactions we find a plateau in the particle conductance at values larger than the expected quantum of $1/h$. Subsequently we observe an onset of superfluidity manifested in a rapid increase of the conductance with density. The presence of a superfluid gap causes a suppression of spin excitations, which we see in a non-monotonous behaviour in spin conductance measurements as a function of density in the QPC.

Extending previous experiments, we use a digital mirror device (DMD) to project holographically shaped optical potentials onto a quantum wire. This allows us to retrieve spatially resolved information about the response of the conductance to local perturbations, a technique called scanning gate microscopy and widely known in solid state physics. The fine control of the DMD laser beam can be extended to project more complex structures: by projecting several consecutive repulsive barriers, a lattice can be formed inside the quantum wire, one lattice site at a time. Upon scaling up the number of sites, we observe the emergence of a band gap, originating from quantum interferences among the scatterers.

Complementary to creating particle and spin bias, we can also apply a temperature gradient between the reservoirs. The thermoelectric response of the system is an interplay between QPC and reservoir contributions. The high tunability of our system opens up a wide parameter range to study thermoeletricity through a QPC.

Inelastic collisions and finite-range interactions in quasi-one-dimensional traps

Krzysztof Jachymski, University of Stuttgart, Institute for Theoretical Physics III

(Drews, Bjorn; Deiss, Markus; Idziaszek, Zbigniew; Hecker Denschlag, Johannes; Veksler, Hagar; Julienne, Paul; Fishman, Shmuel)

Exploring inelastic and reactive collisions on the quantum level is the main goal of the developing field of ultracold chemistry. We present experimental and theoretical study of inelastic collisions of metastable ultracold triplet Rb_2 molecules confined in a quasi-one-dimensioanl trap. As anticipated theoretically, the measured decay rate constants vary considerably when confinement and collision energy are changed. [1]

In the second part [2] we discuss the corrections to effective one-dimensional pseudopotential which arise when the finite range of the interactions is taken into account. We show that the dynamics of the system can be described using generalized Lieb-Liniger model with multiple interaction terms. In the dilute limit this reduces to standard Lieb-Liniger Hamiltonian with single delta function interaction, but with effective interaction strength which can be vastly different from the zero-range approximation.

[1] B.Drews, M. Deiss, K. Jachymski, Z. Idziaszek, J. Hecker Denschlag, Nature Communications, in press

[2] K. Jachymski, H. Veksler, P. S. Julienne, S. Fishman, in preparation

Einstein-Podolsky-Rosen entanglement in spinor Bose-Einstein condensates

Carsten Klempt,

In 1935, Einstein, Podolsky and Rosen (EPR) questioned the completeness of quantum mechanics by devising a quantum state of two massive particles with maximally correlated positions and momenta. The EPR criterion [1] qualifies such continuous-variable entangled states, where a measurement of one subsystem seemingly allows for a prediction of the second subsystem with a precision beyond the Heisenberg uncertainty principle. We have created an EPR-correlated two-mode squeezed state in an atomic Bose-Einstein condensate [2]. The state shows an EPR entanglement parameter of 0.18(3), which is 2.4 s.d. below the threshold 1/4 of the EPR criterion. The data can be analyzed to obtain a full tomographic reconstruction of the underlying many-particle quantum state.

Finally, we show that the created state is useful for atom interferometry and demonstrate the operation of a prototypical atomic clock beyond the Standard Quantum Limit (SQL) [3]. The novel clock configuration surpasses the SQL by squeezing the vacuum in an empty input mode. The improvement of atom interferometers with squeezed vacuum offers exciting advantages which are also exploited in squeezed-vacuum optical interferometers, as they are developed for the detection of gravitational waves.

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Finite range effects in three-body physics

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Three-body Efimov physics is relevant for the understanding of both dynamics and stability of ultracold gases. Efimov predicted the existence of an infinite sequence of three-body bound states, of which many properties scale universally, at diverging scattering length for a zero-range interaction potential. Experiments with ultracold atoms in which the scattering length is tuned through Feshbach resonances have also shown that the three-body parameter is universally linked to the finite-range of the two-body interaction potential. For small scattering lengths non-universal features appear in the Efimov spectrum, which are also linked to the finite-range nature of the interactions. We investigate these effects with a momentum-space model based on a non-separable finite-range potential that is closely related to a realistic position-space finite range potential. This model contains off-the-energy-shell two-body scattering processes, which we generalize to include off-shell Feshbach resonance coupling.

BEC of 41 K in a Fermi Sea of 6 Li

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(Lous, Rianne S.); Fritsche, Isabella; Jag, Michael; Kirilov, Emil; Huang, Bo; Grimm, Rudolf)

We report on the production of a double-degenerate Fermi-Bose mixture of 6 Li and 41 K. In our experimental sequence the potassium atoms are sympathetically cooled by the lithium atoms, which are evaporatively cooled in an optical dipole trap. We obtain ten to the four 41 K atoms with a BEC fraction close to 1 and a T over TF of about 0.05 with ten to the five 6 Li atoms in each spin state. To measure the temperature of our fermionic sample we use the 41 K BEC as a tool for thermometry. As the system is in thermal equilibrium we evaluate the condensed fraction of our 41 K atoms and extract the temperature of the atoms. To investigate the properties of the 6 Li - 41 K mixture near the inter-species Feshbach resonance at 335.8 G we use another scheme of evaporation around 300 G which enables us to achieve similar temperatures. We explore both the repulsive side and attractive side of the Feshbach resonance and observe phase separation for strong repulsive interactions and collapse for attractive interactions. This work is supported by the Austrian Science Fund FWF within the SFB FoQuS.

Phase Separation in a Fermi-Bose Mixture of 6-Li and 41-K

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(Huang, Bo; Fritsche, Isabella; Lehmann, Fabian; Jag, Michael; Kirilov, Emil; Grimm, Rudolf)

We report on the observation of phase separation between a 41-K Bose-Einstein condensate (BEC) and a 6-Li Fermi sea with strong repulsive interspecies interactions. After evaporation in an optical dipole trap, we obtain a BEC of 10^4 41-K atoms and a Fermi sea of 10^5 6-Li atoms with T/TF< 0.07. We explore this double-degenerate mixture by tuning the heternonuclear interaction with the help of a Feshbach resonance at 335.08 G. We use three-body recombination as a probe to study the overlap between the two species for various interaction strengths. We see a decrease in losses when the interactions become strongly repulsive and compare the loss rate to that of a non-condensed bosonic cloud. In a phase-separated mixture, losses only happen at the interface of the two species and are therefore reduced, when compared to a mixed phase of both species. To understand our loss rate results, we calculate the spatial overlap between the two components with a mean-field model. This model fits nicely to our experimental results and reveals effects beyond the local density approximation (LDA). This work is supported by the Austrian Science Fund FWF within the collaborative research grant FoQuS.

Interaction between Bose polarons: from Yukawa to Efimov

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Impurities immersed in a Bose-Einstein condensate form Bose polarons. The polarons can interact with each other through an interaction that is mediated by the Bose-Einstein condensate. For a weak boson-impurity interaction, this mediated interaction is known to be a weak Yukawa attraction. For a resonant boson-impurity, it turns into a strong Efimov attraction involving a single boson as the mediator. In this study, I look into this interesting crossover which bridges few to many-body physics.

A novel Lithium-Chromium Fermi-Fermi mixture

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(Trenkwalder, Andreas; Cosco, Antonio; Jag, Michael; Inguscio, Massimo; Zaccanti, Matteo)

Superfluidity and ferromagnetism represent two major although antithetic manifestations of strong interaction among fermionic particles: superfluidity requires interparticle attraction which in turn leads to pairing, while strong repulsion is required for ferromagnetic correlations to develop.

PoLiChroM aims to explore these two opposite regimes exploiting a novel Fermi-Fermi mixture of Cr-53 and Li-6 ultracold atoms. Our system will allow for the first time a resonant control of 3-body, and possibly 4-body, elastic interactions on top of the standard 2-body ones, thanks to non-Efimovian Cr-Cr-Li trimer and Cr-Cr-Cr-Li tetramer states close to the atomic scattering threshold. On the one hand these few-body properties are expected to greatly enhance the possibility to access exotic superfluid phases within the attractive interaction regime. On the other, the mixture is predicted to feature an unprecedented stability against 3-body recombination into molecular states in the strongly repulsive regime.

Here we present the actual status of the experimental setup of PoLiChroM, and we discuss our strategies to attain quantum degeneracy of Lithium-Chromium Fermi mixtures.

Properties of strongly dipolar Bose gases beyond the Born approximation

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(Jachymski, Krzysztof)

Strongly dipolar Bose gases can form liquid droplets stabilized by quantum fluctuations. In a theoretical description of this phenomenon, the low-energy scattering amplitude is utilized as an effective potential. We show that for magnetic atoms, corrections with respect to the Born approximation arise, and we derive a modified pseudopotential using a realistic interaction model. We discuss the resulting changes in collective mode frequencies and droplet stability diagrams. Our results are relevant to recent experiments with erbium and dysprosium atoms.

Single-atom edgelike states via quantum interference

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(Polo, Juan; Turpin, Alejandro; Lewenstein, Maciej; Mompart, Jordi; Ahufinger, Verònica)

Recent theoretical and experimental studies have shown that it is possible to simulate artificial magnetic fields with ultracold atoms in optical lattices [1]. In particular, the possibility to implement chiral, topologically protected edge states analogous to those found in the context of quantum Hall physics has been demonstrated [2].

In this work we propose an alternative strategy to implement robust edgelike states (ELS) in optical ribbons, which we model by regarding each of the sites a 2D harmonic trap of equal frequency, with a single atom carrying l = 0 or l = 1 orbital angular momentum (OAM) units. First, we consider a system of three in-line sites governed by tunneling dynamics, which can be described by a few-state model. We show that in this system quantum interference effects give rise to spatial dark states (SDS), i.e., states in which one site remains unpopulated along the time evolution. Then, we show that by using the SDS as basic building blocks, global ELS can be created in arbitrarily large ribbons. These ELS are very robust against defects in the ribbon and perturbations in the phase differences between the local eigenstates of the sites required to have quantum interference [3].

For the l = 0 case, the tunneling amplitudes between sites are always real and interference effects are solely induced by phase differences between the populated sites. This fact allows one to create ELS within this manifold and switch between them in a very straightforward manner by applying laser pulses, as shown in the left panel of figure 1, opening the possibility to implement similar ELS in more complex geometries.

For the l = 1 case, the few-state description is richer because the tunneling amplitudes depend both on the spatial localization and the winding number of the local states, and they may become complex depending on the relative position of the sites [4]. The ELS implemented in this manifold can display global chirality, as shown in the right panel of figure 1. Another interesting possibility that this manifold offers is to simulate an extra dimension by regarding the winding number as a synthetic dimension.

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Crossover from a dipolar Bose-Einstein-Condensate to a Macrodroplet

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Dipolar quantum gases offer an ideal playground for investigating the many-body phase diagram in the presence of contact and dipole-dipole interaction. By using a Feshbach resonance in combination with the trap geometry, one can experimentally tune the total interaction from repulsive to attractive. Recent experimental and theoretical observations suggested a dominant role of quantum fluctuations, when the total interaction is sligthly attractive. This beyond mean-field effect leads to the emergence of an unexpected phase transition [1,2,3,4] and a, so far not investigated, crossover region. In our experiment, we use strongly magnetic bosonic erbium in a cigar-shaped trap and discover a crossover region from a dilute Bose-Einstein condensate to a liquid-like macrodroplet, stabilized against collapse by quantum fluctuations. By combining our precise knowledge of the s-wave scattering length with studies of collective excitations and expansion dynamics, we are able to compare our measurements to a parameter-free theory including quantum fluctuations and find very good agreement [5].

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Realization of a dual-species MOT for dysprosium and potassium

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(Tzanova, S.; Kreyer, M.; Soave, E.; Werlberger, A.; Corre, V.; Kirilov, E.; Grimm, R.)

We report on the first realization of a dual-species magneto-optical trap that combines strongly magnetic lanthanide atoms (Dy) with analkali species (K). Advanced cooling techniques in the form of narrow-line laser cooling and grey-molasses cooling give us favorable starting conditions to reach quantum degeneracy. With fermionic and bosonic isotopes of both species, our system offers a great wealth of isotopic mixtures. We are particularly interested in new Fermi-Fermi mixtures. These are expected to exhibit exotic quantum phases and novel pairing mechanisms, including for example mass-imbalanced pairing or a fermionic superfluid with a Fermi surface modified by the dipolar interactions.

Repulsive Fermi polarons in a mass-balanced spin mixture at a broad Feshbach resonance

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Understanding the properties of impurities immersed in a degenerate quantum medium represents a fundamental problem in many-body physics. In particular, the Fermi polaron problem and the associated repulsive quasiparticle are centrally important for describing and realizing many-body states arising from repulsive interactions. We employ radio-frequency spectroscopy to investigate spin mixtures of ultracold Li-6 atoms with tunable polarization in the vicinity of a broad Feshbach resonance. At high spin-imbalance, we report on the observation of well-defined coherent quasiparticles up to unitarity-limited interactions [1]. We characterize the many-body system by extracting the key elastic and inelastic properties of repulsive Fermi polarons: the energy E+, the effective mass m*, the residue Z and the decay rate Γ. Above a critical interaction, we find E+ to exceed the Fermi energy of the bath, while m* diverges and even turns negative, revealing an energetic and thermodynamic instability of the repulsive Fermi liquid. Motivated by these findings, in ongoing experiments we investigate the evolution of the interaction energy and of spin correlations in a balanced spin mixture after a rapid radio-frequency transfer to the strongly repulsive regime.

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Super Efimov trimers in a quasi-two-dimensional trap

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The recently proposed super Efimov physics for identical fermions in two dimension is a fascinating few-body effect which is closely related to the well-known Efimov effect in three dimension. Since the Efimov state is first observed experimentally in ultracold atomic gases, it is natural to seek the super Efimov states in two dimensional quantum gases. While in real cold atom experiments, all the systems are actually quasi-two-dimensional. We calculated the spectrum of three identical fermions near a p-wave Feschbach resonance in a quasi-two-dimensional trap and investigate how the spectrum evolves from the three-dimensional limit to the two-dimenaional limit.

Method of solving Schroedinger equation for a single atom interacting with N ions within a contact potential approximation

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(Wasak, Tomasz; Jachymski, Krzysztof; Idziaszek, Zbigniew)

The many-body atomic quantum degenerate gases offer an important platform for simulating condensed matter systems. What is more, these systems combined in hybrid setups involving both atoms and ions lead to new phenomena, which might find applications in quantum sensing, metrology, or engineering exotic states of matter. The tenability of the properties of such systems is directly related to the interactions between atoms and impurity ions appearing on the single particle scale. In order to develop a complete description of these systems, it is essential to understand the states of a single atom in the presence of many ions. Here, we present a general theory of solving the Schroedinger equation for a single atom interacting in the s-wave regime with N stationary impurities. The method is based on expanding the wavefunction using Green function for an atom without taking into account the presence of other particles. A fundamental object in our approach is an N-dimensional square matrix that is expressed analytically in terms of Green function. We show that the energies of the stationary states are given by the roots of its determinant, whereas the wavefunctions are obtained from its kernel. In addition, the method can be applied to different geometries, configurations, and species of impurities. As an example, we present the results for a system consisting of a single harmonically trapped atom interacting with two ions. In conclusion, our approach provides a starting point to develop a many-body theory of solving time-dependent problems including more than one atom. Furthermore, it also gives a chance to investigate ionic crystals with the motion of ions and interactions with phonons taken into account. Another possible application is the simulation of solid state systems with tunable electron-phonon couplings.

High-temperature virial expansion and Efimov physics in bose polarons

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We introduce a general Feynman diagrammatic method for the high-temperature virial expansion of interacting particles. The method is valid for both fermions and bosons. We adopt it to calculate spectral functions of bose polarons interacting via a zero range potential. By including all three-body correlations (of order z^2, with z being the fugacity), we show that there exist two scenarios generally. While Efimov physics is hardly visible in spectral functions for common mass ratios between the impurity and the boson (e.g., 39K(i)-39K(b)), it is clearly distinguishable for large mass ratios (e.g., 6Li(i)-133Cs(b)). Our results supply a new way to study Efimov physics and they can be directly detected by using radio-frequency spectroscopy in experiments.

Description of dipole-dipole scattering within quantum defect theory

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Recent development in the control over magnetic atoms resulted in the production of dipolar Bose-Einstein condensates. Strong interactions between the dipoles in these systems are responsible for the beyond mean-field effects, such as the existence of droplets in the regime where the usual mean-field treatment predicts collapse of the atomic cloud. The theoretical treatment of the interactions between atoms relies on the Born approximation, which is supposed to be valid if the dipolar interaction is not too strong.

Therefore, it is important to understand properly the scattering properties of the colliding particles also for large dipole moments. Using quantum defect theory, we have calculated the properties of the collision process for different energies, dipole strengths, and reactivity. The results might be useful in understanding the collisions between polar molecules with very large permanent dipole moments.

Topological superfluid in a mix dimensional Fermi-Bose mixture

Zhigang Wu,

(Wu, Zhigang; Bruun, Georg)

We show that a two-dimensional (2D) spin-polarised Fermi gas immersed in a 3D Bose-Einstein condensate (BEC) constitutes a very promising system to realise a p_x+ip_y superfluid. The fermions attract each other via an induced interaction mediated by the bosons, and the resulting pairing is analysed with retardation effects fully taken into account. This is further combined with Berezinskii-Kosterlitz-Thouless (BKT) theory to obtain reliable results for the superfluid critical temperature. We show that both the strength and the range of the induced interaction can be tuned experimentally, which can be used to make the critical temperature approach the maximum value allowed by general BKT theory. Moreover, this is achieved while keeping the Fermi-Bose interaction weak so that three-body losses are small.

Universal Properties in a Fermi Gas with a Resonant p-Wave Interaction

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It has been known that, in the BCS-BEC crossover regime, the short- and long-distance physics are governed by universal laws, which are called the Tan relations; the short-range correlations obey universal power laws, and a single quantity, Tan's contact, gives both their coefficients and thermodynamic information of the gas. They hold quite generally in resonant atomic gases, including those in the strongly correlated regime, as long as the interaction is of the s-wave type.

Recently, such universal properties have been theoretically investigated in a Fermi gas with a resonant p-wave interaction [1, 2]. Also, an experimental evidence of the universal power-laws in a p-wave gas has been reported [3]. An essential difference between s-wave and p-wave interactions is that the latter can be anisotropic. In the presence of a magnetic field, the Feshbach resonance has only the axial symmetry around the magnetic field direction.

Here, we discuss the universal relations of the p-wave Fermi gas and their rotational properties. We show that the momentum distribution has a high-momentum tail, which decays in inverse proportion to k to the second power. We define its coefficient as the p-wave contact tensor. The p-wave contact tensor also has a direct relation to the thermodynamics through the adiabatic sweep theorem. In formulating the theorem, we generalize the p-wave scattering volume to scattering processes in which the angular-momentum changes. In contrast to the previous studies, it has nine components, which transform as $3\otimes 3$ representation of SO(3). That the p-wave contact is a tensor means that the short-distance correlation may not have the axial symmetry which the p-wave Feshbach resonance possesses. This is in stark contrast to the s-wave case in which the short-distance correlation is always isotropic, as predicted by the Tan relations. We discuss two examples, the anisotropic p-wave superfluid and a Fermi gas in an anisotropic trap, in which the axial symmetry is broken spontaneously and externally, respectively. We show that, in these cases, the axially asymmetric components of the p-wave contact tensor actually obtain finite values, which signal the breaking of the axial symmetry in the short-range correlation. We finally discuss possible experimental tests of our results and a direct measurement scheme of the p-wave contact tensor using Raman processes.

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Towards creating Bose Polarons in an ultracold Li-Cs Mixture with a large Mass Ratio

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In our experiment we are working towards the creation of a Bose polaron in an ultracold Bose-Fermi mixture of 133Cs and 6Li atoms with a large mass imbalance. The Bose polaron is a quasiparticle that describes a single Li impurity which is immersed into a Cs BEC. By applying a radiofrequency pulse we want to quench the impurity from a non-interacting state into an interacting state. As the fermionic Li can couple to the phonon excitations of the BEC, this scenario is similar to the Fröhlich polaron problem from condensed matter physics. Via Li-Cs Feshbach resonances we can tune the interparticle interaction strength and change the sign of interaction, thus enabling us to investigate both attractive and repulsive polarons. We describe the creation of a Cs BEC by means of evaporative cooling in an optical dipole trap, after the atoms have been brought to a temperature of around 1 µK in previous cooling stages. In order to reach a high phase-space density we modify our trapping potential by adding a second dipole trap with a smaller waist and applying two consecutive evaporation steps. Furthermore, we give an overview of our plans to characterize the Bose polaron by means of radiofrequency spectroscopy and to study its dynamics.