Abstracts of the posters
Quantum simulation offers the long-standing goal of using a quantum system to face questions that are hard to understand classically. While full-fledged quantum computers may be built in the distant future, the next generations will be limited in size and by the presence of errors [1]. An alternative way to address quantum many-body problems is analog quantum simulation, where a highly controllable quantum system mimics the interactions of the Hamiltonian one wants to investigate. In fact, analog quantum simulators based on atoms in optical lattices [2] have already performed some simulations of condensed matter physics problems that are out of reach of classical computers [3, 4]. All those problems are based on local or short-range interactions, and are ideally suited for the existing simulators. Problems in quantum chemistry, in contrast, require long-range Coulomb interactions, and thus, it is harder to realize whether analog simulation can help in that field.

Here, we propose an experimental setup to solve quantum chemistry problems using cold atoms trapped in state-dependent optical lattices. In the same way that virtual photons mediate electronic interactions in nature, Coulomb interactions are induced by a spin excitation in a Mott insulator with the same spacing as the fermionic lattice. We discuss the main sources of systematic deviations rising from the discretization of the Hilbert space and illustrate this method solving the molecular potential for a molecule of Hydrogen. While the setup is discrete and finite, we show that precise results can be obtained for simple real molecules with moderate lattice sizes, and that it can be scaled. Apart from the standard advantages of analog simulation over quantum computing regarding the required degree of control, the present scheme does not rely on a judicious choice of molecular orbitals, but rather directly operates in real space [5].


Vortices in dipolar Bose-Einstein condensates

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Effects of dipole-dipole interaction can significantly modify properties of Bose-Einstein condensates, as demonstrated in the recent experiment [1], where the Rosensweig instability was observed in a quantum ferrofluid of a strongly dipolar BEC, leading to a formation of atomic droplets. Here we extend previous theoretical description of such a system that takes into account only correction of the ground-state energy [2, 3], and develop a full Bogoliubov-Popov theory, which also accounts for the condensate depletion. Using this approach, we study the generation of vortices and their properties in strongly dipolar $^{164}$Dy BEC, in particular the dependence of the critical velocity of a moving obstacle to shed vortex dipoles. We also use extensive numerical simulations to consider if quantum droplets [1] can emerge in fast rotating BECs.

![Fig. 1: Droplet formation in fast rotating dipolar BEC after a contact interaction quench.](image)


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Poster 3

Interaction Induced Topological Superconductivity in a Dipolar Spin Lattice

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We study the elementary characteristics of turbulence in a quantum ferrofluid through the context of a dipolar Bose gas condensing from a highly non-equilibrium thermal state. Our simulations reveal that the dipolar interactions drive the emergence of polarized turbulence and density corrugations. The superfluid vortex lines and density fluctuations adopt a columnar or stratified configuration, depending on the sign of the dipolar interactions. When the interactions are dominantly dipolar, coherent vortex structures are formed, and quasi-classical quantum turbulence emerges through the quench. This system poses exciting prospects for realizing stratified quantum turbulence and new levels of generating and controlling turbulence using magnetic fields.
2D Fermionic Dipoles at T = 0

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We analyse the ground state of a two-dimensional quantum system of fermionic dipoles in which all dipoles are polarized along the same direction in space. In our choice the dipole moments have X and Z spatial components. In this work, we use the diffusion Monte Carlo method that allows us to obtain ground state of the many body Schrödinger equation. We predict a phase transition from gas to solid at a critical density \( n_r^2 \sim 50 \), which is five times lower than the one for the equivalent bosonic system. The existence of the stripe phase for high polarization angles is also predicted and occurs at a lower density than in the bosonic case.

The aim of this work is to draw the phase diagram for the fermionic system: the inclusion of Fermi statistics makes the dipolar gas more repulsive, which is reflected in the appearance of structure in the gas phase at lower densities than for the bosonic system (see figure 1). Whereas in the solid phase the inclusion of antisymmetry do not give rise to a relevant change in the energy of the system. The net effect in the gas to solid transition is that the critical density gets dramatically reduce its value: especially, for the isotropic case the transition occurs at \( n_r^2 = 50(10)^3 \), compared to \( n_r^2 = 290(30) \) for the analogous bosonic system. Current work is on the determination of the borders of the stripe phase region of the phase diagram by studying both stability and structural properties.

FIG. 1: Radial distribution function (up), and static structure factor (down) for the isotropic system at a density \( n_r^2 = 16 \) compared for the bosonic and the fermionic system.
Towards lattice spin models with Rydberg-dressed atoms

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Rydberg-dressed atoms provide a versatile platform for engineering lattice spin models of interest for quantum simulation and quantum metrology. In our experiment, cesium atoms will be pinned in a blue-detuned two-dimensional optical lattice with a spacing dynamically variable over 1-5 µm. A 320 nm laser will off-resonantly couple ground-state atoms to \(nP\) Rydberg states with a single photon, enabling highly coherent and tunable interactions. The large interatomic spacings in our lattice and close optical access of our imaging system will facilitate single-spin-resolved imaging. We report progress on this apparatus, which will enable us to study frustrated magnetism, create states with metrological gain, and investigate quantum dynamics in lattices with tunable-range interactions.

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Dipolar quantum droplets and striped states

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The dipolar interaction allows for self-organized structure formation similar to the Rosensweig instability in classical ferrofluids. In our experiments with quantum gases of Dysprosium atoms, we observe a phase-transition between a gas and a liquid, characterized by the formation of self-bound droplets [1]. In contrast to theoretical mean field predictions the superfluid droplets did not collapse. We confirmed experimentally that this unexpected stability is due to beyond mean field quantum corrections of the Lee-Huang-Yang type. These droplets are 100 million times less dense than liquid helium droplets and open new perspectives as a truly isolated quantum system.

Under strong confinement in one dimension, we observe the formation of an array of stripes. We also study striped ground states theoretically and outline prospects to reach a phase coherent supersolid ground state [2].

In a further ongoing experiment we rotate the droplets by a spinning magnetic field and observe that they can be rotated faster than the transverse trapping frequency due to a surface tension counteracting the centrifugal force. We also observe the excitation of a scissors mode of the droplets [3].


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Few-body interactions in a cold Rydberg gas


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A gas of cold Rydberg atoms generally interacts through 2-body van der Waals interaction. When applying an electric field, it has long been observed that resonant dipole-dipole interactions can arise [1]. More recently we have demonstrated the possibility to find resonant processes involving 3 Rydberg atoms [2]. Although this experiment was performed with cesium atoms, we argued that similar 3-body interaction resonances should be observed in other atoms. It has now been observed by us in rubidium [3] with a small controlled number of atoms $i = 2-5$ as can be seen in figure 1.

This not only demonstrated the general nature of the process, but also the absence of signature of the three-body Förster resonances for exactly two interacting Rydberg atoms. As the observed three-body resonance appears at a different dc electric field with respect to the two-body resonance, it represents an effective three-body operator, which can be used to directly control the three-body interactions. This can be especially useful in quantum simulations and quantum information processing with neutral atoms in optical lattices.

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FIG. 1. Stark-tuned Förster resonance in Rb atoms observed for various numbers of atoms N=2-5: (a) atoms are in the initial state $37P_{3/2}(|M_J| = 1/2)$; (b) atoms are in the initial state $37P_{3/2}(|M_J| = 3/2)$. The main peaks are 2-body resonances, the additional peaks are 3-body resonances.

Observation of the roton mode population in a dipolar quantum gas


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In my poster, I will present our experimental observation of the roton mode in a dipolar BEC of strongly magnetic erbium atoms. The roton mode denotes an elementary excitation of minimal energy at finite momentum, similar to the celebrated case of superfluid helium He-II, for which the roton mode was an essential key, brought by Lev Landau in the early 1940’s, to understand the mysterious behavior of the quantum fluid at that time [1]. It was then related by Richard Feynman to the strong correlations, resulting from the strong interactions occurring in the liquid. In contrast to He-II, the roton mode in a dipolar BEC does not require strong interactions, but arises from the long-range and anisotropic nature of the dipolar interactions, already at a mean-field level. First predicted in 2003 [2], it has remained elusive to observation. To investigate the roton mode in our experiment, we perform an interaction quench on an elongated BEC of 166Er atoms and observe the apparition of symmetric side peaks in the momentum distribution of the atomic cloud, when quenched below a threshold scattering length. We have probed the scaling of the momentum and the imaginary energy of the roton mode via a detailed study of the measured density distribution and a comparison with theory predictions from both an analytical model and extensive numerical simulations [3].


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The transport of excitations between pinned particles in many physical systems may be mapped to single-particle models with power-law hopping, $1/r^a$. For randomly spaced particles, these models present an effective peculiar disorder that leads to surprising localization properties. We show that in one-dimensional systems almost all eigenstates (except for a few states close to the ground state) are power-law localized for any value of $a > 0$. Moreover, we show that our model is an example of a new universality class of models with power-law hopping, characterized by a duality between systems with long-range hops ($a < 1$) and short-range hops ($a > 1$) in which the wave function amplitude falls off algebraically with the same power $\gamma$ from the localization center.


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Ground state spectroscopy of ultracold dipolar $^6$Li$^{40}$K molecules

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With the creation of dipolar molecules in their ro-vibrational ground state, a long-standing scientific goal has been achieved. In the ultracold quantum regime such molecules are a promising tool for the quantum simulation of a large class of many body effects and for quantum information processing, ultracold chemistry and metrological applications. In our experiment, we use bosonic heteronuclear dimers of $^6$Li and $^{40}$K. Their deeply-bound ro-vibronic state possess a large permanent electric dipole moment of 3.6 Debye. This makes them a suitable candidate for investigating the plethora of effects originating from the long-range anisotropic dipole interaction.

Here we describe our two-photon spectroscopy scheme that recently enabled us to experimentally identify and address the dipolar ground state of LiK. Our scheme differs from spectroscopic routes previously used for other alkali heteronuclear dimers, as only unperturbed molecular spin singlet states are involved and predominantly only one sole hyperfine state is addressed. As an important consequence this establishes an ideal three level system for the transfer by stimulated rapid adiabatic passage (STIRAP) to a single hyperfine component of the ground state.

We start from a sympathetically cooled, quantum-degenerate Fermi-Fermi mixture, and create weakly-bound $^6$Li-$^{40}$K molecules via magnetic Feshbach association at 215.6 G in an optical dipole trap. We use the asymptotic bound state model (ABM) [1] to calculate the hyperfine composition of the Feshbach state and identify a spin singlet admixture of up to 52%. We then present data from our one-photon spectroscopic survey of the $B^1Π$ and $A^1Σ$ electronically excited states of the LiK* asymptote. A variety of new lines have been found and analyzed for the suitability as intermediate states for the transfer. In particular, we were able to address very deeply bound states of the $A^1Σ$ potential that offer a large overlap with the ground state at this inner turning point. Navigating a path written by the the available laser wavelengths, power and Franck-Condon overlap, we were first able to locate the $v = 3$ state by two-photon spectroscopy and Autler-Townes spectroscopy. Subsequently, the implementation of a new dye laser setup provided the necessary output power.

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and wavelength tuning range for the discovery of the lower vibrational states $v = 2$ and $v = 1$ and eventually $v = 0$ (see Fig.1). We further present our efforts to coherently populate the ground state via STIRAP, and to apply a static electric field to investigate the high ground state dipole moment of the $^6\text{Li}^{40}\text{K}$ molecule.

![Two-photon spectroscopy of the absolute electronic and ro-vibronic ground state ($X^1\Sigma, v = 0$) of LiK.](image)

**FIG. 1:** Two-photon spectroscopy of the absolute electronic and ro-vibronic ground state ($X^1\Sigma, v = 0$) of LiK.

Quantum Fluctuations in Quasi-One-Dimensional Dipolar Bose-Einstein Condensates and Bose-Bose mixtures

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Recent experiments have revealed that beyond-mean-field corrections are much more relevant in weakly-interacting dipolar condensates and mixtures of two different Bosons than in usual non-dipolar single-species systems. We show that in quasi-one-dimensional geometries quantum corrections in dipolar Condensates and Bose-Bose mixtures are strikingly different than in their three-dimensional cases. The energy correction of the condensates presents not only modified density dependencies, but it may even change from attractive to repulsive at a critical density due to the surprising role played by the transversal directions. The anomalous quantum corrections translates into a strongly modified physics for quantum-stabilized droplets.
We present a toolbox for the controlled manipulation of ultracold polar molecules, consisting of detection of molecules, atom-molecule entanglement and engineering dissipative dynamics. Our setup is based on fast chemical reactions between molecules and atoms leading to a quantum zeno based collisional blockade in the system. We discuss the optimization of the relevant parameters as well as the consequences of residual imperfections.
Long range interactions in time lattices

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Time crystals are many-body systems that, due to interactions between particles, are able to spontaneously self-organize their motion in a periodic way in time by analogy with the formation of crystalline structures in space in condensed matter physics.

In solid state physics properties of space crystals are often investigated with the help of external potentials that are spatially periodic and reflect various crystalline structures. Similar approach can be applied for time crystals because periodically driven systems constitute counterparts of spatially periodic systems but in the time domain. Wide class of condensed matter problems can be realized in the time domain if single-particle or many-body systems are resonantly driven. It opens up unexplored territory for investigation of condensed matter physics in time and for invention of novel "time devices" because time is our new ally. We propose [1] a way of creating time lattices similar to optical(space) lattices. In this new type of systems almost any long range interactions can be engineered in effective Hubbard or Bose-Hubbard types of Hamiltonians. This can be achieved by a proper periodic modulation of s-wave scattering length of atoms which are resonantly driven, for example, by a periodically oscillating atomic mirror.


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FIG. 1: Example of a system with exotic interactions: ultra-cold atoms bouncing on a harmonically oscillating mirror in a 1D model (left panel). The 20:1 resonance condition between mirror oscillations frequency and periodically moving atoms is fulfilled and the many-body system is described by the Bose-Hubbard Hamiltonian $\hat{H}_{\text{eff}} = -\frac{J}{2} \sum_{(i,j)} \hat{a}_i \hat{a}_j + \frac{1}{2} \sum_{i,j} U_{ij} \hat{a}_i^{\dagger} \hat{a}_j^{\dagger} \hat{a}_j \hat{a}_i$. In the middle panel we show the interaction coefficients $U_{ij}$ corresponding to the periodically modulated scattering length $g_0(t)$ as presented in the right panel.
Quantum Monte Carlo methods provide a powerful tool for predicting quantitatively the properties of many-body quantum system [1]. At the level of few-body physics, existence of bound-states (trimers, tetramers, etc.) for dipolar molecules in a bilayer is an open and controversial question. Anisotropy of the dipolar interaction (which can be attractive or repulsive) complicates the study but leads to rich physics [2]. The problem of two and three dipolar molecules can be solved analytically, the last one with more effort. However, as the number of dipoles is increased, the problem becomes essentially intractable using standard approaches. At this point Monte Carlo methods become highly competitive. We use Diffusion Monte Carlo method [3] to obtain the ground state energy and spatial distribution function of a bilayer system of dipolar bosons, where dipoles are oriented perpendicularly to the parallel planes. It is known that a dimer exists for arbitrary separation between layers [4]. For three and four dipoles, the bound state does not exist for small separation between the two layers. We find the critical value of the interlayer separation at which the trimer and tetramer appear. For the trimer, we have found that the dominant structure close to the critical separation is halo state, where two dipoles are close to each other while the third is far away. Five- and six-body bound states also exist (work in progress).

Dimensional Crossover for the Beyond-Mean-Field Corrections in the Confined Weakly Interacting Bose Gas

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We investigate the beyond-mean-field corrections in a confined weakly interacting Bose gas at zero temperature. We start our study with a box with periodic boundary conditions. The transverse directions are tightly confined and we show that the system can exhibit three-dimensional as well as quasi-low-dimensional behavior. We are able to express the ground state energy for the 3D-2D and 3D-1D crossover in terms of well known functions. The correct inclusion of the beyond-mean-field terms naturally includes the confinement induced shift of the scattering length and we observe the occurrence of an effective three-body interaction due to quantum fluctuations. With this qualitative understanding in mind, we investigate the crossover in a harmonic trapping potential under the constraint, that the condensate remains in the lowest harmonic oscillator state as we are interested in the effect of the quantum fluctuations. This can be achieved by an additional attractive long-range potential. Then, we are able to give analytic expressions for the ground state energy in the quasi-low-dimensional regime and observe the analogue behavior as in periodic boundary conditions.

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Rydberg physics and quantum-gas microscopy with multi-electron Er and Dy atoms

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In recent years experiments with highly magnetic lanthanoid atoms have attracted great attention due to their rich interaction properties, allowing the study of few- and many-body effects arising from long-range and anisotropic dipole-dipole interactions. Here, we will present the future extensions to our new experimental apparatus for ultracold dipolar mixtures of erbium and dysprosium [1].

Unlike in alkali or alkaline earth metals, lanthanoides, with their complex electronic structure, offer the possibility to excite electrons not only from the 6s-shell but also from the open anisotropic 4f-shell to Rydberg states. Thus, s-, p-, d-, f- or h-Rydberg states can be excited via a simple two-photon excitation scheme. This allows for the investigation of Rydberg-Rydberg or Rydberg-ground state atom interactions for a larger set of parameters. A further noteworthy feature of lanthanoid Rydberg atoms is their optically active core. Since these species have several valence electrons, the core remains optically active even when one of those is excited to a Rydberg level. As a consequence, the Rydberg atom can be optically manipulated, cooled or even trapped.

Finally, novel concepts for quantum-gas microscopy in lanthanoides will be presented. Such schemes have been developed in collaboration with the Greiner group at Harvard University.

The latest results on our ultracold mixtures, including the production of double BECs, will be presented in a second poster "Quantum Degenerate Mixtures of Erbium and Dysprosium Atoms".


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Quantum Phase Transitions of Water Molecules

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We study a one-dimensional chain of identical dipolar particles embedded in the six-fold degenerate potential. The goal is to find the phase transitions and inspect the full phase diagram of the system as the dipolar interaction strength $D$ is varied. The current research is motivated by the following experimental paper [1] about quantum behaviour of water molecules confined in nanocavities.

First we study a one-dimensional chain of dipolar particles interacting with each other through the dipole-dipole interaction. The phase diagram of the system is obtained within mean-field approximation. We find a disordered phase for $D < D_{\text{crit}}$, where all dipoles are oriented at random directions and an ordered phase for $D > D_{\text{crit}}$. For asymptotically large value of interaction strength, we observe that the dipolar particles are in a highly ordered phase, where all dipoles are oriented along the quantisation axis. Adding the six-fold degenerate potential does not change the global phase diagram of the system. Using perturbation theory we are able to calculate the new critical interaction strength $D'_{\text{crit}} > D_{\text{crit}}$.

The ongoing research is on the two-dimensional system of dipolar particles imbeded in the six-fold degenerate potential and as an outlook we present results obtained for this system.


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Near-threshold bound states of the dipole-dipole interaction

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We study the two-body bound states of a model Hamiltonian[1] that describes the interaction between two field-oriented dipole moments. This model has been used extensively in many-body physics of ultracold polar molecules, but its few-body physics has been explored less fully. We characterize the pattern of bound states and their avoided crossings in the case of hard-wall short-range interactions. For more realistic Lennard-Jones short-range interactions, we consider parameters representative for magnetic atoms and polar molecules. For magnetic atoms, we find that the bound states are dominated by the Lennard-Jones potential, and the perturbative dipole-dipole interaction is suppressed by the special structure of van der Waals bound states. For polar molecules, we recover a dense manifold of dipole-dipole bound states that shows an induced-dipole or applied-field dependence that is similar to the patterns observed for hard-wall boundary conditions. This universal pattern of states may be observable spectroscopically for pairs of ultracold polar molecules.

FIG. 1. Pattern of avoided-crossing bound states as a function of the field-induced dipole moment. The model parameters for the dipole-dipole and Lennard-Jones interaction are representative of polar molecules. Different colours correspond to results obtained for different well depths that sample a cycle of the $s$-wave scattering length.
Microwave Shielding of Polar Molecules

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We study microwave shielding of collisions of polar molecules, analogous to blue shielding for atoms. The goal is to engineer effective interaction potentials that are repulsive at long range, preventing short-range encounters of the molecules, thereby suppressing various loss mechanisms. In contrast to previous studies,$[1, 2]$ we perform full coupled-channels scattering calculations to determine the efficiency of the shield, rather than drawing only qualitative conclusions from model adiabatic potentials. Furthermore, we also include molecular hyperfine structure. Hyperfine interactions lead to new loss channels, which are dominant in some realistic cases, and are suppressed by appropriate magnetic fields. We present numerical results for RbCs($^1\Sigma^+$) and CaF($^2\Sigma^+$) molecules. We find that for experimentally achievable static fields and microwave intensities, the probability of short-range encounters can be reduced by orders of magnitude without causing prohibitive microwave-induced losses.


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FIG. 1. Suppression of the probability of reaching short-range in a CaF-CaF collision, as a function of the microwave blue detuning, $\Delta$, and the Rabi frequency, $\Omega$. 
We perform a variational analysis of driven-dissipative Rydberg gases. As a first step, we extend the variational principle for dissipative many-body systems to long-range interaction and long-range correlation. We focus on dissipative Rydberg gases in the blockade regime and investigate the interplay between driving strength and dimensionality.
Light scattering from dense and quantum degenerate atomic ensembles

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The scattering of light from dense atomic gases has received considerable recent interest [1]. At low density a medium is typically well described by a susceptibility formed by a simple product of atom number density and the atomic polarizability. For high atomic densities, however, dipole-dipole interactions may become considerable and affect the character of transmitted and scattered light [2].

In conjunction with dipolar interactions, the optical properties of a trapped, cooled gas may also be modified by the onset of quantum degeneracy. In the case of bosons, a change in the refractive index happens at the transition temperature [3] as was recently experimentally demonstrated [4]. For quantum degenerate fermions a suppression of light scattering has been predicted [5], but its direct observation has so far remained elusive [6].

Here we report on our experiments on light scattering from dense, trapped ultracold gases. We observe a marked difference in the scattering of light from a quantum degenerate gas of fermionic $^{40}$K to that of a thermal gas of bosonic $^{87}$Rb under similar conditions. In our experiments, probe light propagates along the axis of prolate atomic clouds and our observations involve complimentary measurements of light scattered in the sideways and forward directions.

Generally, for dense atomic samples - thermal or degenerate - the apparent extinction of light we observe in the forward direction (or more accurately in a small solid angle about the atomic and optical axis) deviates significantly from that predicted by naïvely accounting for diffusely scattered light as governed by the imaginary part of the medium susceptibility. We believe this effect is predominantly attributable to lensing of the Gaussian probe laser beam by the atomic sample [7]. We present measurements on dense but thermal gases of $^{40}$K, where we can vary the temperature independently of atom number by sympathetically cooling the gas with $^{87}$Rb.

Finally (and somewhat unrelated to the above), we will report on a demonstration of an optical
antenna for ‘radio-over fiber’ based on Rydberg states of atoms [8].

Towards an Erbium BEC in an Optical Box Potential

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This poster reports our progress towards producing a Bose-Einstein condensate (BEC) of dipolar erbium atoms in an optical box potential[1]. Our cooling protocol will closely follow existing methods [2]; a narrow line magneto-optical trap will be loaded using a Zeeman slowed atomic beam from an erbium oven. The atoms will then be optically trapped, and undergo optical transport to a separate glass cell for enhanced optical access. The atoms will then be confined to a quasi-2D box potential. The ability to tune the nature and the strength of the interactions, as well as the confining geometry, will allow us to probe many-body phenomena such as the appearance of a roton minimum in a quasi-2D dipolar gas [3] and supersolidity [4]. Furthermore, we also plan to investigate non-equilibrium many-body physics in quenched and driven quantum systems.


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Motivated by recent experiments on strong coupling of a cloud of Rydberg atoms coupled to a propagating light field [1], we study the effect of interaction-induced dephasing in an atomic cloud of atoms coupled to an optical one-dimensional waveguide. The system’s dynamics can then be described by dissipative terms characterising the collective emission of photons and coherent interaction due to the virtual exchange of photons. We show that the coherent exchange interaction gives rise to a universal dynamics with coherent oscillations and dephasing on a time scale that grows with the number of atoms in the cloud. Further, we discuss a possible experimental setup to decouple coherent and dissipative dynamics in order to observe the universal dynamics.

Towards Direct Laser Cooling of Barium Monofluoride

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We present a new experimental setup for the laser cooling and trapping of barium monofluoride molecules. Laser cooling of molecules had long been considered impossible due to their complex vibrational and rotational level structure. However, beneficial Franck-Condon factors and selection rules allow for optical cycling in many molecular species [1–3], including barium monofluoride [4]. The molecules are generated through laser ablation in a 4K cryostat and precooled by collisions with a helium buffer gas. This results in a cold and intense beam that provides ideal starting conditions for transversal laser cooling, slowing and subsequent loading of a 3D magneto-optical trap. The resulting cold gas of heavy diatomic molecules will pave the way for a large number of novel and interdisciplinary applications ranging from few- and many-body physics to cold chemistry and tests of fundamental symmetries.

FIG. 1. Absorption spectroscopy of buffer-gas-cooled $^{138}$B$^{19}$F molecules around the main cooling transition.

Spin exchange dynamics in chromium dipolar quantum gases

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We study out-of-equilibrium spin dynamics of an ensemble of chromium atoms produced at the Magnetic Quantum Gases team of the Laboratoire de Physique des Lasers. This atomic species has a large $S = 3$ spin in its ground state, resulting in a magnetic dipole moment of $6\mu_B$ ($\mu_B$ is the Bohr magnetron) which induces significant dipole-dipole interactions between atoms. We start with a quantum gas of $^{52}\text{Cr}$ in the $|S = 3, m_S = -3\rangle$ absolute ground state. We trigger the dynamics by rotating the spins of all atoms with respect to the magnetic field, using a resonant radio-frequency pulse. The evolution of the system is then characterized by monitoring the populations of the 7 spin components after Stern-Gerlarch separation. We tailor the initial spin tilting angle, the magnetic field properties (strength, direction and inhomogeneities), and the trapping scheme, for which we investigated the case of a Bose-Einstein condensate (BEC) in a harmonic trap, and the case of a 3D optical lattice with one atom per site. Comparison with numerical simulations provide an insight on the origin of the dynamics and the quantum state obtained during the evolution of the system.

In the superfluid case of a BEC, described in [1], the population dynamics is governed by the interplay between spin-dependent contact interactions, dipole-dipole interactions, and spin-orbit coupling provided by magnetic field gradients. It is well described by a mean field model, where each spin precesses around the field created by all other dipoles. The dynamics is induced by

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magnetic field gradients, either external or resulting from dipolar coupling, but once it has started it is mainly driven by strong spin-dependent contact interactions. We found that this driving results in the conservation of the initial ferromagnetic character of the condensate, and that this protection of ferromagnetism is a universal feature of spin mixing governed by contact interactions, provided they are large enough compared to the effect of the gradients.

In the case of a deep optical lattice, described in the Arxiv preprint [2], the atoms now solely interact via long range, anisotropic dipole-dipole interactions, realizing a spin-3 XXZ Heisenberg model for a unit filled array of $10^4$ atoms. Mean field simulations fail to account for the observed dynamics, while it is well reproduced by a model adapted from the truncated Wigner approximation (Generalized Discrete Truncated Wigner Approximation [3], GDTWA). This indicates the emergence of quantum correlations between atoms. According to the GDTWA simulations, this isolated macroscopic system undergoes quantum thermalization, where wide scale entanglement between particles leads to thermal statistics for individual spin components.

Rydberg quantum optics in an ultracold atomic gas

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Mapping the strong interaction between Rydberg excitations in ultracold atomic ensembles onto single photons enables the realization of optical nonlinearities which can modify light on the level of individual photons [1, 2].

We present the investigation of higher-order photon correlations imprinted onto initially uncorrelated photons through an optical medium smaller than a single Rydberg blockade volume. We show that this single Rydberg superatom shows clear signatures in the connected part of the three-body correlation function. An idealized but exact solvable model of a two-level system coupled to a photonic mode allows for an interpretation of our experimental observations in terms of bound states and scattering states [3].

Additionally, we present the development of a new experiment designed to study the interactions between a large number of Rydberg polaritons simultaneously propagating through a medium with extremely high atomic density. It is proposed to achieve this aim by the use of Ytterbium, an alkaline-earth-like element, which possess, among others, an ultraviolet probe wavelength, a high optical depth per blockade volume and long coherence times.


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Recent experiments [1, 2] have reported on the formation of stable quantum droplets containing approximately from several hundreds to several thousands of $^{164}$Dy atoms in the region of mean-field collapse. In these systems, beyond-mean-field effects become very important and dramatically limit the stability of the formed droplets through the compensation of attractive and repulsive forces, by means of a mechanism similar to the one described in [4].

From a theoretical point of view, these droplets have been analyzed in the framework of the extended Gross-Pitaevskii equation [3], which incorporates Lee-Huang-Yang corrections to the energy functional but still provides a mean-field picture of the system. In this work we use the Path Integral Ground State (PIGS) [5] method to describe the formation of droplets of dipolar bosons. Starting from a sensible model wave function of the many-body problem, stochastic propagation in imaginary time leads to an unbiased decryption of the exact ground state without further approximations. In this sense, the result is exact within statistical uncertainties. We analyze the critical number of atoms required to form a droplet as a function of the initial trapping aspect ratio, using a model two-body interaction that describes the known scattering properties of the Dy-Dy potential. Parameters such as the scattering length are fixed by solving the T-matrix problem corresponding to the combined two-body isotropic potential and the dipole-dipole force.

Spin mixing and protection of ferromagnetism in a spinor dipolar condensate

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Our work focuses on the study of Bose-Einstein condensates with internal spin degrees of freedom, commonly known as spinor BECs. We study out-of-equilibrium physics of spin-3 chromium dipolar BECs following an excitation of the spin degree of freedom. We describe in particular spin dynamics which, we find, results from an interplay between contact and dipolar interactions. Here we focus on the theoretical studies in contact with the experiment at Villetaneuse [1].

Starting from a fully polarized spin 3 chromium dipolar BEC in state \( m = -3 \), we numerically investigate spin mixing dynamics after rotation of the collective spin by an angle \( \theta \) compared to the magnetic field. For \( \theta \neq \pi/2 \) dynamics is triggered by dipolar interactions [2]. On the contrary, for \( \theta = \pi/2 \) dipolar interaction does not drive any dynamics and magnetic field gradient is necessary to trigger dynamics.

Just after rotation, all spins are aligned and the sample therefore has a ferromagnetic character. One striking observation derived from our simulations of the spinor Gross-Pitaevskii equation, which are in good agreement with experimental results, is a protection of a local ferromagnetic character of the gas while dynamics proceeds. Indeed, the local spin length remains close to its maximum, 3. Surprisingly the spinor remains locally ferromagnetic, despite the fact that spin dependent interactions energetically favor depolarization.

To understand this effect, we have solved the spinor Gross-Pitaevskii equation for a homogeneous BEC in presence of magnetic field gradients. We find that the initial ferromagnetic character of the BEC is protected by spin exchange contact interactions, which provide self-rephasing of the spinor components. Taking the phenomenological assumption that the spinor remains ferromagnetic, we developed a simple analytical model based on spinor hydrodynamic approach [3] to investigate the short time dynamics induced by a magnetic field gradient \( b \).

Ground state of an ultracold Fermi gas of tilted dipoles

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Many-body dipolar effects in Fermi gases are quite subtle as they energetically compete with the large kinetic energy at and below the Fermi surface (FS). Recently it was experimentally observed in a sample of erbium atoms that its FS is deformed from a sphere to an ellipsoid due to the presence of the anisotropic and long-range dipole-dipole interaction [1]. Moreover, it was suggested that, when the dipoles are rotated by means of an external field, the Fermi surface follows their rotation, thereby keeping the major axis of the momentum space ellipsoid parallel to the dipoles. Here we generalise a previous Hartree-Fock mean-field theory [2, 3] to systems confined in an elongated triaxial trap with an arbitrary orientation of the dipoles relative to the trap. With this we study for the first time the effects of the dipoles’ arbitrary orientation on the ground-state properties of the system. Furthermore, taking into account the geometry of the system, we show how the ellipsoidal FS deformation can be reconstructed, assuming ballistic expansion, from the experimentally measurable real-space aspect ratio after a free expansion. We perform new and extensive measurements for various parameters to study the full angular dependence of the FS deformation and show that the FS does not simply follow rigidly the orientation of the dipoles, but depends additionally on the dipoles’ orientation relative to the trap geometry, as well as on the trap anisotropy itself, see the illustration in Fig. 1. The presented direct comparison of the obtained analytical and numerical results with our experimental observations shows very good agreement. The developed theory is relevant for understanding and interpreting future experiments.

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with ultracold fermionic dipolar quantum gases, where the investigated physics depends on the underlying structure of the FS.

Fig. 1: Illustration of angular dependence of FS deformation in momentum space for system in anisotropic trap: (a) for weak DDI, when FS ellipsoid just rotates like a rigid object; (b) for strong DDI, when FS deformation strongly depends on dipoles’ orientation.

The Collective Lamb Shift of a Nanoscale Atomic Vapour Layer within a Sapphire Cavity

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Collective effects in light scattering have gained a renewed interest recently with the recognition that they can bias the accuracy of atom-based sensors such as optical clocks by introducing unwanted energy level shifts. The resonant dipole-dipole interactions between atoms should lead to a collective frequency shift of the atomic lines. This shift, unfortunately named the cooperative or collective Lamb-shift (CLS) despite its classical nature, depends on the shape of the sample.

Here, I will present our recent measurements of the near-resonant transmission of light through a dense vapour of potassium confined in a slab cell with nanometer thickness in order to investigate the origin and validity of the collective Lamb-shift [1]. A complete model including the multiple reflections in the nano-cell accurately reproduces the observed strong asymmetry of the line shape and allows extraction of a density dependent shift of the atomic resonance.

Finally, I will present a new generation of glass nano-cells with super-polished surfaces. These cells are promising tools for revisiting long-range atom-surface interactions with thermal vapours.

Dissipative cooling of spin chains by a bath of dipolar particles

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The coupling of quantum systems to environments can lead to various consequences: typically it produces decoherence towards classical behaviors, but specific situations on the contrary produce quantum correlations [1, 2]. This is an exciting new paradigm, that opens the fascinating perspective of environment engineering to protect or produce entangled states. In the context of quantum simulation of magnetism with cold atoms, this kind of dissipative approaches may contribute in preparing low energy many-body spin states of atoms in optical lattices. Recent such proposals involve the use of light as a bath, and spontaneous emission as the dissipative process [3, 4].

In the present work [5], we explore theoretically binary atomic mixtures, one species acting as spin chain, the other as bath. Namely, the spin chain is composed of spinful fermionic atoms in the Mott insulating regime, and it is coupled to a Bose Einstein condensate of a different species. The low-energy many-body states of the spin chain are driven by nearest-neighbor super-exchange interactions. Magnetic dipole interaction between fermions and bath lead to spin flips in the chain, associated with spontaneous phonon emission in the BEC. Thus, spin-thermalization can arise, due to the spin-orbit coupling conveyed by dipole-dipole interactions, an effect which is connected to the Einstein-de Haas effect. As we show here, spin-orbit coupling offers a possibility to directly cool the collective spin degrees of freedom in a spin-chain.

Starting from an uncorrelated thermal sample, we demonstrate in realistic settings, with spin chains of alkali atoms interacting with a BEC of a strongly dipolar species, that the dissipative cooling produces highly entangled low energy spin states of the chain in a timescale of a few seconds. In practice, the lowest energy singlet state driven by super-exchange interactions is efficiently produced. This dissipative approach is a promising alternative to cool spinful atoms in spin-independent lattices. It provides direct thermalization of the spin degrees of freedom, while traditional approaches are plagued by the inherently long timescale associated to the necessary spatial redistribution of spins under the effect of super-exchange interactions [6]. Furthermore, * martin.rdsv@univ-paris13.fr
while the many-body ground state of the Heisenberg antiferromagnetic Hamiltonian has a singlet character at half-filling, in most experiments the collective spin is a conserved quantity which is typically not under control; thus, the possibility to couple to the total spin of the chain is essential to generically provide cooling down to the lowest energy states of spin chains.

One of the most remarkable properties of ultra cold atomic gases is the occurrence of superfluid states characterized by dissipationless irrotational flow. This dissipationless behaviour only appears below a certain “critical” flow velocity and is well-known for decades in liquid helium [1]. Similar to liquid helium superfluid phenomena like the critical velocity for vortex creation have also been observed in ultra-dilute superfluids of quantum-degenerate gases. In systems with non-negligible dipole interaction the superfluidity acquires the anisotropic character of the interaction resulting in the system’s critical velocity depending highly on the flow direction [2].

Here we present transport measurements on a dipolar superfluid using a Bose-Einstein condensate of $^{162}$Dy with strong magnetic dipole-dipole interactions. By moving an attractive laser beam through the condensate we observe an anisotropic critical velocity for the breakdown of dissipationless flow, which, in the spirit of the Landau criterion, can directly be connected to the anisotropy of the underlying dipolar excitation spectrum. In addition, the heating rate above this critical velocity reflects the same anisotropy. Our observations are in excellent agreement with simulations based on the Gross-Pitaevskii equation and highlight the effect of dipolar interactions on macroscopic transport properties, rendering anisotropic dissipation [3].

Rotational coherence of polar molecules in a magic trap

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Quantum gases with dipolar interactions are a fascinating prospect for quantum simulation. Polar molecules have large electric dipole moments and long lifetimes, which makes them ideal candidates for realizing long range physics beyond nearest neighbor interactions.

The rotational degree of freedom of molecules can be used to encode spins. The ground and first excited rotational state however possess different parity. Therefore their polarizabilities at the optical frequencies employed for trapping can differ significantly. This leads to decoherence. Due to the anisotropy of the molecular polarizability, the polarization of the trapping field can be used to tune this differential light shift, even to a so-called magic condition, where it is zero. Then long coherence times between the two states can be achieved.

We experimentally explored the first excited rotational state manifold of ground state fermionic NaK [1] using microwave spectroscopy. We demonstrate how small static electric fields can be used to decouple nuclear spin and molecular rotation and thus to simplify the complex rotational state spectrum, enabling an even longer coherence time. Finally we study the rotational coherence of the molecules. We observe a density dependence of the coherence time, which we attribute to the movement of the molecules in the trap or the dipolar interaction between the molecules, as the $^{23}\text{Na}^{40}\text{K}$ rotational transition dipole moment amounts already to $2.72\text{D}/\sqrt{3} = 1.57\text{D}$.


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FIG. 1. (a) Microwave pulse sequences. Ramsey (only $\pi/2$-pulses) and Spin-Echo (all pulses) sequences are used to study the coherent evolution of molecules between the $|J, m_J\rangle = |0, 0\rangle$ and $|1, 0\rangle$ rotational states. To obtain a Ramsey or Spin-Echo fringe, the phase of the second $\pi/2$ pulse is scanned by $\Delta \phi$ compared to the first pulse for each evolution time $t$. b) Two exemplary Ramsey fringes are shown in the inset. Contrast of Ramsey fringes at different evolution times. The Ramsey coherence time $t_2$ is obtained by fitting a Gaussian evolution (red line). Error bars are calculated from the covariance matrix of the fit. c) Ramsey and Spin-Echo at various molecule numbers. Using Ramsey spectroscopy (red symbols) we obtain coherence times of up to 8 ms. A Spin-Echo sequence can remove residual single-particle effects due to eg. electric field gradients. Indeed we observe even larger Spin Echo coherence times $t_2^*$ of up to 12.5 ms. However both $t_2$ and $t_2^*$ dependent of the molecule number on the trap, that we vary by changing the hold time after Feshbach association. Both coherence times are shorter than the ground state molecule lifetime $t_1$ shown in the inset.
Dysprosium dipolar condensate with broad Feshbach resonances

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We report on the production of a Bose-Einstein condensate of 162Dy atoms and on the characterization of its scattering properties. We employ an innovative technique based on a resonator-enhanced optical trap, allowing an efficient capture of the atoms from the magneto-optical trap. We use ultracold samples at temperatures just above condensation to investigate the spectrum of Feshbach resonances. Besides the chaotic distribution of narrow Feshbach resonances, typical of Lanthanides, we discover two rather isolated features at around 22 G and 27 G, with widths $\Delta \simeq 0.1-1$ G, comparable to the typical spacing between narrow resonances. A characterization using complementary measurements such as losses, thermalization, anisotropic expansion and molecular binding energy, points towards resonances of predominant s-wave character. Such resonances appear particularly appealing for a precise tuning of the contact interaction over a broad range, easing the investigation of quantum phenomena relying on the interplay between dipole and contact interactions.

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Highly magnetic atoms have proven to be successful and versatile model systems to investigate long-range dominated physics in both bulk as well as lattice systems. So far all experiments with dipolar gases have been using as atomic species either chromium, dysprosium, or erbium. Here, we demonstrate a dipolar mixture operation, which, for the first time, combines Er and Dy together. We efficiently produce double Bose-Einstein condensates, as well as a cold Bose-Fermi mixture.

The similar optical and physical properties of Er and Dy makes it convenient to combine both species in one apparatus: For both elements, optical transitions with high scattering rates can be used for Zeeman slowing and imaging, while narrow transitions allow to cool the atoms in a MOT with very low Doppler temperature. This narrow-line MOT needs only five beams [1], leaving enough optical access to use the MOT chamber as a full science chamber. We present our next steps after capturing the atoms in the MOT, namely the loading of a far detuned optical dipole trap. Due to the similar mass and polarizability at 1064 nm, efficient evaporative cooling in a single trap is possible, and efficient Bose-Einstein condensation of all abundant isotopes is achieved.

A major step toward future experiments is the achievement of double Bose-Einstein condensates: We are able to combine five different isotope mixtures to achieve double degeneracy. This requires a careful fine tuning of the magnetic fields due to the very dense Feshbach spectrum of either species as well as inter-species losses. We also present preliminary studies of the interspecies interaction between the two degenerate clouds.

In addition to the possibilities the main chamber of this setup offers, two additional chambers are under construction, dedicated to the study of Rydberg physics in ultracold lanthanoides as well as a quantum gas microscope, which are presented in a second poster “Rydberg physics and quantum-gas microscopy with multi-electron Er and Dy atoms”.

Laser cooling of Dysprosium

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Ultra-cold dipolar quantum gases enable the study of many-body physics with long-range, inhomogeneous interaction effects due to the anisotropic character of the dipole-dipole interaction. These systems are expected to show novel exotic quantum phases and phase transitions which can be studied with dysprosium atoms. Dysprosium is a rare-earth element with one of the largest ground-state magnetic moments (10 Bohr magnetons) in the periodic table. Therefore, the dipole-dipole interaction is not a small perturbation but becomes comparable in strength to the s-wave scattering. This influences significantly the physical properties of the trapped atomic sample, such as its shape and stability.

This poster presents the current status of our experimental setup to generate dysprosium quantum gases. We present our results in laser cooling of dysprosium atoms and give an overview of our laser system and vacuum design.

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Feshbach spectroscopy and dual-species Bose-Einstein condensation of $^{23}$Na - $^{39}$K mixtures

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Ultracold polar ground state molecules are a powerful tool for the investigation of a wide range of physical phenomena as quantum chemical processes or exotic dipolar quantum phases. One way to prepare ultracold ground state molecules is based on a two-photon coherent Raman transfer starting from ultracold weakly-bound Feshbach molecules.

Here, we report on magnetic Feshbach resonance loss spectroscopy in all possible combinations of hyperfine sub-levels with an ultracold atomic mixture of $^{23}$Na and $^{39}$K. We use our results to refine potential energy curves for bosonic NaK molecules. Further, we identify and discuss the suitability of different magnetic field regions for the purposes of sympathetic cooling of $^{39}$K in a bath of $^{23}$Na atoms. We use our findings for the demonstration of dual-species degeneracy in the $^{23}$Na $^{39}$K mixture. The two condensates are created simultaneously by evaporation at a magnetic field of about 150 G, which provides sizable intra- and interspecies scattering rates needed for fast thermalization. Finally, we discuss the pathway for the production of Feshbach molecules as well as the two-photon Raman transfer to the rovibronic ground state.

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Accurate Rydberg quantum simulations of spin-1/2 models

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Using non-perturbative calculations of the interaction potentials between two Rydberg atoms taking into account both electric and magnetic fields, we can simulate a broad range of two-atom Rydberg systems. Benchmarks against varied experimental data show an excellent agreement between the simulations and experiments. We apply our simulation procedure to investigate under which experimental conditions spin-1/2 models can be accurately simulated using Rydberg atoms. More specifically, we determine experimental parameters for which a system of atoms that are laser driven to \( nD_{3/2} \) Rydberg states and interacting via the van der Waals interaction can be mapped accurately to an Ising-like spin-1/2 model, despite the large number of Rydberg levels involved. Our investigations show the importance of a careful selection of experimental parameters in order not to break the Rydberg blockade mechanism which underlies the mapping. By selecting appropriate parameters, a good agreement is achieved between the measured time evolution and the numerically calculated dynamics of the Ising-like spin-1/2 model in systems with up to 49 atoms, i.e. in systems that are at the edge of numerical accessibility. This result opens exciting prospects for the realization of high-fidelity quantum simulators of spin Hamiltonians.

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Equation of State and Universality of a 2D Dipolar Gas

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For a gas at thermodynamic equilibrium, the equation of state relates quantitatively thermodynamic variables, e.g. the particle density $n$ as a function of temperature $T$ and the chemical potential $\mu$ at fixed volume.

For a dilute two-dimensional Bose gas with contact-like inter-particle interactions, the equation of state exhibits a particular scale invariance. For constant interaction strength, the phase-space density, $n\lambda_T^2 T$, where $\lambda_T$ denotes the thermal de Broglie wavelength, becomes simply a function of the dimensionless parameter $\mu/k_BT$. Furthermore, in the vicinity of the Berenzinskii-Kosterlitz-Thouless phase transition, such universal scaling between systems of different interaction strengths emerges when thermodynamic variables are renormalized by the strength of collisions.

Here we report experimental studies of 2D dipolar excitons trapped in a bilayer heterostructure and then reveal that the equation of state exhibits such universal scaling behavior, despite the dipolar character of repulsive interactions.
Magnetically tunable Feshbach resonances in ultracold gases of europium atoms and mixtures of europium and alkali-metal atoms

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We investigate magnetically tunable Feshbach resonances between ultracold europium atoms and between europium and alkali-metal atoms using multichannel quantum scattering calculations. For ultracold gases of europium atoms both homonuclear $^{153}\text{Eu}^+^{153}\text{Eu}$ and heteronuclear $^{151}\text{Eu}^+^{153}\text{Eu}$ systems are studied. Calculations for mixtures of europium and alkali-metal atoms are carried out for prototype systems of $^{153}\text{Eu}^+^{87}\text{Rb}$ and $^{153}\text{Eu}^+^{7}\text{Li}$. We analyze the prospects for the control of scattering properties, observation of quantum chaotic behavior, and magnetoassociation into ultracold polar and paramagnetic molecules. We show that favorable resonances can be expected at experimentally feasible magnetic field strengths below 1000 G for all investigated atomic combinations. For Eu atoms, the dipolar interaction induces measurable resonances as a result of the competition between relatively weak short-range spin-exchange and strong long-range magnetic dipole-dipole interactions and a high density of resonances is expected at magnetic field strengths below 200 G without pronounced quantum chaos signatures. The present results may be useful for the realization and application of dipolar atomic and molecular quantum gases based on europium atoms in many-body physics.

Poster 42

Trap-induced shape resonances in an ultracold few-body system of an atom and static impurities

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Hybrid systems of ultracold atoms and trapped ions or Rydberg atoms can be useful for quantum simulation purposes. By tuning the geometric arrangement of the impurities it is possible to mimic solid state and molecular systems. Here we study a single trapped atom interacting with a set of arbitrarily arranged static impurities and show that the problem admits an analytical solution [1]. An example of such a situation is displayed in Fig. 1, where a single atom moves in a harmonic trapping potential with two different impurities localized by separate traps. We analyze in detail the case of two impurities, finding multiple trap-induced resonances which can be used for entanglement generation. Our results serve as a building block for the studies of quantum dynamics of more complex systems.

FIG. 1. An interaction potential experienced by a trapped atom (red sphere) in the presence of two localized impurities (purple and green spheres), which are localized by external trapping potentials (purple and green).

Quantum phases of dipolar rotors on two-dimensional lattices

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The quantum phase transitions of dipoles confined to the vertices of two dimensional (2D) lattices of square and triangular geometry is studied using path integral ground state quantum Monte Carlo (PIGS) [1], generalized to include rotational degrees of freedom [2]. We analyze the phase diagram as a function of the strength of both the dipolar interaction and a transverse electric field. The study reveals the existence of a class of orientational phases of quantum dipolar rotors whose properties are determined by the ratios between the strength of the anisotropic dipole-dipole interaction, the strength of the applied transverse field, and the rotational constant. For the triangular lattice, the generic orientationally disordered phase found at zero and weak values of both dipolar interaction strength and applied field, shows a transition to a phase characterized by net polarization in the lattice plane as the strength of the dipole-dipole interaction is increased, independent of the strength of the applied transverse field, in addition to the expected transition to a transverse polarized phase as the electric field strength increases. The square lattice is also found to exhibit a transition from a disordered phase to an ordered phase as the dipole-dipole interaction strength is increased, as well as the expected transition to a transverse polarized phase as the electric field strength increases. In contrast to the situation with a triangular lattice, on square lattices the ordered phase at high dipole-dipole interaction strength possesses a striped ordering. The properties of these quantum dipolar rotor phases are dominated by the anisotropy of the interaction and provide useful models for developing quantum phases beyond the well-known paradigms of spin Hamiltonian models, realizing in particular a novel physical realization of a quantum rotor-like Hamiltonian that possesses an anisotropic long range interaction [3].