Long range interactions in quantum systems:

Welcome to the second workshop on "Long-range interactions in the ultra cold", following the one held last year in Stuttgart!
This workshop is an opportunity to discuss recent advances on the physics of Rydberg atoms, magnetic atoms, and dipolar molecules. In addition, this year we also focus on emerging ideas and experiments, regarding effective spin-spin interactions in ions, light-induced dipoles, as well as dipolar interactions between artificial atoms. Given how fast our field is expanding in various directions, we feel that it is important that experts in the field meet and exchange ideas.

Invited speakers:

- Blair Blakie (Otago)
- Rémi Carminati (Paris)
- Donatella Ciampini (Pisa)
- Francesca Ferlaino (Innsbruck)
- Jean-Jacques Greffet (Palaiseau)
- Thomas Maier (Stuttgart)
- Christian Gross (Garching)
- William Guérin (Nice)
- Stewart Jenkins (Southampton)
- James Keaveney (Durham)
- Thierry Lahaye (Palaiseau)
- Robert Löw (Stuttgart)
- Christopher Monroe (JQI)
- Silke Ospelkaus (Hannover)
- Pierre Pillet (Orsay)
- Diego Porras (Madrid)
- Goulven Quemener (Orsay)
- Christian Roos (Innsbruck)
- Gora Shlyapnikov (Orsay)
- Laurent Vernac (Villetaneuse)
- Matthias Weidemuller (Heidelberg)
- Bo Yan (JILA)

Dipolar gases workshop: tentative program

	Tuesday 23-Sep	Wednesday 24-Sep	Thursday 25-Sep	Friday 26-Sep
09:00		Ferlaino	Shlyapnikov	Pillet
09:45		Blakie	Yan	Loew
10:30		Coffee break	Coffee break	Coffee break
11:00		Vernac	Ospelkaus	Lahaye
11:30		Maier	Quemener	Ciampini
12:00		Lunch	Lunch	Lunch
14:00		Carminati	Monroe	Weidemuller
14:45		Greffet	Roos	Gross
15:30		Coffee break	Porras	End of workshop
16:00		Jenkins	Free time in Paris	
16:30		Keaveney	or/and lab visits	
17:00		Guérin		
17:30	Registration	Poster session		
19:00	Get -together buffet	Dinner		

Abstract Oral Presentations

Flattened dipolar condensates: rotons and fluctuations

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There is significant interest in flattened dipolar condensates produced by an external trapping potential that tightly confines the system along one direction. Predictions for this regime include the emergence of novel density oscillating condensate ground states, enhanced density fluctuations, roton-like excitations, and modified collective and superfluid properties. Additionally, by tilting the polarization axis of the dipoles relative to the trap leads to anisotropic superfluid properties, spectra and density fluctuations.

In this work I will discuss the properties of the roton-like excitations that emerge in a flattened dipolar condensate. A focus will be on the localized nature of these excitations in three-dimensional harmonic traps, and the ability to modify these excitations by adjusting the trap shape. Rotons enhance the density fluctuations of the condensate, and we show that *in situ* fluctuation measurements could be used to reveal the roton character [1]. Additionally, for tilted dipoles, fluctuations measurements within finite sized cells are anisotropic [2], so that the variance in atom number measured within a cell depends of the cell orientation. Finally, we note that in the regime where roton-like excitations emerge the condensate is metastable, and the validity of meanfield theory needs careful attention. I will discuss the potential role of a local collapse instability this regime.

[1] R.N. Bisset and P.B. Blakie, *Phys. Rev. Lett.* 110, 265302 (2013).

[2] D. Baillie, R.N. Bisset, C. Ticknor, and P.B. Blakie, arXiv:1406.3453

Light fluctuations produced by nanosources in disordered media

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Coherent light scattering in a disordered medium produces a spatially fluctuating intensity distribution known as a speckle pattern. When the speckle pattern is produced by a light source placed inside the scattering medium (e.g., a point dipole source embedded in a powder), intensity fluctuations exhibit specific signatures that are not described in the fully developed speckle model.

Fluctuations of the electromagnetic local density of states (LDOS) at the position of the source induce the so-called C_0 correlation in the speckle pattern. By studying the full statistical distribution of the LDOS, short-range (near field) and long-range (collective) interactions can be identified [1,2]. Measuring LDOS fluctuations provides a method to probe the photonic modes of a complex system from the inside, and to reveal the role of short-range interactions [3] or spatial localization due to collective interactions [4].

Beyond LDOS fluctuations, the intrinsic spatial coherence, i.e. the coherence sustained by the photonic modes of the system independently on the illumination conditions, can be characterized by the cross density of states (CDOS) [5]. Its width defines an intrinsic spatial coherence length that can be strongly influenced by multiple scattering. We show that the intrinsic spatial coherence length can be reduced in strongly scattering media. This reduction of intrinsic spatial coherence is the signature of light localization on scales that can become much smaller than the wavelength [5]. Light localization provides an way to enhance light-matter interactions [6].

Finally, we discuss speckle fluctuations produced by two incoherent light sources. We show that the speckle contrast reveals the fluctuations of the CDOS connecting the two point sources [7]. This suggests the intriguing possibility that intensity measurements at only one point in a speckle pattern produced by two incoherent sources can provide information about the relative distance between the sources, with a resolution that is limited by the extent of eigenmodes inside the system, and not by free-space diffraction.

[1] A. Cazé, R. Pierrat and R. Carminati, Phys. Rev. A **82**, 043823 (2010)
[2] R. Pierrat and R. Carminati, Phys. Rev. A **81**, 063802 (2010)
[3] R. Sapienza, P. Bondareff, R. Pierrat, B. Habert, R. Carminati and N.F. van Hulst, Phys. Rev. Lett. **106**, 163902 (2011)
[4] V. Krachmalnicoff, E. Castanié, Y. De Wilde and R. Carminati, Phys. Rev. Lett. **105**, 183901 (2010)
[5] A. Cazé, R. Pierrat and R. Carminati, Phys. Rev. Lett. **110**, 063903 (2013)
[6] A. Cazé, R. Pierrat and R. Carminati, Phys. Rev. Lett. **111**, 053901 (2013)
[7] R. Carminati, G. Cwilich, L.S. Froufe-Pérez and J.J. Sáenz, submitted (2014)

Excitation dynamics and full counting statistics for resonant and off-resonant excitation of a strongly correlated cold Rydberg gas

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Atoms in high-lying Rydberg states strongly interact with each other via the dipole-dipole or van-der-Waals potential thus permitting the exploration of a wide range of many-body phenomena in strongly interacting systems. The strong interactions between Rydberg atoms under resonant laser driving become manifest either as spatial correlations compatible with a radius of blockade around an excited atom or through a reduction of fluctuations leading to sub-Poissonian statistics [1]. On the other hand, away from resonance, the detuning can compensate for the energy shift induced by the Rydberg-Rydberg interaction, giving rise to resonant interaction processes [2, 3]. In such an off-resonant excitation scheme, two atoms can undergo a pair excitation if the atomic interaction matches the laser energy defect/excess. As a consequence an already excited Rydberg atom pair (or a Rydberg atom, off-resonantly excited) can shift other atoms into resonance [4], in a domino effect, leading to an increasing overall number of Rydberg excitations. This resonant condition is the opposite of the blockade effect, where the interactions suppresses excitations, allowing at most one single excitation within a blockade radius.

I will present experimental observations for both the resonant and the off-resonant excitation scheme, with the excitation laser having a finite detuning from the ^{87}Rb 70S state. I will illustrate the off-resonant excitation dynamics and full counting statistics in experiments in which the growth of excitations is controlled by using an initial Rydberg excitation as a seed. The information extracted from the full counting distribution makes possible a direct comparison with theoretical predictions that is far more sensitive than, i.e., the mean and standard deviation alone.

[1] M. Viteau, P. Huillery, M.G. Bason, N. Malossi, D. Ciampini, O. Morsch, E. Arimondo, D. Comparat and P. Pillet, *Phys. Rev. Lett.*, 109, 053002 (2012).

[2] N. Malossi, M.M. Valado, S. Scotto, P. Huillery, P. Pillet, D. Ciampini, E. Arimondo and O. Morsch, *Phys. Rev. Lett.*, 113, 023006 (2014).

[3] H. Schempp, G. Günter, M. Robert-de-Saint-Vincent, C.S. Hofmann, D. Breyel, A. Komnik, D.W. Schönleber, M. Gärttner, J. Evers, S. Whitlock and M. Weidemüller, *Phys. Rev. Lett.*, 112, 013002 (2014).

[4] I. Lesanovsky and J.P. Garrahan, *Phys. Rev. A*, 90, 011603(R) (2014).

Dipolar physics with ultracold atomic magnets

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Given their strong magnetic moment and exotic electronic configuration, rare-earth atoms disclose a plethora of intriguing phenomena in ultracold quantum physics. Here, we report on the first degenerate Fermi gas of erbium atoms, based on direct cooling of identical fermions via dipolar collisions [1]. We study the impact of the anisotropic character of the interaction following the re-thermalization dynamics of a dipolar Fermi gas driven out of equilibrium [2]. At the many-body level, we prove the long-standing prediction of a deformed Fermi surface in dipolar gas [3]. Finally, scattering experiments show a spectacularly high number of Fano-Feshbach resonances. This complexity, arising from the anisotropy of the interactions, escapes to traditional scattering models and requires novel approaches based on statistical analysis. Using the powerful toolset provided by Random-Matrix theory, we elucidate the chaotic nature of the scattering [4].

[1] K. Aikawa, A. Frisch, M. Mark, S. Baier, R. Grimm, and F. Ferlaino, ?Phys. Rev. Lett. 112, 010404 (2014).

[2] K. Aikawa, A. Frisch, M. Mark, S. Baier, R. Grimm, J. L. Bohn, D. S. Jin, G. M. Bruun, F. Ferlaino?arXiv:1405.1537 (2014)

[3] K. Aikawa, S. Baier, A. Frisch, M. Mark, C. Ravensbergen, F. Ferlaino?arXiv:1405.2154 (2014)

[4] A. Frisch, M. Mark, K. Aikawa, F. Ferlaino, J. L. Bohn, C. Makrides, A. Petrov, and S. Kotochigova, Nature 507, 475-479 (2014).

Theoretical study of scattering by a dense system of two-level atoms

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It is well-known since the seminal work of Dicke [1] that an ensemble of N atoms displays both superfluorescence and superadiance due to collective effects. Yet, in the Dicke analysis, interaction between atoms is not accounted for. Here, we study a cigar-shaped cloud of two-level atoms with a density $n(l/2\pi)^3=1$ and dimensions comparable to the wavelength [2]. In this regime, dipole-dipole interaction and retardation effects cannot be neglected so that Dicke analysis is not valid. An eigenstate analysis of this dense system will be presented to analyse spontaneous emission. The second part of the study is devoted to the resonant light scattering by this system.

To study the spontaneous emission in the low excitation limit, Svidzinsky *et al.* [3] used a (scalar) Wigner-Weisskopf theory. This analysis will give the coupled dipole equations. From this set of equations, the eigenstates of the system can be derived. We will follow Svidzinsky's procedure, but instead of using scalar fields, we take into account the vectorial nature of EM-fields which cannot be ignored in the near field. The obtained eigenstates will shortly be discussed. We then move on to the study of the scattering and investigate which of the eigenmodes are contributing the most to the total emission pattern. Although the set of eigenmodes is not orthogonal, we managed to investigate the contribution of each individual mode to the emission pattern. This will lead to the conclusion that superradiant states are directional, while subradiant states are not.

Classically, we observe something similar. Under illumination, the scattered light from a random system shows two distinct features. First, there is a speckle pattern visible which is quasi-isotropically distributed. This speckle pattern originates from fluctuations in the medium. Second, there is a diffraction pattern visible, which is similar to the diffraction pattern of a macroscopic medium described by an effective index of refraction n (mean-field theory). This diffraction pattern is directional, like the superradiant modes are. Hence it is possible to establish a link between collective effects and classical scattering theory as already suggested by Bienaimé *et al.* [4]. Here, we propose that the effective index of refraction is determined by the superradiant states so that we can establish a link between the nanophotonics point of view and the quantum optics point of view.

[1] R.H. Dicke, *Physical Review*, **93**, 99-110 (1954).

[2] J. Pellegrino, R. Bourgain, S. Jennewein, Y.R.P. Sortais, A. Browaeys, *arXiv : 1402.4167* (2014)

[3] A.A. Svidzinsky, J.-T. Chang, M.O. Scully, *Physical Review A*, **81** (2010).

[4] T. Bienaimé, R. Bachelard, N. Piovella, R. Kaiser, *Fortschr. Phys.*, **61** (2012).

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Rydberg many-body physics in tailored systems.

The long-range character of the Rydberg-Rydberg interaction leads to strong boundary effects especially in small low-dimensional systems. Thus, control of the initial density distribution is crucial for the coherent manipulation of such many-body systems. Based on the preparation of uniform atomic density distributions with sub-shotnoise atom number fluctuations we succeeded to realize crystalline states by adiabatic ramping techniques. Furthermore, we report on the coherent manipulation of a single superatom whose "size" is tunable between one and a hundred atoms.

Cooperative scattering of light in cold atoms

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When a photon is sent onto an atomic ensemble, it interacts collectively with the *N* atoms of the cloud and not simply with one of them. This can result in measurable modifications in the scattering rate, the emission diagram or the temporal dynamics of the scattering. We study these cooperative effects experimentally and theoretically. In particular, we are investigating these effects with a *dilute* cold-atom sample, when the very existence of these cooperative effects is somewhat counter-intuitive.

I will discuss two experiments in this context. The first one has demonstrated the reduction of the radiation pressure force due to cooperativity [1]. The second one, which is still a work in progress, aims at observing subradiance [2].

[1] T. Bienaimé *et al.*, *Phys. Rev. Lett.* **104**, 183602 (2010); S. Bux *et al.*, *J. Mod. Opt.* **57**, 1841 (2010); H. Bender *et al.*, Phys. Rev. A **82**, 011404(R) (2010); J. Chabé *et al.*, *Phys. Rev. A* **89**, 043833 (2014).

[2] T. Bienaimé, N. Piovella, and R. Kaiser, *Phys. Rev. Lett.* **108**, 123602 (2012).

Cooperative light-matter interactions in cold atomic gases, optical lattices and metamaterials

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Light scattering in a cold atomic sample mediates long-range, inter-atomic interactions. We will show how the resulting cooperative behavior can manifest itself in the optical response of a cold atomic gas. Further, we will consider how a cooperative response can be exploited to manipulate systems such as optical lattices and metamaterial arrays comprising magnetodielectric resonators.

When an incident light field impinges on an ensemble of atoms, the individual atoms scatter the light. The scattered light then drives other atoms, which re-scatter the field. In a cold gas, recurrent scattering, where light scatters more than once from the same atom, results in long-range dipole-dipole interactions between the atoms. The ensemble, therefore, responds cooperatively to the incident field. This cooperative response cannot be described using a mean field treatment. For example, cooperative effects lead to long-range correlations between density and atomic polarization [1]. When the atoms are at fixed positions, the cooperative response can be described by collective modes of excitation distributed over the ensemble. These modes have distinct resonance frequencies and decay rates with superradiant or subradiant character. Cooperative effects can also be observed in systems where atoms are replaced by other electromagnetic emitters, such as magnetodielectric resonators that comprise metamaterials.

We consider a cold atomic gas, and evaluate its collective response to incident light. By performing linear simulations of randomly distributed emitters, we show the appearance of collective behavior as one increases the number of atoms in the system. Such stochastic simulations capture non-classical correlations that can form between atomic density and atomic polarization [2]. Our simulations account for the magnetic field interactions and Zeeman degeneracy of the trapped atoms. We compare our results to recent experimental observations [3], where a suppression of light scattering intensity was observed.

In addition, we discuss how cooperative effects can be exploited in systems where the positions of electromagnetic resonators can be controlled. An optical lattice in a Mott-insulator state with precisely one atom per site is such a system. A metamaterial array, where, conceptually, the atoms in an optical lattice are replaced by sub-wavelength, magnetodielectric resonators [4], is another. Cooperative interactions, for example, can produce narrow transparency windows in otherwise opaque systems [5], or, in conjunction with a modulated incident field, can produce sub-wavelength excitations at isolated lattice sites [6]. Cooperative interactions in atomic samples may also have implications for quantum information processing.

[1] J. Ruostekoski and J. Javanainen, *Physical Review A*, 55, 513 (1997).
[2] J. Javanainen *et al*, *Physical Review A*, 59, 649 (1999).
[3] J. Pellegrino *et al*, arXiv:1402.4167 (2014).
[4] S. D. Jenkins and J. Ruostekoski, *Physical Review B*, 86, 085116 (2012).
[5] S. D. Jenkins and J. Ruostekoski, *Physical Review Letters*, 111, 147401 (2013).
[6] S. D. Jenkins and J. Ruostekoski, *Physical Review A*, 86, 031602 (2012).

Collective dipole-dipole interactions in thermal atomic vapours confined in nano-scale vapour cells

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Armen Sargsyan[2], David Sarkisyan[2]
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The propagation of light through an ensemble of interacting dipoles is a rich and complex topic, giving rise to effects such as superradiance [1], the cooperative (or collective) Lamb shift [2] and optical bistability [3]. We present experimental studies of these effects, realized with hot rubidium and cesium vapours confined in 'nano-cells', whose thickness in the propagation direction is much shorter than the optical wavelength. A key advantage this confinement gives is limiting the resonant optical depth, meaning that the experimental approach can be made as simple as possible whilst still being able to extract the underlying physics. In addition to strong dipole-dipole interactions, the cells also make possible the investigation of near-field atom-surface interactions [4], which we also explore in this talk.

[1] R. Dicke, *Phys. Rev.* **93**, 99 (1954).

[2] J. Keaveney *et. al., Phys. Rev. Lett.* **108**, 173601 (2012).

[3] C. Carr *et. al., Phys. Rev. Lett.* **111,** 113901 (2013).

[4] K. A. Whittaker *et. al.*, *Phys. Rev. Lett.* **112**, 253201 (2014).

Robert Loew
Stuttgart University

Hot Rydberg atoms

The interactions between Rydberg atoms are strong enough to play even in room temperature gases the dominating role. In Stuttgart we try to employ these interactions in various ways and I will give an overview on our recent experiments with Rubidium and Cesium gases in various vapor cell designs. I will especially focus on our attempts to realize a room temperature single photon sources and the aggregation dynamics towards a state with soft matter like correlations.

Bose-Einstein Condensation of Dysprosium

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Strongly dipolar quantum gases enable the observation of many-body phenomena with anisotropic, long-range interaction. Rotonic features, 2D stable solitons and the supersolid state are some of the exotic many-body phenomena predicted for dipolar quantum gases.
Recently a magneto-optical trap for thulium [1] and holmium atoms [2] was realized and quantum degeneracy of both bosonic and fermionic erbium [3,4] and dysprosium [5,6] was achieved. The element with the strongest magnetic dipole moment is Dysprosium. It is a rare-earth element with a complex energy level structure with several possible cooling transitions. We have prepared samples of dysprosium atoms at 10 μK in a magneto-optical trap by laser cooling on a narrow transition at 626nm [7]. We load these cooled atoms into an optical dipole trap and transport them to a glass cell with high optical access. To finally reach quantum degeneracy we perform evaporative cooling in a crossed optical dipole trap.
We discuss future perspectives based on a high resolution imaging system combined with tailored potentials.

[1] D. Sukachev, A. Sokolov, K. Chebakov, A. Akimov, S.Kanorsky, N. Kolachevsky, and V. Sorokin, *Phys. Rev. A*, 82, 011405 (2010)

[2] J. Miao, J. Hostetter, G. Stratis, and M. Saffman, *Phys. Rev. A*, 89, 041401 (2014)

[3] K. Aikawa, A. Frisch, M. Mark, S. Baier, A. Rietzler, R. Grimm, and F. Ferlaino, *Phys. Rev. Lett.*, 108, 210401(2012)

[4] K. Aikawa, A. Frisch, M. Mark, S. Baier, R. Grimm, and F. Ferlaino, *Phys. Rev. Lett.*, 112, 010404 (2014)

[5] M. Lu, N. Q. Burdick, S. H. Youn, and B. L. Lev, *Phys. Rev. Lett*., 107, 190401 (2011)

[6] M. Lu, N. Q. Burdick, and B. L. Lev, *Phys. Rev. Lett.*, 108, 215301 (2012)

[7] T. Maier, H. Kadau, M. Schmitt, A. Griesmaier, and T. Pfau, *Opt. Lett.*, 39, 3138-3141 (2014)

Rydberg atoms in Förster coupling: Interplay between two-body, few-body and many-body effets

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Resonant dipole-dipole interaction or Förster coupling leads Rydberg atoms to interact at amazing long-range distances, making them a "probe" to explore the interplay between two-body and many-body effets.

A rapid review of the Förster coupling between hot and cold Rydberg atoms will be presented. The behavior of an ensemble of cold Rydberg atoms is determined by the dipole-dipole coupling. It allows one to investigate the frontier between cold Rydberg atoms and ultracold neutral plasmas, or to explore the deep links between cooperative radiation as supperradiance and dipole-dipole coupling. The dipole blockade of the Rydberg excitation of cold atoms is a collective effect, the many-body character of which is clearly shown by the sub-Poissonnian statistics of the excited Rydberg atoms [1,2].

In a resonant Förster coupling, cold Rydberg atoms exchange resonantly internal energy. The process can be very efficient and the saturation regime can be reached. In a sparse medium of so interacting particles, the dynamics of the ensemble is expected to be governed by the two-body interactions, whereas the few-body effects are considered as negligible. For a denser and denser medium, three-body then four-body effects can appear, as so long they stay as rare events, they act as a perturbation in the dynamics of the ensemble. When the perturbative picture is no longer valid, and a many-body problem has to be considered. Cold Rydberg gases in mutual Förster coupling offer a great opportunity to isolate and to separate different few-body processes from the two-body ones. They can provide a test the interplay between two-body, few-body and many-body processes. A four-body Rydberg Förster resonance has been demonstrated [3]. It corresponds to a weak process, very far of the saturation of the effect. Very recently, an efficient three-body process has been observed [4].

The perspectives of few-body processes have many consequences for understanding and controlling a large ensemble of Rydberg atoms by taking into account not only their physical properties but also the chemical ones.

1- M. Viteau, P. Huillery, M. Bason, N. Malossi, D. Ciampini, O. Morsch, E. Arimondo, D. Comparat, P. Pillet, Phys. Rev. Lett.109, 053002 (2012).
2- N. Malossi, M.M. Valado, S. Scotto P. Huillery, P.Pillet, D. Ciampini, E. Arimondo, O. Morsch, Phys.Rev.Lett. 113, 023006 (2014).
3- J.H. Gurian, P. Cheinet, P. Huillery, A. Fioretti, J. Zhao, P.L. Gould, D. Comparat, P. Pillet, Phys. Rev. Lett. 108, 023005 (2012).
4- R. Faoro, B. Pelle, A. Zuliani, P. Cheinet, E. Arimondo, P. Pillet, to be submitted (2014).

Hidden long-range frustrated interactions in trapped ion spin-phonon chains

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Systems with frustrated interactions play an important role in fields from magnetism to molecular biology. Frustrated systems exhibit fascinating properties, like the strong thermal or quantum fluctuations that characterize spin-liquid phases. Trapped ion quantum simulators are an ideal test-bed to explore frustration and quantum annealing [1]. In this work we depart from schemes simulating effective spin-spin couplings and consider the limit of strong spin-phonon coupling leading to cooperative Jahn-Teller or Rabi-Lattice models [2]. We consider that spin-phonon couplings are dressed by optical phases induced by lasers naturally arising in trapped ion experiments.

We unveil the existence of hidden long-range frustrated interactions leading to the competition between different magnetic and structural orders (see Figure 1). Frustration arises by the interplay of two effects: (a) an effective long-range coupling between different ions, and (b) the dressing of spin-phonon interactions by means of the optical phases of lasers. Our scheme can be easily implemented with many ions, since it only relies on one single optical force acting on the ion chain. It also allows for higher simulation speeds, since we consider a non-perturbative spin-phonon coupling regime.

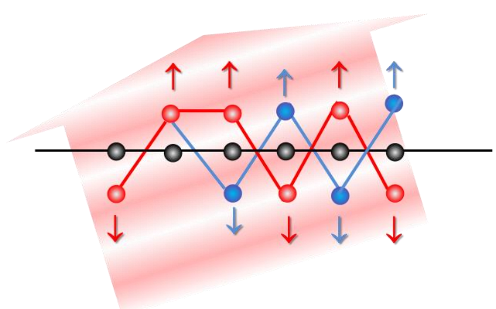

Fig. 1: Trapped ion chain under a spin-dependent force dressed by the laser optical phase. Competing magnetic orders lead to frustration and spin-liquid phases.

Our calculations [3] show that trapped ion chains in a regime of strong spin-phonon couplings can be used to study *quantum spin-liquid phases*, since frustration leads to long-range quantum correlations. We have used a non-equilibrium mean-field approach to describe the quasi-adiabatic evolution of the system towards the ground state. Quantum simulation experiments implementing our model may be used to study the role of quantum fluctuations and entanglement in quantum annealing schemes. From the theory side, our model is ideally suited to explore the physics of spin-liquid phases, since it is one-dimensional, and thus suitable for numerical methods such as the Density Matrix Renormalization Group.

[1] *Experimental quantum simulations of many-body physics with trapped ions*, Ch. Schneider, D. Porras and T. Schaetz, Reports on Progress in Physics **75**, 024401 (2012).

[2] *Quantum Simulation of the Cooperative Jahn-Teller Transition in 1D Ion Crystals*, D. Porras, P.A. Ivanov and F. Schmidt-Kaler, Physical Review Letters **108**, 235701 (2012).

[3] *Hidden Frustrated Interactions and Quantum Annealing in Trapped Ion Spin-Phonon Chain*, P. Nevado and D. Porras, eprint arXiv:1406.5094.

Long-range anisotropic effects in collisions of electric and magnetic polar molecules

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The recent formation of electric and magnetic ultracold polar molecules has led to the observation of strong dipolar signatures. Ultracold polar molecules interact mainly at long-range via the dipole-dipole interaction. The anisotropy of this interaction shows up in the collisional processes when a confinement is set up. Using a time-independent quantum formalism, we describe the two-body collision properties of such molecules. We compute the rate coefficients for different strengths and tilts $\theta_{E/B}$ of the electric (E) or magnetic fields (B), see Figure 1, and for different strengths of a one-dimensional confinement. Fermionic KRb electric polar molecules and bosonic Er_2 magnetic polar molecules are taken as examples and we will compare our results with available experimental data. We will discuss on the suppression or enhancement of the collisions depending on the fields and confinement configurations.

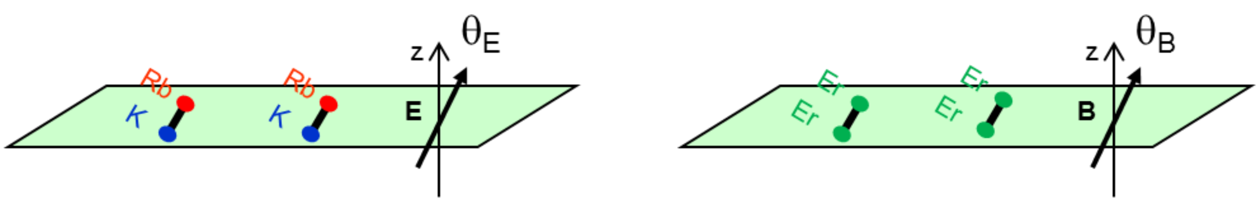

Figure 1: Quasi-2D collisions of KRb and Er_2 molecules in tilted electric and magnetic fields.

Engineering and observation of interacting quasiparticles in a trapped-ion many-body system

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Quantum dynamics in many-body systems can often be described by in terms of quasiparticles whose properties are determined by the interactions between the constituents of the system. Using state-dependent forces and single-ion addressing, we engineer a 1D transverse Ising Hamiltonian with a tunable interaction range in a linear chains of up to 20 ions, create quasiparticle excitations and investigate their dynamics.
I will report on our recent work [1] studying the propagation of entanglement in this system in different experimental regimes. In an extension to this work, we make use of a spin-wave description of the system's excitations and directly extract a dispersion relation from the dynamics of superpositions of quasiparticles and observe signatures of quasiparticle interactions by a kind of generalized Ramsey spectroscopy[2].
The entangled states, created at various times during the laser-driven dynamics, are no longer accessible to full state tomography nor can they easily be characterized by a simple entanglement witness. Based on tomographic measurements of subsets of the full chain, we are currently investigating the use of matrix product states and operators [3,4] in the efficient representation of the system's full quantum state. I will report on preliminary results that we have obtained in this manner.

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Stable dilute supersolids of two-dimensional dipolar bosons

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I will give an overview of the search for supersolid states in bosonic systems, the states in wqhich the order parameter exhibits a periodic structure on top of a uniform background. I then discuss two-dimensional bosonic dipoles oriented perpendicularly to the plane. In addition to the usual two-body contact and long-range dipolar intertactions, I include three-body contact repulsion as expected, in particular, for dipoles in the bilayer geometry with tunneling. It will be shown that this system allows for a variety of dilute supersolid states, and I present the phase diagram. Importantly, three-body repulsion is crucial for stabilizing the supersolid states and, being combined with the two-body repulsion, can lead to self-trapped asupersolid droplets.

Spin exchange with ultracold chromium atoms

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I will present recent experimental results obtained in the Villetaneuse group with ultra cold chromium atoms. The main part of the talk will be dedicated to spin exchange with ultracold bosons ^{52}Cr, in different geometries. I will as well shortly present the route we followed to produce a ^{53}Cr Fermi Sea.
Due to the high spin (S=3) in the ground state of chromium, there are large magnetic dipole-dipole interactions between chromium atoms. They can lead to spin changing collision, thus offering a free magnetization [1] to chromium samples. They can as well produce spin exchange (SE) dynamics between atoms separated by a large distance.
When we load our chromium BEC in a 3D lattice, we can reach the Mott state with one or two atoms per site, and we can get rid of spin changing collisions. After atoms are prepared in the first excited Zeeman state (m_s=-2), we can specifically study spin exchange dynamics. When we only keep singlons (one atom per site), we observe spin dynamics which can only result from intersite interaction. This dipolar SE is in agreement with simulation including 9 spins on a 3*3 plaquette: this reveals the inherent many body character of the system. When we keep doublons (2 atoms per site) we observe first fast intrasite SE, followed by a slower dynamics, which we attribute to dipolar intersite SE [2].
When we load the BEC in a double well trap, we can obtain the following spin state preparation: about 5000 atoms are in the lowest energy ms=-3 state in one of the well, and 5000 are in the highest energy ms=+3 state in the other well. A naive estimate of the dipolar SE rate for this initial distribution predicts a full inversion of the spin orientation in the two wells in less than 100 ms, but we observe no spin dynamics on this time scale. We interpret this freezing of SE as a results of the emergence of a classical behaviour for large ensemble of spins. By merging the two wells, we are able to observe a contact SE dynamics from which we can measure the S=0 scattering length a_0 of ^{52}Cr [3].
In parallel to boson studies, we tried to cool the fermionic ^{53}Cr isotope. We performed sympathetic cooling with the bosons in the same optical trap in which we obtain a BEC. The starting point for evaporation is 3.10^4 fermions with 1.10^6 bosons at 100 µK. We observe a good thermalization between the two species, and a reduced loss rate at the end of the evaporation for the fermions. These features can be explained from an interspecies cross section equal to about half of the boson-boson one. We obtain a degenerate gas with a temperature of 0.6 T_F and about 1000 atoms.

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A many-body spin system with ultracold polar molecules

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Long-range dipolar interactions are expected to facilitate an understanding of strongly correlated many-body quantum systems such as quantum magnets and high T_c superconductors. Ultracold polar molecules are an excellent experimental platform for studying interactions, since they possess a large electric dipole moment and can be created at ultracold temperatures and manipulated with exquisite precision. Here we report the first observation of long-range dipolar spin exchange interactions for ultracold polar molecules confined in a deep three-dimensional optical lattice. The single-particle dephasing is largely suppressed by choosing "magic angles" of the lattice polarizations and implementing a spin echo technique, in order to reveal dipolar exchange interactions. With spin encoded in rotational states, the interactions manifest as a density dependent and oscillating decay of the spin coherence of the system. These results motivated and are consistent with a new many-body theoretical calculation. Our current experimental efforts are focused on increasing the lattice filling fraction, which should enable the study of many-body dynamics with long-range interactions, such as transport of excitations in an out-of-equilibrium long-range interacting system.

Abstract Posters

Long coherence times for Rydberg qubits on a superconducting atom chip

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Rydberg atoms are the focus of a thriving experimental and theoretical activity. Many proposals for quantum simulation of condensed matter systems and quantum information processing exploit their strong, long-range, dipole interaction. Exciting Rydberg atoms in a BEC prepared on a superconducting atom chip [1], is particularly promising in this context. It opens the route to a hybrid interface between on-chip quantum superconducting circuits and atomic ensembles.

Manipulating Rydberg atoms with an atom chip, however, requires a good control of electric field nearby a metallic surface, as highly excited atoms are very sensitive to Stark effect. The problem is more crucial as soon as there is formation of dipolar patches due to uncontrolled Rb deposition on the chip surface [2, 3, 4, 5]. A simple solution for our particular experiment with superconducting atom chip consists in covering all essential metallic surfaces by a layer of Rb. Thanks to that we could demonstrate unprecedented long coherent manipulation for transition between adjacent Rydberg levels with principal quantum number $n \approx 60$, by using standard microwave spectroscopy techniques (Rabi oscillation, Ramsey interference and spin echo). The measured coherence time is in the ms range, exceeding the lifetime of Rydberg atoms themselves [6]. This reveals new perspectives for studying the collective excitation dynamics of ultra cold atomic ensemble in the strong dipole blockade regime.

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[6] Arxiv XXX

Active magnetic field compensation

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For high precision measurements it is necessary to control or account for changes in ambient conditions. When studying dipolar interactions within a ^{87}Rb BEC, the ambient magnetic field should be kept below a level of 1 μG and ideally have a flat noise spectrum. Whilst passive magnetic shields can offer high shielding factors it is difficult to obtain the required 10^7 shielding factor as well as having a flat residual noise spectrum. Using passive shielding in combination with active magnetic shielding eases the requirements of the passive shield as well as improving the spectral content of the residual noise. Our active magnetic field compensation system utilises a solid-state magnetic sensor with a 10 MHz bandwidth, which is much higher than that of the more common fluxgate sensors whilst still having a low minimum sensitivity of 4 nT and low spectral noise of 25 pT/Hz$^{1/2}$. This sensor in conjunction with amplification, a PID circuit, voltage-controlled current source and a pair of Helmholtz coils comprise a 1-axis compensation system that can readily be extended to a full 3-axis system. We have demonstrated that this system can reduce the ambient magnetic field to <1 mG peak to peak fluctuations and have begun characterisation and optimisation of the noise spectrum. In addition, the magnetic field set-point of this system can be controlled digitally from a computer and as such is ideal for implementation in an ultracold atom experiment. We intend to utilise the described system to build an experiment to study dipolar interactions on a lattice using a ^{87}Rb BEC.

Transport and phase transitions of trapped ion clouds

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An ion cloud confined in a linear RF-quadrupole trap is an example of a non-neutral plasma, a plasma consisting of particles with a single sign of charge. Its thermal equilibrium state has been widely studied by Dubin, O'Neil and co-workers in the context of large ion clouds in Penning traps and extrapolated to ions in RF-quadrupole traps (for a complete review, see [1]) and even to ions in multipole traps [2]. We are interested in the study of the dynamics of large ion clouds, in particular of out-of-equilibrium issues. For that purpose we have set-up a double linear RF-trap, being composed of three trapping zones of different potential geometries along a common z-axis.

One of the important issues in this configuration is the transport of an ion cloud by the translation of the trapping potential, with the objective of being as fast as possible without loosing ions. Among others, the transport duration is a critical parameter in order to increase the frequency stability of microwave ion clock like the NASA prototype dedicated to Deep Space Navigation and soon to be tested in a flight demonstration mission [3]. In our trap, the geometry induces a deformation of the trapping potential during translation, which is responsible for heating of the center of mass motion as well as of motion in the center of mass frame. Although the electric field along the ion path is not known precisely, we show that it is possible to transport an ensemble of several tens of thousands of ions over distances of a few centimeters in times as short as 100~µs, loosing only few % of the ions. The role of the Coulomb repulsion induced spreading on the cloud heating is also be presented and compared to molecular dynamics simulations [4].

Moreover, we are interested in the phase transition that cold ions encounter when they are laser-cooled. The structural organization of cold ions depends on their density, temperature and storage potential. Cold ions in a linear octupolar trap are expected to organize in a hollow structure, formed of concentric tubes. If the number of ions is decreased, the tube reduce a single ring, that can be a relevant support for quantum information protocol or frequency metrology [5]. The transition from one to two rings is an example of structural phase transition in a system submitted to long-range interactions and is analyzed in [6].

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Prospects for vibrational cooling for RbCs ultra-cold molecules

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Hetero-nuclear ultra-cold molecules are the object of many experimental and theoretical efforts because of their promising applications in precise measurements of fundamental physical constants, in quantum computation and in the so-called ultra-cold chemistry [1].

Beside the very successful results obtained with the magneto-association technique followed by stimulated Raman adiabatic passage , which produces almost quantum degenerate samples of molecules in a definite ground level [2,3], photo-association (PA) of cold atoms in a double-species magneto-optical trap remains an experimentally simpler option. In this case, spontaneous emission distributes molecules over many ground-state levels. Nevertheless, the ro-vibrational laser cooling technique, which uses a combination of broad-band and narrow-band lasers, is in principle able to pump most of the molecules in a target level [4, 5,6].

In this poster we present our experimental and theoretical efforts for the RbCs case. In this system, quite efficient, short-range PA transitions have been found [7], some of them already naturally producing a large fraction of molecules in the (v=0, J=0) level of the ground-state [8]. As we will show, the structure of the potential energy curves of RbCs is rather unfavorable to the vibrational cooling of the molecules into the (v=0) level, and indeed it was not observed experimentally. On the contrary, vibrational cooling into a higher level, for example the (v=3), should be possible although needs a more complex spectral shaping of the pumping laser.

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Quantum chaos in ultracold collisions of erbium

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In the 1950's the Nobel Laureate Eugene Wigner designed a revolutionary statistical theory, based on random matrices, to describe complex systems. Originally created for nuclear matter, Random Matrix Theory (RMT) has today a vast domain of applications from solid-state disordered systems and quantum chromodynamics to number theory and wireless communication [1]. Remarkably, the Bohigas-Giannoni-Schmit (BGS) conjecture ties RMT to classical and quantum chaos [2]. Inspired by [3], we show that even ultracold quantum gases, whose high tractability has been hymned for decades, can escape a deterministic logic and show chaotic behavior in the sense of the BGS conjecture.

In particular, we perform high-resolution trap-loss spectroscopy of Fano-Feshbach resonances with two bosonic and one fermionic isotopes of erbium. We observe an unprecedented high density of resonances [4], which allows a statistical analysis of the position of resonances according to the toolset provided by RMT. From a bottom-up approach unique to ultracold atoms, we elucidate the native source of chaotic scattering in the anisotropy of the interactions [5].

Furthermore, the so-called Porter-Thomas distribution of transition strengths is a central aspect of complex systems [6]. The degree of freedom of this distribution is just determined by the number of open channels in the system. We apply a similar analysis to the widths of Fano-Feshbach resonances in Er and find a clear difference between bosons and fermions. This difference is well in agreement with the larger density of states of fermionic ^{167}Er due to its additional hyperfine structure.

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Entangled motion using Rydberg blockade – from single atom source to atom clouds

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When excited to Rydberg states, atoms are subject to strong long range interactions, e.g. van-der-Waals or resonant dipole-dipole interactions. They give rise to strong correlations, as in Rydberg blockade [1], and state-dependent atomic motion [2]. These two effects occur jointly when one considers resonant dipole-dipole interactions between atom clouds which are in the van-der-Waals blockade regime. Here, we present the results of our recent work [3-6] on Rydberg excitation exchange and atomic motion for this setup and propose potential applications in entanglement protocols.

We distinguish between two possibilities to introduce the Rydberg excitation into the clouds: A resonant two-photon transition, which leads to a coherent collective state [7] (sometimes called "superatom"), or an off-resonant coupling which yields a small admixture of Rydberg state properties to the atoms, often referred to as "Rydberg dressing" [8].

We then focus on the atomic motion induced by resonant dipole-dipole interactions: In the case of superatoms, the atom clouds eject an atom pair, which carries the entire Rydberg excitation [3]. A periodic excitation scheme then realizes a source of pairwise entangled atoms which can be ejected on-demand [4]. In the dressed case, we show that the motional dynamics is very different – here both clouds are set in motion as a whole [5]. Moreover, for some initial states a coherent superposition of attractive and repulsive motion of the clouds can be created. Such a scenario presents a mesoscopic Schrödinger cat, where the entanglement is encoded in the motion [6]. It prevails for several microseconds and is maintained over a distance of several micrometers.

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Toward Rydberg blockade in an optical lattice

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Ultracold Rydberg atoms are a promising system to study quantum many body effects due to their strong Rydberg interactions. The strength of the interaction is tunable via the principal quantum number of the Rydberg state, and we choose a regime where only nearest neighbors in our optical lattice are strongly blockaded. We perform fluorescence spectroscopy of the 18S Rydberg level in ultracold Rb-87 by exciting a two-photon transition with intermediate detuning near the D1 line and detecting photons emitted on the D2 line with a single photon avalanche diode. We use this technique to measure a magic wavelength, where there is no differential light shift between the ground and Rydberg state, near 1064 nm to better than 1 GHz. We also report initial progress toward spectroscopy in a 3D optical lattice in which the Rydberg blockade effect should allow us to generate collective states that exhibit large spatial and temporal correlations.

Dipole-dipole interaction in a dense cold Rubidium cloud

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When atoms with a transition at wavelength λ are trapped within a volume smaller than λ^3 they are coupled by resonant dipole-dipole interactions [1]. In this regime, atoms do not behave individually, but rather in a collective way. In particular, when illuminated by near-resonant light, the collective scattering response of the atomic ensemble should be strongly dependent on the resonant dipole-dipole interaction. Here, we demonstrate a strong suppression of the scattering of light induced by the dipole-dipole interactions in a cold atom sample with a volume smaller than λ^3 , produced by confining atoms at a temperature of $\sim 100\mu$K in a microscopic optical dipole trap. This suppression is gradually more and more pronounced when we increase the number of atoms in the sample. We also observe that interactions then gradually broaden and shift the spectrum with respect to the case of N non-interacting atoms. Our results are consistent with a model of collective scattering based on 2-level coupled atomic dipole equations [2], which we have generalized to take into account the full Zeeman level structure of Rubidium 87. Future work will consist in studying the time resolved response of the atomic sample to a pulsed excitation of light to demonstrate collective effects such as super-radiance and sub-radiance.

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Ultracold Rydberg Atom Formation in Magnetic Field

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The recombination rate in ultracold neutral plasma under influence of strong magnetic field is discussed [1]. It is known that for high temperature three-body recombination law is scaled as $\alpha_0 = T_e^{-4.5}$ depending on electron temperature T_e. Obtained in [2] results reproduce this behavior at high temperature but show recombination slow down with decreasing T_e. Additional slowdown is expected due to magnetic field influence. Considering extremely strong magnetic field recombination rate can be estimated as $T_e^{-1.5}B^{-2}$, where B is magnetic field. Molecular dynamics simulation of fully ionized ultracold neutral plasma under influence of magnetic field is presented for B=50-10^4 Gs in wide range of Coulomb coupling parameter values. Electrons' energy distribution function is calculated as well as electrons' energy diffusion coefficient. It was found that while B increases kinetic bottleneck moves deeper to the bound states region and three-body collisions frequency dramatically changes [3] due to many-body interactions. This causes recombination slowdown in several orders of magnitude in compare to α_0. Obtained from simulation recombination rate α_B is consistent to experimental data [1] and proves strong field estimation.

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Strongly dipolar Fermi gases of erbium atoms

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We report on the observation of few- and many-body dipolar phenomena in a quantum degenerate Fermi gas of strongly magnetic erbium atoms. We demonstrate a new evaporative cooling scheme where spin-polarized fermions are directly cooled down to 0.1 times the Fermi temperature via universal dipolar scattering [1]. In cross-dimensional rethermalization measurements, where the sample is driven out of equilibrium, we reveal the anisotropic character of the interaction and observe that the system relaxes to equilibrium with speeds that strongly depend on the dipole orientation [2]. Furthermore, we show that the Fermi surface of our sample is deformed to an ellipsoid by the many-body DDI and that the magnitude of the deformation is tunable via an external trapping potential. The observed Fermi surface deformation represents a crucial step for exploring exotic anisotropic phases [3].

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Trapping single atoms in arbitrary arrays of optical tweezers

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Controlling individual neutral atoms in arrays of optical tweezers is a promising avenue for quantum science and technology [1, 2]. We demonstrate the trapping of single-atoms in two-dimensional arrays of microtraps with arbitrary geometries [3]. We generate the arrays using a Spatial Light Modulator (SLM), with which we imprint an appropriate phase pattern on an optical dipole trap beam prior to focusing. We trap single ^{87}Rb atoms in the sites of arrays containing up to $\sim$ 100 microtraps separated by distances as small as 3 μm, with complex structures such as triangular, honeycomb or kagome lattices (see Fig. 1). Using a closed-loop optimization of the uniformity of the trap depths ensures that all trapping sites are equivalent. This versatile system opens appealing applications in quantum information processing and quantum simulation, e.g. for simulating frustrated quantum magnetism using Rydberg atoms [4].

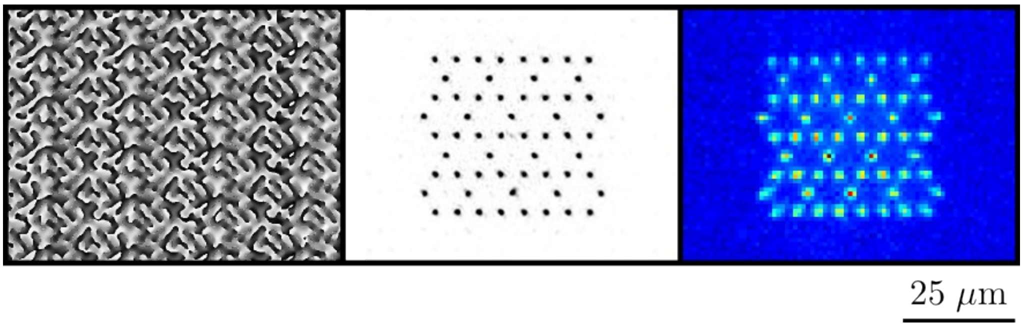

FIG. 1. left: Phase imprinted on the trap beam; center: resulting trap pattern; right: time averaged singleatom fluorescence.

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Long-range interactions between ultracold particles in external fields

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In the field of ultracold matter, dipolar gases have attracted considerable attention over the last few years. The atoms or molecules composing such gases, which possess a strong permanent electric or magnetic dipole moment, interact through long-range and anisotropic forces, which make dipolar gases into ideal candidates to study highly-correlated quantum matter. However other contributions to the long-range forces, for example quadrupolar or van der Waals interactions, can compete with the dipole-dipole interactions. Those higher-order terms of the multipolar expansion must be carefully described, in order to understand precisely the gas properties.

In this work we present our calculations on long-range interactions between various neutral atomic and molecular systems, in the presence of external electromagnetic fields, focusing on dipolar, quadrupolar and van der Waals interactions. Due to the crucial role of the particles' angular momenta, whether they are orbital, electronic or nuclear spins, the formalism of long-range interactions turns out to be very flexible and applicable to a wide variety of atomic and molecular symmetries. In addition we show that the quantum states of individual particles which are coupled by the long-range interactions must be carefully chosen. In this respect we show that, due to rotational couplings, a static electric field can turn the interaction between two ground-state polar bialkali molecules from purely van der Waals to purely dipolar.

Cold Atoms in Optical Cavity: Tool to Distinguish Between Different Phases

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Ultracold atoms in optical lattices provide an opportunity to study quantum many body systems. Such a study is useful in condensed matter, quantum optics and quantum information processing. Further, when this system is coupled with an optical cavity, it offers additional interesting features to be explored and exploited. In this work, we have used the coherent atom photon interaction exhibited by the atoms and the cavity mode, to study quantum features of this many body system. This interaction can be modeled using Jaynes Cummings Hamiltonian. It has been found that atom photon interaction on the one hand modifies the statistical properties of the cavity photons and on the other hand, the cavity mode mediates the inter atom interaction and results in long range interactions between them. In this work, we specifically focused on the former aspect and used this as a measurement tool for characterizing different phases of cold atoms in an optical lattice and study the respective phase transition. The standard methods to observe cold atoms are based on matter wave interference and their absorption image is taken with a laser. For this, atoms have to be released from the traps; destroying the coherent superposition of various many body states of these atoms. In an alternate method, these ultracold atoms interact with the quantized cavity modes of a Fabry Perot cavity [1]. In this paper, we have used this method (Fig. 1) and studied the transmission spectra of such a cavity [2]. In the first part of the paper, we have analyzed the phase transition of ultracold atoms in an optical lattice, from a superfluid (SF) to a Mott insulator (MI), and see how the transmission spectra gradually changes. In the second part, we have proposed optical measurements to distinguish between two insulating phases: MI and density wave (DW) and also scan the phase transition from a DW to SF via supersolid (SS) phase for an extended Bose Hubbard model (eBHM). The corresponding results are shown in Fig. 1 (b,c,d).

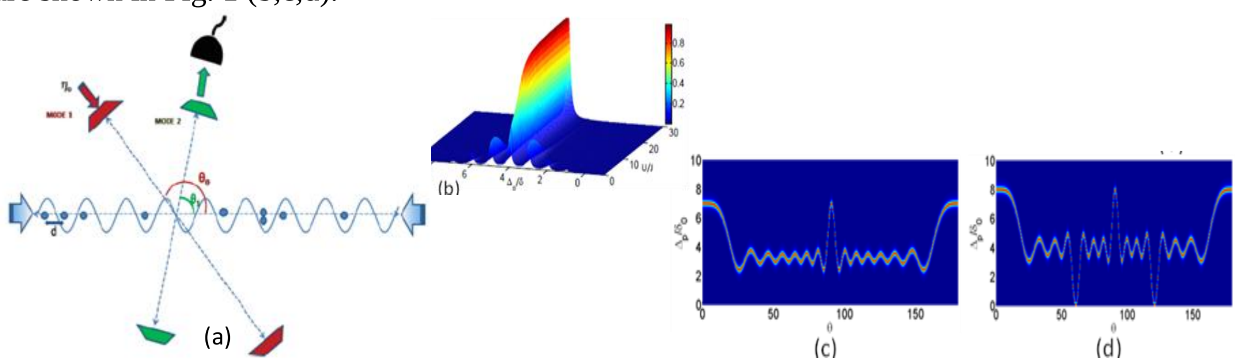

Fig.1 (a) The schematic of the model, b) Transmission spectra corresponding to the SF to MI phase transition. Spectrum as a function of angle for c) MI and d) DW.

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Many-body dynamics in long-range tunneling after a quantum quench

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Higher-order processes involving correlated tunneling across multiple lattice sites can give rise to longer-range effective interaction terms and more complex many-body critical phenomena. Here we present our experimental results where we observe long-range tunneling following a quantum quench in tilted one-dimensional Bose-Hubbard chains. We are able to directly identify that the dynamics is governed by higher-order tunneling processes scaling with $J^n/(U/n)^{n-1}$. For the second-order process a spin-echo type experiment allows for a partial revival of the phase evolution indicating a coherent quench dynamics.

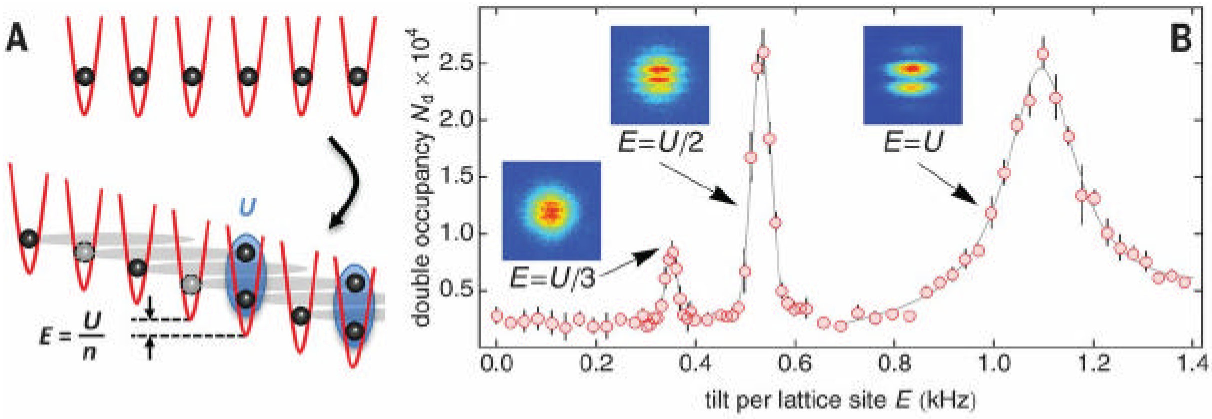

Figure 1: A) Schematic view of the long-range correlations across n sites for a tilt of E = U/n after the quench from the initial 1D one-atom Mott insulator (top) to the tilted configuration (bottom). **B)** Number of doublons as a function of the tilt per lattice site 200 ms after the quench. Here, U = 1.077(20) kHz. The solid lines are Lorentzian (for E = U) and Gaussian (for E = U/2 and E = U/3) fits to the data to determine the center positions and widths. The insets show matter-wave interference patterns obtained in TOF at E_1 = U, E_2 = U/2, and E_3 = U/3 taken after 1 ms, 9 ms, and 28 ms, respectively.

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A ^{52}Cr BEC in a double well trap
A ^{53}Cr degenerate Fermi Gas

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In our experiment, we study the effect of dipole-dipole interactions on the magnetic properties of dipolar Chromium atoms. In this poster I will present two new results.

In a first experiment, we load a Chromium Bose-Einstein Condensate in a double well trap. We prepare the atoms of each well in opposite spin states. We study spin dynamics due to dipole dipole exchange interaction. No spin dynamics is observed: the spin state is frozen. We interpret this behaviour as a classical behaviour of two macroscopic ensembles of spins, each one behaving like a giant spin S located in one well, for which spin fluctuations due to exchange interaction are reduced as 1/S [1]. This is the opposite of a BEC loaded in a lattice which exhibits spin dynamics and quantum phenomena arise [2].

I will also present the first production of a degenerate Fermi gas of ^{53}Cr atoms. To compensate for the very low ^{53}Cr atom number which we optically trap at Doppler temperature, a few 10^4 atoms at 100 µK, we load the Fermionic isotope with the Bosonic isotope in the optical trap. The atoms are then co-evaporatively cooled to degeneracy efficiently to produce a dipolar Degenerate Fermi Gas of Chromium of a 1000 atoms at 0.6 T_F

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Controlled few body Förster resonances in a frozen Rydberg gas

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Resonant energy transfer in Rydberg atoms is well known to enhance 2-body interactions between adjacent atoms [1], which is also called Förster resonances in analogy with the biological process known as FRET (Förster Resonant Energy Transfer). We use this process to realize new resonant 3-body or n-body interactions extending the pre-existing 2-body FRET processes in cold Rydberg atoms. Compared to previous results on a 4-body interaction [2] which was a coincidence product of two independent 2-body FRET processes in cesium, this new scheme can be generalized to any atoms having a total angular momentum J > 1=2.

Experimentally, we realize a magneto-optical trap where we excite atoms to the Rydberg states. Tuning a static electric field, 2-body Förster resonances can be observed due to the Stark shift of the Rydberg levels. A Förster resonance results then in a population transfer between different states involved in this energy transfer, as expressed below for a 2-body Förster resonance:

$$2\,np \;?\;\; ns + (n+1)s.$$

Considering a density high enough in order to allow the occurrence of more than two excited Rydberg atoms close to each other, we can expect a 3-body Förster resonance of the form:

$$3\,np_{3/2}\,m_{\mathrm{j}} \;?\;\; ns + (n+1)s + np_{3/2}\,m_{\mathrm{j'}}$$

where m_{j} and $m_{\mathrm{j'}}$ are two different magnetic quantum numbers.

We have observed the presence of this 3-body Förster resonance for different $np_{3/2}$ states in cesium. The 3-body Förster resonance appears in the vicinity of the 2-body resonant Stark field, being a detuned 2-body resonance assisted by a third atom. We explain then this difference in the energy exchange between the 2 and 3-body processes by the m_{j} change of the third atom.

Our observations are likely to have implications in various domains, from quantum physics to biology and new materials. This new FRET process could be used to design a 3-qubit quantum gate as proposed in [3] or to realize a heralded entanglement between two atoms, measuring the third one. FRET is also widely used in biology as an imaging tool [4] which could be extended using additional molecules inducing 3-body FRET. Finally, 3-body FRET could help improving new solar cell technology [5] which already tries to mimic light-harvesting in plants [6].

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Dipole-Induced Electromagnetic Transparency

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We determine the optical response of a thin and dense layer of interacting quantum emitters. We show that in such a dense system, the Lorentz redshift and the associated interaction broadening can be used to control the transmission and reflection spectra. In the presence of overlapping resonances, a Dipole-Induced Electromagnetic Transparency (DIET) regime, similar to Electromagnetically Induced Transparency (EIT), may be achieved. DIET relies on destructive interference between the electromagnetic waves emitted by quantum emitters. Carefully tuning material parameters allows achieving narrow transmission windows in otherwise completely opaque media [1]. We analyze in details DIET using a generalized Lorentz model and show how it can be controlled. Several potential applications of the phenomenon are proposed.

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Quantum optics and Rydberg EIT in intracavity cold atomic medium.

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Quantum states of light are one of the foremost and robust candidates for quantum information transportation and processing. Cold atomic ensembles are a prime choice to store and manipulate quantum states of light [1]. However, very often the light states stored or engineered in such systems are characterized only partially using photon counting statistics [2-4]. We demonstrate an on-demand retrieval of single photons by implementing the DLCZ protocol [5] in a cavity enhanced cold atomic memory. Single photon states were recovered with high efficiency (up to 82%) in a well defined spatio-temporal mode and consistently characterized by photon counting and homodyne tomography [6].

We theoretically investigate the quantum statistical properties of light transmitted through a cavity-enhanced atomic medium with strong optical nonlinearity induced by Rydberg-Rydberg van der Waals interactions [7]. Currently, an experiment is in progress to characterize the transmitted light by measuring the second order correlation function.

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Towards a Fermi-Fermi mixture of dysprosium and potassium

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Ultracold Fermi-Fermi mixtures with tunable interactions represent an intriguing test bed for exploring the physics of strongly interacting many-body quantum systems and few-body quantum states. Two-species Fermi gases extend the variety of phenomena thanks to mass imbalance. This motivates us to construct a dysprosium - potassium experiment exploiting the favorable mass ratio of 4. The strong magnetic moment of dysprosium allows elastic dipolar scattering between identical fermions and offers an additional degree of freedom to our system.

Coherent dipole-dipole coupling between two single atoms at a Förster resonance

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Resonant energy transfers, the redistribution of an electronic excitation between two particles coupled by the dipole-dipole interaction, occur in a variety of chemical and biological phenomena [1], most notably photosynthesis. Here, we study, both spectroscopically and in the time domain, the coherent, dipolar induced exchange of electronic excitations between two single Rydberg atoms separated by a controlled distance, and brought in resonance by applying electric or microwave fields [2]. The coherent oscillation of the system between two degenerate pair states occurs at a frequency that scales as the inverse third power of the distance, the hallmark of dipole-dipole interactions [3]. We finally study the propagation of an excitation in a three-atom system. These results show our ability to actively tune strong, coherent interactions in quantum many-body systems.

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Efficient demagnetization cooling and its limits

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We present the latest data on the demagnetization cooling of a dipolar chromium gas and discuss the limitations regarding reabsorption of optical pumping photons and light assisted collisions [1]. Demagnetizaiton cooling utilizes dipolar relaxations that couple the internal degree of freedom (spin) to the external (angular momentum) to efficiently cool an atomic cloud [2]. Optical pumping into a dark state constantly recycles the atoms that were promoted to higher spin states. The net energy taken away by a single photon is very favorable as the lost energy per atom is the Zeeman energy rather than the recoil energy. The cooling scheme was proposed by Kastler already in 1950 [3] and demonstrated in a proof of principle experiment in 2006 [4].

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Dynamical crystallization in a low-dimensional Rydberg gas

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The strong van der Waals interactions in Rydberg gases offer the possibility to study long-range correlated many-body states. In our setup, we optically excite and detect Rydberg atoms with submicron resolution, which allows us to measure spatial correlations of resulting ordered states [1]. Starting from a two-dimensional array of ground state atoms in an optical lattice, we couple to a Rydberg state in a two-photon excitation scheme. Using numerically optimized pulse shapes for coupling strength and detuning, we deterministically prepare the crystalline state in this long-range interacting many-body system [2]. Control of the spatial configuration of the initial state is of outstanding importance for our investigation of the phase diagram und the crystallization dynamics. We achieved the required control using a single-site addressing scheme allowing for preparation of initial states with sub-Poisson number fluctuations. The developed techniques clear the path towards the detailed study of quantum crystalline phases.

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The latest news about ultralong-range Rydberg molecules

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Scattering between a Rydberg electron and ground state atoms can lead to the formation of ultralong-range Rydberg molecules in an ultracold gas. We will report on the creation of D-state and S-state molecules with high principle quantum numbers *n* ranging from 40 to 111. With increasing principle quantum numbers we observe decreasing binding energies, resulting eventually in a broadening and a shift of the spectral lines [1]. We selectively excite rovibrational states of D-state molecules and by that generate alignment of these molecules [2]. We study their binding energies and the shape of the binding potential at the crossing of two m_j-states in an external electric field. The degeneracy of the electronic orbitals leads to stronger binding energies and different symmetries of the bound molecular states.

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Rydberg atoms inside hollow-core photonic crystal fibres

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Rydberg atoms have peculiar properties as enhanced sensitivities to AC/DC electric fields or exaggerated strong interactions between them, leading to optical nonlinearities on the single photon level. These properties are mostly studied with spectroscopic methods often limited by the free space diffraction limit. This can be avoided by confining Rydberg atoms inside hollow core fibres offering a perfect match of guided light modes with the atomic gas in terms of atom-light coupling. Additionally we choose Kagome type fibres due to their extremely thin structures, promising a reduced atom wall coupling. With coherent three photon spectroscopy we can show that Rydberg atoms can be excited within these fibres up to states of n=40 without severe perturbations by the fibre environment [1].

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Rydberg Ensembles: The single photon toolbox

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Deterministic excitation of a single atom to Rydberg state from an ensemble of atoms can have useful applications in single atom loading of optical lattices [1], single photon sources, and for inducing nonlinear effects in the probe field by deterministically subtracting single photons [2]. While some of the approaches that realize the deterministic excitation process use either coherent or incoherent time-dependent fields [2, 3, 4], we show that the same can be realized even with constant driving fields in the presence of a probe atom.
We show also show that the proposed scheme can be used for storage and on-demand retrieval of single photons from an ensemble of Rydberg interacting atoms, allowing them to be used as photonic memory devices.

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Electromagnetically induced transparency in an entangled medium

We theoretically investigate light propagation and electromagnetically induced transparency (EIT) in a quasi one-dimensional gas in which atoms interact strongly via exchange interactions. We focus on the case in which the gas is initially prepared in a many-body state that contains a single excitation and conduct a detailed study of the absorptive and dispersive properties of such a medium. This scenario is achieved in interacting gases of Rydberg atoms with two relevant S-states that are coupled through exchange. Of particular interest is the case in which the medium is pre- pared in an entangled spinwave state. This, in conjunction with the exchange interaction, gives rise to a non-local susceptibilty which — in comparison to conventional Rydberg EIT — qualitatively alters the absorption and propagation of weak probe light, leading to non-local propagation and enhanced absorption.

A high-resolution imaging system for Dysprosium

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Strongly dipolar quantum gases enable the observation of many-body phenomena with anisotropic, long-range interaction. Rotonic features, 2D stable solitons and the supersolid state are some of the exotic many-body phenomena predicted for dipolar quantum gases.
Recently quantum degeneracy of dysprosium, the element with the strongest magnetic dipole moment, was achieved [1,2]. After preparation of a Dysprosium condensate we plan to use a diffraction-limited custom objective with high numerical aperture for in-situ imaging. This allows to reveal the structure of the quantum gas on a sub-micron level. Combined with an electro-optical deflector system and a Pockels cell the objective is used to create tailored potentials. With this setup we want to investigate multi-well potentials [3] or ring-shaped potentials [4].

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