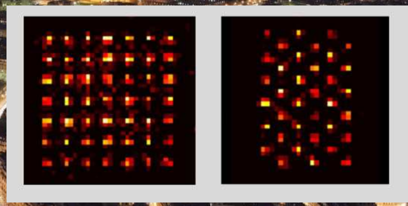
ICQSIM – 2017

International Conference on Quantum Simulation



13-17 Nov. 2017 – Paris (France)

Book of Abstracts

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General Planning

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10:15		C6 : FLURIN	C12 : SAYRIN	C18 : LOEW	C26 : DE HOND
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Pierre Pillet	*Fast thermalization of a frozen Rydberg gas in long-range interatomic dipole-dipole coupling*
Sylvain Schwartz	*Programmable quantum simulator based on a 51-atom array with Rydberg interactions*

Oral Presentations

Monday 13/11

Quantum simulations with trapped ions

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The quantum toolbox of the Innsbruck ion-trap quantum computer is applied to simulate the dynamics and to investigate the propagation of entanglement in a quantum many-body system represented by long chains of trapped-ion qubits [1]. With strings of up to 10 ions, a dynamical phase transition was recently observed [2] and an efficient procedure for the characterization of a quantum many-body system of up to 14 entangled ions has been implemented [3].

Moreover, using the quantum toolbox operations, universal (digital) quantum simulation was realized with a string of trapped ions [4]. Here we report the experimental demonstration of a digital quantum simulation of a lattice gauge theory, by realizing (1 + 1)-dimensional quantum electrodynamics (the Schwinger model) on a few-qubit trapped-ion quantum computer [3]. We are interested in the real-time evolution of the Schwinger mechanism, describing the instability of the bare vacuum due to quantum fluctuations, which manifests itself in the spontaneous creation of electron–positron pairs. To make efficient use of our quantum resources, we map the original problem to a spin model by eliminating the gauge fields in favor of exotic long-range interactions, which can be directly and efficiently implemented on an ion trap architecture.

[1] P. Jurcevic et al., Nature **511**, 202 (2014)
[2] P. Jurcevic et al., Phys. Rev. Lett. **111**, 080501 (2017)
[3] B. P. Lanyon et al., Nat. Phys. 10.1038/nphys4244 M3 (2017)
[4] E. A. Martinez et al., Nature **534**, 516 (2016)

Quantum Simulation of QED in 1D: Evidence of a Phase Transition

Elisa Ercolessi[1], Paolo Facchi[2], Giuseppe Magnifico[1], Saverio Pascazio[2], Francesco V. Pepe[2]

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INFN, Sezione di Bologna, I-40127 Bologna, Italy
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We study a lattice and finite version of QED in 1+1 dimensions, where the gauge group U(1) is discretized with $\mathbb{Z}_n$. The model is obtained by requiring that the unitary character of the minimal coupling structure is preserved and has therefore the property of formally approximating lattice quantum electrodynamics in the large-n limit. The numerical study of such approximated theories is important to determine their effectiveness in reproducing the main features and phenomenology of the target theory. We perform a careful scaling analysis, by means of a DMRG code that exactly implements the Gauss law, and show that, in absence of a background field, all $\mathbb{Z}_n$-models exhibit a phase transition which falls in the Ising universality class, with spontaneous symmetry breaking of the CP symmetry. We then perform the large-n limit and confirm that the zero-charge sector of lattice U(1)-model has a phase transition at a negative critical value of the mass parameter, that we calculate.

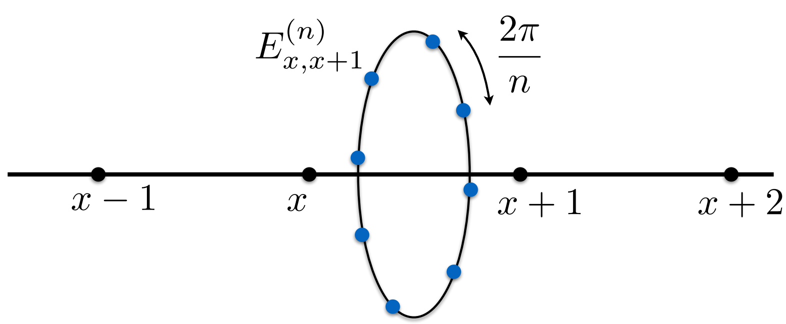

Figure 1. Discretization of QED in 1+1 dimensions (Schwinger model). Fermionic matter lives on sites x. The electric field $E^{(n)}_{x,x+1}$ lives on links and takes discrete values.

[1] Elisa Ercolessi, Paolo Facchi, Giuseppe Magnifico, Saverio Pascazio and Francesco V. Pepe, "Quantum Simulation of QED in 1D: Evidence of a Phase Transition", arXiv:1705.11047 [quant-ph] (2017).

Controlling transport and localization with an artificial gauge field

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[1] Laboratoire PhLAM – Université de Lille 1, CNRS - UMR 8523, Villeneuve d'Ascq, F-59655, France

For a long time a paradigm in condensed matter physics, Anderson localization has been observed and studied in the last decades in many different disordered systems, both classical and quantum. The symmetry characteristics of the disordered system are expected to greatly affect its localization and transport properties, yet few experimental results are available in this direction. Here we report the experimental realization of an artificial gauge field in a synthetic (temporal) dimension of a disordered, periodically driven (Floquet) quantum system. Our remarkably simple technique is used to control the Time-Reversal Symmetry properties, and leads to two novel experimental observations, representing 'smoking-gun' signatures of this symmetry breaking. The first consists in the observation of the "Coherent Forward Scattering" (CFS) [1], a genuine interferential signature of the onset of the (strong) Anderson localization. The second is the measurement of the $\beta(g)$ scaling function [2], with a direct test of the one-parameter scaling hypothesis, and of its universality in two different symmetry classes.

[1] T. Karpiuk, N. Cherroret, K. L. Lee, B. Grmaud, C. A. Mller, and C. Miniatura, Phys. Rev. Lett. **109**, 190601 (2012).
[2] E. Abrahams, P. W. Anderson, D. C. Licciardello, and T. V. Ramakrishnan, Phys. Rev. Lett. **42**, 673 (1979)

Quantum fluids of light in semiconductor lattices

Jacqueline Bloch

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Semiconductor microcavities appear today as a powerful platform for the study of quantum fluids of light. They enable confining both light and electronic excitations (excitons) in very small volumes. The resulting strong light-matter coupling gives rise to hybrid light-matter quasi-particles named cavity polaritons. Polaritons propagate like photons but strongly interact with their environment via their matter part: they are fluids of light and have been shown to exhibit fascinating properties such as superfluidity or nucleation of quantized vortices. Sculpting microcavities at the micron scale, it is possible to engineer lattices of various geometries and use this photonic platform for the emulation of different Hamiltonians.

I will illustrate with some examples the potential of this non-linear photonic platform for quantum simulation. Polariton lasing can be triggered in the topological edge states of a 1D SSH chain, with robustness to disorder related to the underlying topology. Quasi periodic lattices have shown fractal energy spectrum and edge states related to structural topological invariants. Finally honeycomb lattices of coupled cavities reveal Dirac physics and new edge states related to high energy modes emulating p orbitals. When controlling the interplay between pump, on-site nonlinearity and dissipation, this photonic platform opens the way to the exploration of complex non-linear dynamics, non-linear topological physics and in a near future quantum many body physics with light.

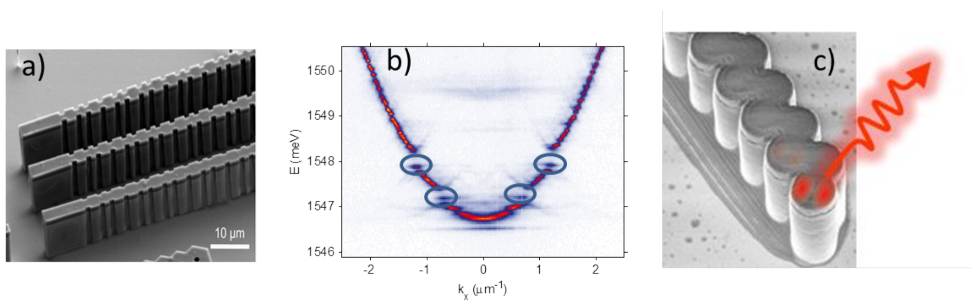

Figure 1. a) Scanning electron microscopy (SEM) image of a 1D polariton quasi-crystal; b) Measured polariton far field emission in a 1D quasi-crystal: a fractal band structure is observed with edge states (encircled); c) SEM image of a 1D SSH chain of coupled micropillars with schematic representation of polariton lasing in a topological edge state.

[1] F. Baboux et al., PRB 95, 161114(R) (2017)
[2] M. Milicevic et al., Phys. Rev. Lett. 118, 107403 (2017)
[3] P. Saint Jean et al., Nature Photonics 11, 651 (2017).

Quantum simulation of a Fermi-Hubbard model using a semiconductor quantum dot array

C.J. van Diepen[1,2], T. Hensgens[1], T. Fujita[1], L. Janssen[1], Xiao Li[3], C. Reichl[4], W. Wegscheider[4], S. Das Sarma[3] & L.M.K. Vandersypen[1]

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[2] Netherlands Organisation for Applied Scientific Research (TNO), 2600 AD Delft, The Netherlands
[3] Condensed Matter Theory Center and Joint Quantum Institute, University of Maryland, College Park, Maryland 20742, USA
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Interacting fermions on a lattice show many exotic phases of matter. Semiconductor quantum dots are widely tunable and allow for versatility in design, which makes them very promising quantum simulators. Furthermore, quantum dots readily adhere to an engineerable Fermi-Hubbard model. Due to substantial electrostatic disorder inherent to solid state few attempts have been made at performing analog quantum simulations. Here we demonstrate the development of a semi-automated toolbox in order to suppress this disorder. By utilizing the individual control over chemical potentials and inter-dot tunnel couplings we explore the parameter space of the Fermi-Hubbard model. We show (see Figure 1) the first detailed characterization of the collective Coulomb blockade transition, which is the finite-size analogue of the interaction-driven Mott metal-to-insulator transition. As control over semi-conductor quantum dot arrays continues to improve, the ideas presented here show how this platform can be used for the investigation of complex many-body physics.

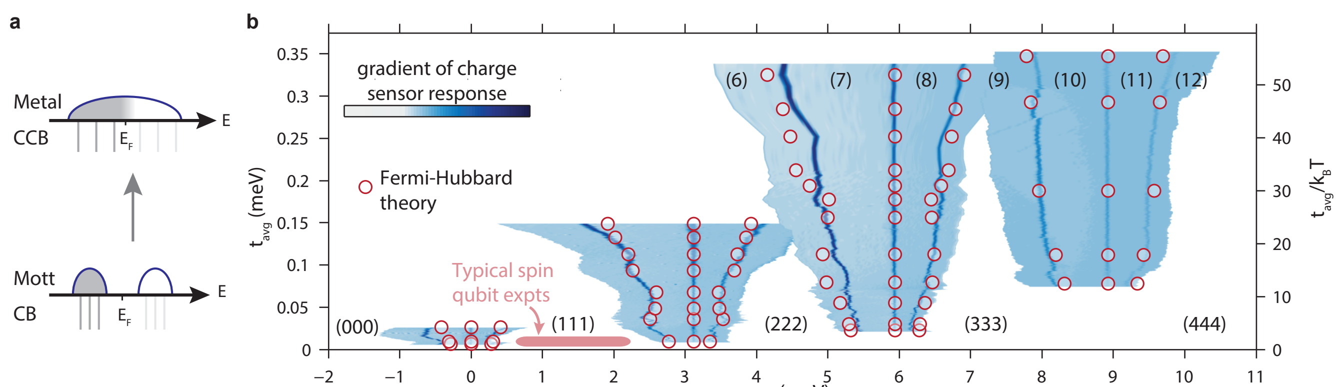

Figure 1. a) Schematic comparison of the charge addition spectrum of a Mott insulator and a triple quantum dot array in Coulomb blockade (bottom) and a metallic phase at half filling and a triple quantum dot array in collective Coulomb blockade (top). **b)** The measured parameter space of the Fermi-Hubbard model as a function of electron filling and tunnel coupling. The blue lines indicate the addition of an electron to the system, while the red circles show extended Hubbard model simulations. Text in brackets denotes electron filling.

[1] T. Hensgens, T. Fujita, L. Janssen, Xiao Li, C.J. van Diepen, C. Reichl, W. Wegscheider, S. Das Sarma and L.M.K. Vandersypen, Nature in print, see arXiv:1702.07511.

Quantum simulation of mesoscopic Fermi systems

Philipp Preiss[1], Andrea Bergschneider[1], Vincent Klinkhamer[1], Ralf Klemt[1],Gerhard Zuern[1], Selim Jochim[1]

[1] Physikalisches Institut, Heidelberg University, Germany

Ultracold quantum gases in optical potentials have achieved spectacular progress in the experimental simulation of complex quantum systems. Complementary to many-body experiments, mesoscopic systems comprised of a small number of atoms offer the possibility to study entangled quantum states with an exceptional degree of versatility and control.

We have implemented a highly tunable platform to study such correlated few-fermion systems. Using reconfigurable optical microtraps, we prepare quantum states of ^{6}Li atoms with a deterministic atom number and spin configuration and tune interactions via a magnetic Feshbach resonance. A novel readout scheme with single-particle sensitivity allows us to measure spin-resolved correlations in time of flight.

Such momentum correlations characterize few-body systems via the coherence and symmetry of the wavefunction. Focusing on the Fermi-Hubbard double-well, we observe high-contrast interference of indistinguishable fermions, the build-up of correlations due to interactions and the emergence of entanglement between particles. Our techniques can be applied to larger systems to characterize many-body phases via their high-order correlation functions.

Tuesday 14/11

Spectral signatures of many-body localization of interacting photons

P. Roushan[1], C. Neill[2], J. Tangpanitanon[3], V.M. Bastidas[3], A. Megrant[1], R. Barends[1], Y. Chen[1], Z. Chen[2], B. Chiaro[2],A. Dunsworth[2], A. Fowler[1], B. Foxen[2], E. Jeffrey[1], J. Kelly[1], E. Lucero[1], J. Mutus[1], M. Neeley[1], C. Quintana[2], D. Sank[1], A. Vainsencher[2], J. Wenner[2], T. White[1], H. Neven[1], D. G. Angelakis[3,4], J. Martinis[1,2]

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[2]Department of Physics, University of California, Santa Barbara, California, USA
[3]Centre for Quantum Technologies, National University of Singapore, Singapore
[4]School of Electrical and Computer Engineering, Technical University of Crete, Chania, Crete, Greece

Statistical mechanics is founded on the assumption that a system can reach thermal equilibrium, regardless of the starting state. Interactions between particles facilitate thermalization, but, can interacting systems always equilibrate regardless of parameter values ? The energy spectrum of a system can answer this question and reveal the nature of the underlying phases. However, most experimental techniques only indirectly probe the many-body energy spectrum. Using a chain of nine superconducting qubits, we implement a novel technique for directly resolving the energy levels of interacting photons. We benchmark this method by capturing the intricate energy spectrum predicted for 2D electrons in a magnetic field, the Hofstadter butterfly. Increasing disorder leads to the formation of a mobility edge, where the spatial extent of energy eigenstates shrink at the edge of the energy band. At strong disorder, the energy levels cease to repel one another and their statistics approaches a Poisson distribution - the hallmark of transition from metallic to the many-body localized phase. Our work introduces a new many-body spectroscopy technique to study quantum phases of matter.

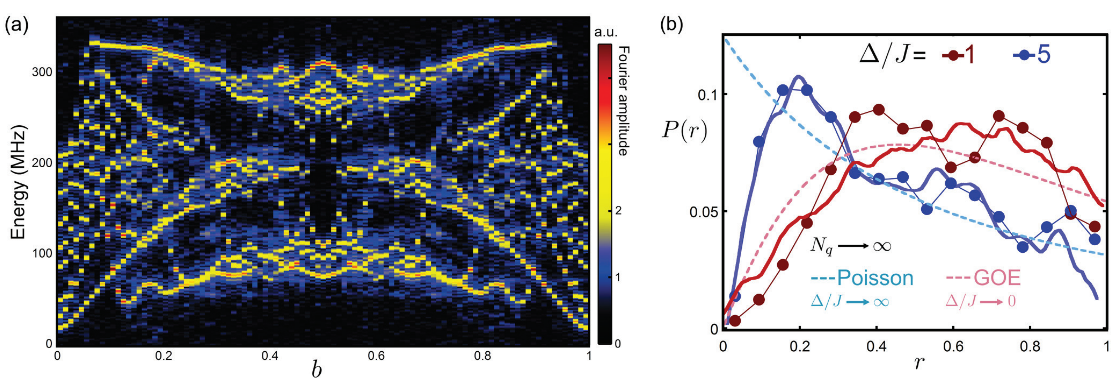

Figure 1. (a) Experimental realization of Hofstadter butterfly with our 9 qubit chain. (b) We use the distribution of the energy levels to study ergodic dynamics and its breakdown. When there are two photons in the system, for small disorder, the measured histogram of levels shows GOE distributions, which is predicted when the energy eigenstate repel each other. For large disorder, the histogram tends toward a Poisson distribution, which is the signatory of transition to the many-body localized phase.

Circuit quantum simulation of a Tomonaga-Luttinger liquid with a single impurity

A. Anthore[1,2], Z. Iftikhar[1], E. Boulat[2], F.D. Parmentier[1], A. Cavanna[1], A. Ouerghi[1], U. Gennser[1], and F. Pierre[1]

[1] Centre de Nanosciences et de Nanotechnologies (C2N), CNRS, Univ Paris Sud-Université Paris-Saclay, 91120 Palaiseau, France
[2] Univ Paris Diderot, Sorbonne Paris Cité, 75013 Paris, France

One-dimensional (1D) systems at low temperatures form exotic phases of strongly-correlated matter believed to be generically described by the so-called Tomonaga-Luttinger liquid (TLL) concept. A hallmark signature in 1D conductors is that, when the temperature is reduced, even a single impurity can drive them into an insulating state. However, the extreme sensitivity of this metal-insulator transition impedes experimental explorations of real-world TLLs. Furthermore, its theoretical treatment has only been achieved exactly for specific strengths of interaction. A quantum simulator can provide a powerful workaround, as we here show with a hybrid metal-semiconductor dissipative quantum circuit (Fig. 1a), implementing a TLL analogue with adjustable electronic interactions and a fully tunable scattering impurity. Measurements reveal the renormalization group 'beta-function' for the conductance (Fig. 1b), which completely determines the scaling flow to an insulating state upon cooling. Moreover, we establish the quantitative scaling temperature versus model parameters and explore the out-of-equilibrium regime. With the quantum simulator quality demonstrated by the precise quantitative agreement with existing and novel predictions, we then achieve quantum simulation in its strongest sense by elucidating theoretically unsolved regimes. Additional probes (dynamics, fluctuations, heat) and device evolutions could open the path to investigations of a broad variety of correlated phenomena, with direct nanoelectronic implications.

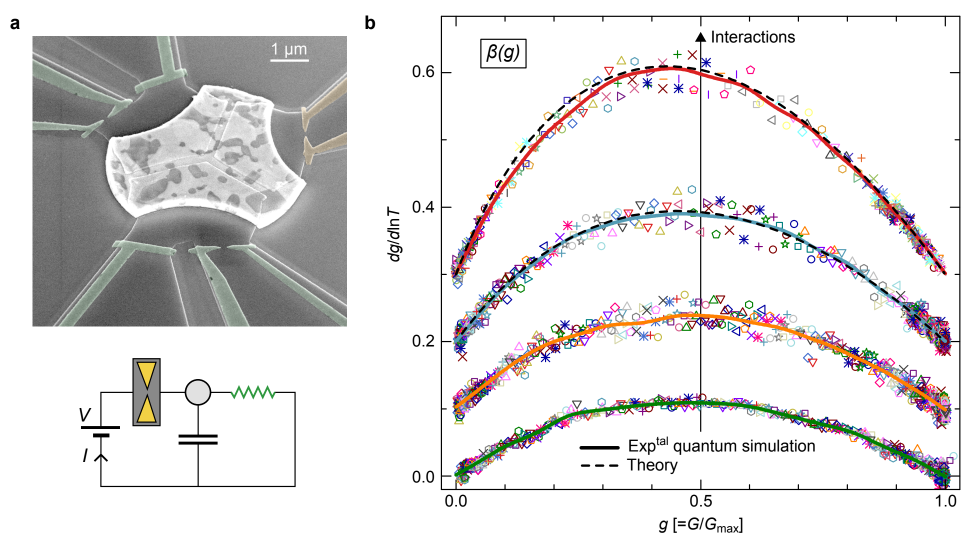

Figure 1. a, TLL analogue quantum simulator: device micrograph (top), circuit (bottom). **b**, Conductance renormalization group beta-function: theory and quantum simulation.

Observing The Topological Invariant of Bloch Bands Using Quantum Walks in Superconducting Circuits

E. Flurin[1], V.V. Ramasesh[1], N. Yao[1], I. Siddiqi[1]

[1] Quantum Nanoelectronics Laboratory, UC Berkeley

The direct measurement of topological invariants in both engineered and naturally occurring quantum materials is a key step in classifying quantum phases of matter. Here we motivate a toolbox [1] based on time-dependent quantum walks as a method to digitally simulate single-particle topological band structures. Using a superconducting qubit dispersively coupled to a microwave cavity, we implement two classes of split-step quantum walks and directly measure the topological invariant (winding number) associated with each. The measurement relies upon interference between two components of a cavity Schrödinger cat state and highlights a novel refocusing technique which allows for the direct implementation of a digital version of Bloch oscillations. Our scheme can readily be extended to higher dimensions, whereby quantum walk-based simulations can probe topological phases ranging from the quantum spin Hall effect to the Hopf insulator.

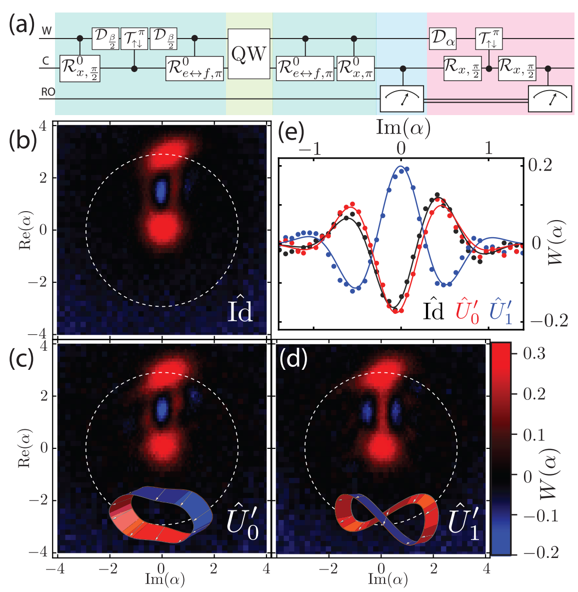

Figure 1. Winding number measurement via direct Wigner tomography of refocused Schrdinger cat states. (a) Protocol for measuring topology via a Bloch oscillating quantum walk. Wigner tomography of (b) the cat undergoing no quantum walk, (c) the cat after undergoing the trivial walk, and (d) the cat after undergoing the topological walk. The Berry phase — captured by the phase difference between the topological and the trivial walks — is $1.05\pi \pm 0.06\pi$ in experiment, consistent with the theoretical expectations of π.

[1] E Flurin, VV Ramasesh, S Hacohen-Gourgy, LS Martin, NY Yao, I Siddiqi - Physical Review X 7 (3), 031023. (2017)

Detection of bulk topological features in real time

Pietro Massignan[1,2]

[1] Universitat Politècnica de Catalunya, Barcelona, Spain
[2] ICFO – Institute of Photonic Sciences, Castelldefels (Barcelona), Spain

Topological insulators are fascinating states of matter exhibiting protected edge states and robust quantized features in their bulk. Topological features are usually detected by means of transport measurements in systems with filled bands, or by direct imaging of the edge states. Here we show that the topological invariants characterizing one-dimensional chiral systems may be read out by performing a simple bulk measurement in real time [1]. To this aim, we introduce the mean chiral displacement, and we show analytically that this observable rapidly converges to the chiral winding. Then we discuss how periodically-driven (Floquet) systems are characterized by two windings, and we present experimental measurements of both invariants in a quantum walk with twisted photons. Combining the two windings allows us to retrieve the bulk-boundary correspondence, and to characterize the complete topological phase diagram of this system. Finally, we prove that the proposed detection is robust to spatial and temporal disorder. The method outlined here is extremely general, as it can be applied to all one-dimensional platforms simulating static or periodically-driven chiral systems.

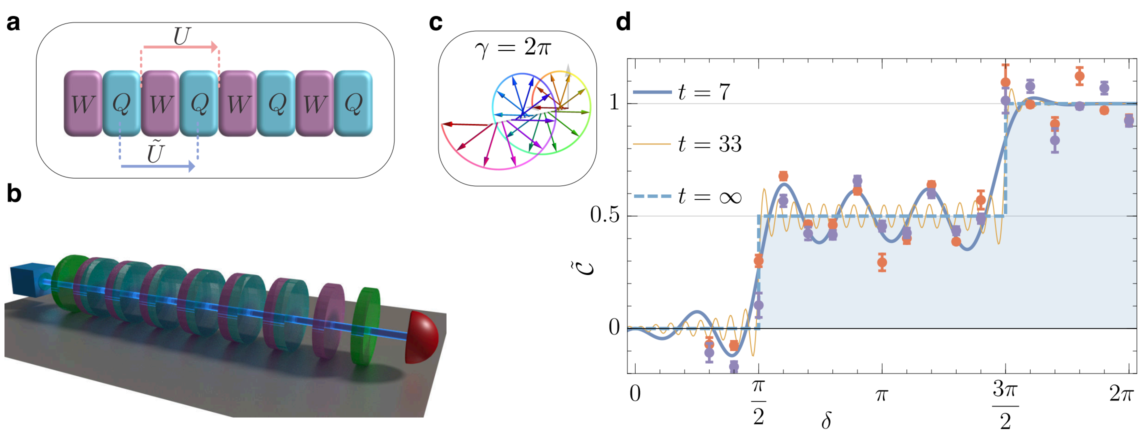

Figure 1. (a) Different choices of the time origin in a periodically-driven system lead to effective Hamiltonian with different windings. (b) Sketch of the experimental setup. (c) Winding of the effective Hamiltonian. (d) Experimental measurement of the mean chiral displacement (points) and analytical results (lines). In the long-time limit, the mean chiral displacement converges to the chiral winding (dashed line).

[1] F. Cardano, A. D'Errico, A. Dauphin, M. Maffei, B. Piccirillo, C. de Lisio, G. De Filippis, V. Cataudella, E. Santamato, L. Marrucci, M. Lewenstein, and P. Massignan, *Detection of Zak phases and topological invariants in a chiral quantum walk of twisted photons*, Nature Communications **8**, 15516 (2017).

Studying the Functional Quantum Biology of Light-Harvesting Processes with Superconducting Circuits

Anton Potočnik,[1] Arno Bargerbos,[1] Florian A. Y. N. Schröder[2], Saeed A. Khan[3], Michele C. Collodo,[1] Simone Gasparinetti,[1] Yves Salathé,[1] Celestino Creatore,[2] Christopher Eichler,[1] Hakan E. Türeci,[3] Alex W. Chin,[2] Andreas Wallraff[1]

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[2] Cavendish Laboratory, University of Cambridge, J. J. Thomson Avenue, Cambridge CB3 0HE, United Kingdom.
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The process of photosynthesis is despite almost a century long investigation still not fully understood. With recent observations of quantum coherent effects in light harvesting protein complexes the interesting question whether an interplay of quantum and classical effects can play an important functional role in biological processes emerged. In particular, the high efficiency of the energy transport has been theoretically shown to result from such an interplay. Testing these ideas in biological systems is extremely challenging due to an immense molecular complexity and the lack of precise control of system parameters. Comprehensive model systems are therefore needed to verify the models and gain an experimental insight into the basic concepts behind energy transfer in disordered systems. To address this problem we employ an analog quantum simulator based on superconducting circuits to study energy transport in a system of three qubits exposed to Markovian and non-Markovian environments. Our results show the existence of an optimal noise power that maximizes the energy transport, which is in good agreement with the theoretical models of noise-assisted transport. Furthermore we show that highly structured non-Markovian environments can lead to higher transfer efficiencies where transport is highly sensitive to the features of the noise spectrum. These observations are also relevant for understanding olfactory processes giving rise to the sense of smell.

Quantum annealing, gauge theories, and optimal control

Simone Montangero

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Institute for Complex Quantum Systems & Center for Integrated Quantum Science and Technologies, Universität Ulm, D-89069 Ulm, Germany.

Quantum optimal control allows finding the optimal strategy to drive a quantum system in a target state. We review an efficient algorithm to optimally control many-body quantum dynamics and apply it to quantum annealing, going beyond the adiabatic strategy. We report some theoretical and experimental applications of optimal quantum annealing, among which, its application to Rydberg atoms in optical lattices and to the gauge theory resulting from the mapping of classical hard problems to short-range quantum Hamiltonians. Finally, we present an information theoretical analysis of quantum optimal control processes and speculate on their implications on quantum annealing.

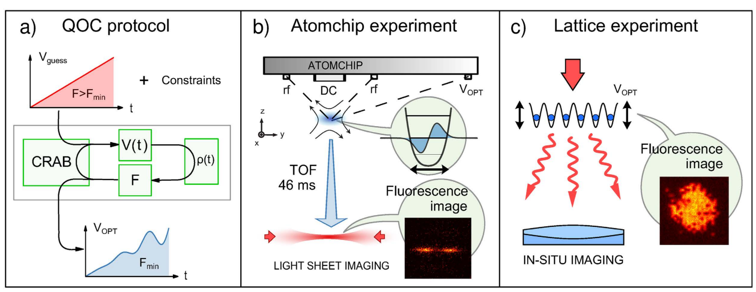

Figure 1. Optimal control protocols applied to quantum technologies experiments, from [2].

[1] J. Cui et al. Quantum Sci. Technol. **2**, 35006 (2017).
[2] S. van Frank et al. Sci. Rep. **6**, 34187 (2016).
[3] M. Dalmonte and S. Montangero, Contemp. Phys. **7514**, 1 (2016).
[4] S. Lloyd and S. Montangero, Phys. Rev. Lett. **113**, 10502 (2014).

Quenches of the coupling constant in 1D Bose gases : evolution of squeezed Bogoliubov modes monitored by density ripples analysis

Isabelle Bouchoule, Maximilian Schemmer

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Out-of-equilibrium dynamics of interacting many-body systems is a central subject in the domain of quantum simulation, both because of its relevance, being ubiquitous in nature, and because of the enormous complexity of its theoretical and even numerical description. Here we investigate out-of-equilibrium dynamics induced by a sudden change of the interaction strength in a Bose gas. More specifically, we experimentally probe one-dimensional Bose gases in the low-temperature quasi-condensate regime. Low energy modes are the phononic modes, their conjugate quadratures corresponding to density and phase fluctuations. The effect of a sudden change of the interaction strength is to squeeze each phononic mode, the energy being no longer equally distributed on both quadratures. At the linearised level, the subsequent evolution is, for each mode, a rotation of the squeezed phase space distribution, at the frequency of the mode. Observing this dynamic is however challenging. Density fluctuations are strongly reduced by the repulsive interactions and very difficult to measure. Phase fluctuations on the other hand are large. They give the dominant contribution to the first order-correlation function and its Fourier transform, the momentum distribution. However, in these functions, the contribution of all Bogoliubov modes are mixed, the large phase fluctuations rendering lowest order Taylor expansion inaccurate. The behavior after a modification of the interaction strength is a light cone effect [1] and the underlying oscillatory behavior of each Bogoliubov mode is not transparent. On the opposite, we show that the analysis of the density ripples that emerge from small time-of-flight experiments [2] permits to retrieve the behavior of individual Bogoliubov modes, providing small enough time of flight are used.

Experimentally, we investigated quenches of the interactions strength in 1D Bose gases using our atom-chip experiment [3]. Quench the effective 1D interaction strength is realized performing a fast modification of the transverse confinement. We then probe the system, after different evolution times. The probing consists in analyzing the density ripples that emerge after a short time-of-flight. More precisely, we extract the weight of the different Fourier component of the density ripples, using a set of data taken in the same conditions. We observed the oscillatory behavior of the squeezed Bogoliubov modes, each at its own frequency. We probe different quench amplitude and different quench directions. We also analyze the observed damping of the oscillations.

[1] T.Langen, R. Geiger, M. Kuhnert and J. Schmiedmayer, Nat. Phys. **9**, 640 (2013).
[2] A. Imambekov *et al.*, Phys. Rev. A **80**, 033604 (2009).
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Probing superfluidity in a quasi two-dimensional Bose gas through its local dynamics

R. Dubessy[1], C. De Rossi[1], K. Merloti[1], M. de Goër de Herve[1], T. Badr[1], A. Perrin[1], L. Longchambon[1], and H. Perrin[1]

[1] Laboratoire de physique des lasers, UMR 7538, CNRS & Université Paris 13, Villetaneuse, France

We report [1] direct evidence of superfluidity in a quasi two-dimensional Bose gas by observing its dynamical response to a collective excitation, the scissors mode. Relying on a novel local average analysis, we are able to probe inhomogeneous clouds and reveal their local dynamics. Using principal component analysis we evidence the localization of the scissors mode dynamics. We identify in this way the superfluid and thermal phases inside the gas and locate the boundary at which the Berezinskii–Kosterlitz–Thouless (BKT) crossover occurs.

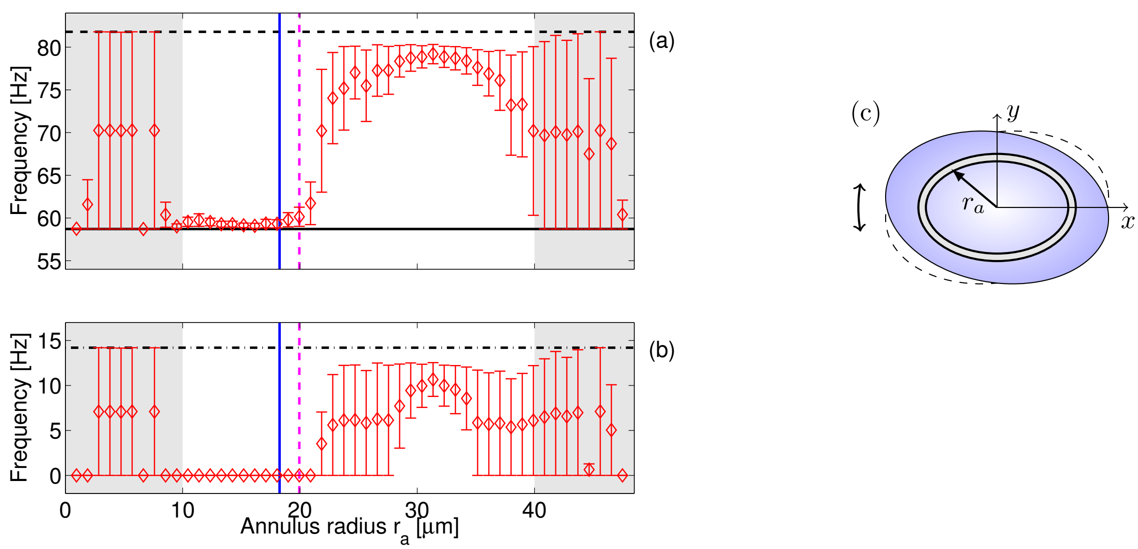

Figure 1. (a,b) Local frequency of the scissors mode in a quasi two-dimensional Bose gas as a function of the local analysis radius r_a, as sketched in (c). At small radii we find only a single frequency corresponding to the superfluid prediction. For larger radii we find both high and low frequency components, as expected for a collisionless thermal gas. The vertical lines report the expected location of the BKT boundary within the local density approximation (infinite system, solid blue, including finite size corrections, dashed magenta).

[1] C. De Rossi, R. Dubessy, K. Merloti, M. de Goër de Herve, T. Badr, A. Perrin, L. Longchambon, and H. Perrin, New J. Phys. **18**, 062001 (2016)

Annual meeting of GdR Atomes Froids

Tan's contact for one-dimensional $SU(N)$ Fermi gases

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A universal decay power-law of the large-momentum tails of the momentum distribution, fixed by Tans contact coefficients, constitutes a direct signature of strong correlations in a short-range interacting quantum gas. We derive the Tan's contact of one-dimensional, strongly interacting gases under harmonic confinement, both in the case of a $SU(N)$ Fermi gas [1,2] and of a Bose-Fermi mixture [3]. In both types of multicomponent mixtures, we find a direct correspondence between the value of the Tan's contact and the symmetry of the state. We show that a local density approximation on the Bethe-Ansatz equation of state for the homogeneous gas is in excellent agreement with the results for the harmonically confined gas and predicts a scaling behavior of the Tan's contact. This provides useful analytical expressions for the dependence on the number of particles, number of components and on interaction strength.

[1] J. Decamp, Pacome Armagnat, Bess Yiyuan Fang, M. Albert, Anna Minguzzi, Patrizia Vignolo New J. Phys. **18**, 055011 (2016)
[2] J. Decamp, Johannes Jünemann, M. Albert, Matteo Rizzi, Anna Minguzzi, Patrizia Vignolo Phys. Rev. A **15**, 053616 (2016)
[3] J. Decamp, Johannes Jünemann, M. Albert, Matteo Rizzi, Anna Minguzzi, Patrizia Vignolo, arXiv:1707.09206

Non-equilibrium quantum magnetism with ultracold Rydberg atoms

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We experimentally investigate highly tunable quantum systems made of ultracold atoms coupled to highly-excited Rydberg states. Due to their strong and long-range dipolar interactions, these systems provide well controlled models for simulating quantum magnetism and exotic quantum matter, especially in out-of-equilibrium scenarios. In the first set of experiments we investigate dipole mediated transport of spin excitations as they migrate through a disordered medium dressed by a laser field [1]. By tuning the laser field we introduce a controllable dissipative environment which causes a transition from classical (diffusive) spreading to a coherent non-ergodic regime in which spreading stops almost completely. In the second set we explore driven-dissipative and non-equilibrium quantum spin systems formed by dressing the Rydberg states with lasers or microwave fields [2,3]. We find that the rate of relaxation and the steady state magnetisation are convenient observables for distinguishing key relaxation processes and vastly different regimes of many-body quantum systems driven away from equilibrium.

*work performed in collaboration with Alda Arias, Jürgen Berges, Stephan Helmrich, Graham Lochead, Asier Piñeiro Orioli, Adrien Signoles, Matthias Weidemüller, Hendrik Weimer

[1] G. Günter, H. Schempp, M. Robert-de-Saint-Vincent, V. Gavryusev, S. Helmrich, C.S. Hofmann, S. Whitlock, M. Weidemller, Science **342**, 954–956 (2013).

[2] Stephan Helmrich, Alda Arias, Shannon Whitlock, arXiv:1605.08609 (2016).

[3] A. Pineiro Orioli, A. Signoles, H. Wildhagen, G. Günter, J. Berges, S. Whitlock, M. Weidemller, arXiv:1703.05957 (2017).

A three-(optical) photon coherent population trapping demonstrated, toward quantum manipulations of a cloud of trapped ions.

Caroline Champenois[1], Mathieu Collombon[1], Cyril Chatou[1], Gaétan Hagel[1], Didier Guyomarc'h[1], Marie Houssin[1], Jofre Pedregosa-Gutierrez[1], Martina Knoop[1]

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The three photon coherent population trapping identified in [1] for calcium-like ions is observed in a cloud of several hundreds of laser-cooled calcium ions in an RF-linear quadrupole trap. This coherent process takes the ions to a dark state built on the linear superposition of the ground state and the two fine structure components of the metastable D-state which can serve as optical or THz qu-bits (see Figure 1). The ion state could then be coherently transferred between the naked eigenstates by a STIRAP-like process [3]. The advantage of a coherent three-photon process compared to two-photon one lies in the possibility of exact cancellation of the first order Doppler shift, even for very different wavelengths : 397, 729 and 866 nm in our case. The dark line is referenced to the magnetic dipolar transition between the two D-states and could serve as a THz frequency standard [2]. To take full advantage of this dark line, we use a dedicated frequency comb to simultaneously lock the 3 involved lasers and constrain their relative phase fluctuations.

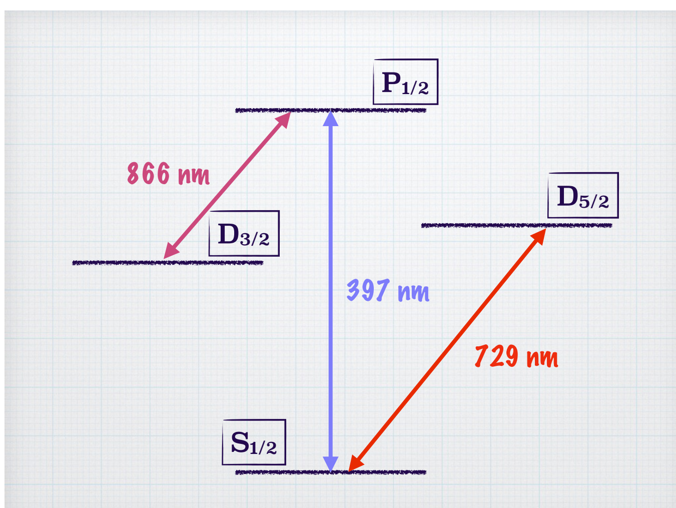

Figure 1. Relevant atomic states and transitions involved in the three-photon coherent population trapping in Calcium ions.

[1] C. Champenois, G. Morigi, J. Eschner, Phys. Rev. A **74** 053404 (2006).

[2] C. Champenois, G. Hagel, M. Houssin, M. Knoop, C. Zumsteg, and F. Vedel, Phys. Rev. Lett. **99** 013001 (2007).

[3] M. R. Kamsap, T. B. Ekogo, J. Pedregosa-Gutierrez, G. Hagel, M. Houssin, O. Morizot, M. Knoop and C. Champenois, Phys. B, At. Mol. Opt. Phys. **46** 145502 (2013) .

Single-atom-resolved probing of lattice gases in momentum space

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Measuring the full distribution of individual particles is of fundamental importance to characterize many-body quantum systems through correlation functions at any order. Real-space probes of individual quantum objects – ions, superconducting qbits, Rydberg atoms or neutral atoms throuhg a quantum gas microscope – have indeed paved the way to unprecedented investigations of many-body physics. Here I will present an experiment that provides the possibility to reconstruct the momentum-space distribution of three-dimensional interacting lattice gases atom-by-atom [1]. This is achieved by detecting individual metastable Helium atoms [2,3,4] in the far-field regime of expansion, when released from an optical lattice. We benchmark our technique with Quantum Monte-Carlo calculations, demonstrating the ability to resolve momentum distributions of superfluids occupying 10^5 lattice sites. It permits a direct measure of the condensed fraction across phase transitions, as we illustrate on the superfluid-to-normal transition. Our single-atom-resolved approach opens a new route to investigate interacting lattice gases through momentum correlations.

[1] H. Cayla, C. Carcy, Q. Bouton, R. Chang, G. Carleo, M. Mancini and D. Clément, submitted (2017).
[2] Q. Bouton, R. Chang, L. Hoendervanger, F. Nogrette, A. Aspect, C. Westbrook and D. Clément, Phys. Rev. A **91**, 061402(R) (2015).
[3] F. Nogrette, D. Heurteau, R. Chang, Q. Bouton, C. Westbrook, R. Sellem and D. Clément, Rev. Scient. Instrum. **86**, 113105 (2015).
[4] R. Chang, Q. bouton, H. Cayla, C. Qu, A. Aspect, C. Westbrook and D. Clément, Phys. Rev. Lett. **117**, 235303 (2016).

Wednesday 15/11

Many-body physics with arrays of individual Rydberg atoms

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This talk will present our on-going effort to control the dipole-dipole interaction between cold Rydberg atoms in order to implement spin Hamiltonians that may be useful for quantum simulation of condensed matter problems. In our experiment, we trap individual atoms in two-dimensional arrays of optical tweezers [1] separated by few micrometers and excite them to Rydberg states using lasers. The arrays are produced by a spatial light modulator, which shapes the dipole trap beam. We can create almost arbitrary, two-dimensional geometries of the arrays with near unit filling [2].

The talk will present our demonstration of the coherent energy exchange in small chains of Rydberg atoms resulting from their dipole-dipole interaction [3]. This exchange interaction realizes the XY spin model. We have also implemented the quantum Ising model [4]. The spin Hamiltonian is mapped onto a system of Rydberg atoms excited by lasers and interacting by the van der Waals Rydberg interaction. We study various configurations such as one-dimensional chains of atoms with periodic boundary conditions, rings, or two-dimensional arrays containing up to 30 atoms. We measure the dynamics of the excitation for various strengths of the interactions between atoms. We compare the data with numerical simulations of this many-body system and found excellent agreement for some of the configurations.

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

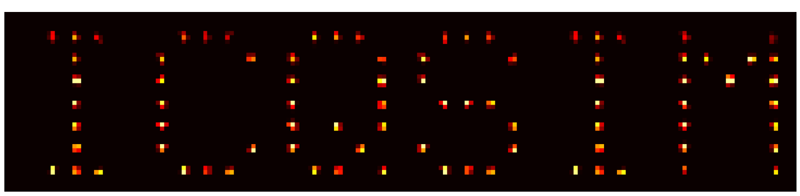

Figure 1. Fluorescence images of individual atoms trapped in arrays of optical tweezers separated by a few micrometers.

[1] F. Nogrette *et al*, Phys. Rev. X **4**, 021034 (2014).
[2] D. Barredo *et al*, Science **354**, 1021 (2016).
[3] D. Barredo *et al*, Phys. Rev. Lett. **114**, 113002 (2015).
[4] H. Labuhn *et al*, Nature **534**, 667 (2016).

Studying absorbing-state phase transitions in a cold Rydberg gas

C. Simonelli[1,2], M. Archimi[2], F. Castellucci[2], E. Arimondo[1,2], D. Ciampini[1,2], R. Gutierrez[3,4], M. Marcuzzi[3,4], I. Lesanovsky[3,4], O. Morsch[1,2]

[1] INO-CNR, Via G. Moruzzi 1, 56124 Pisa, Italy
[2] Dipartimento di Fisica E. Fermi, Università di Pisa, Largo Bruno Pontecorvo 3, 56127 Pisa, Italy
[3] School of Physics and Astronomy, University of Nottingham, Nottingham, NG7 2RD, UK
[4] Centre for the Mathematics and Theoretical Physics of Quantum Non-Equilibrium Systems, University of Nottingham, Nottingham, NG7 2RD, UK

Phase transitions in non-equilibrium systems have been extensively studied in recent years but continue to pose challenges. One example of such a phase transition is that between a non-fluctuating absorbing phase [1], e.g., an extinct population, and one in which the relevant order parameter, such as the population density, assumes a finite value. Here we report on experimental studies of such a non-equilibrium phase transition in an open driven quantum system. In our experiment, rubidium atoms in a quasi one-dimensional cold disordered gas are excited to Rydberg states by the facilitation mechanism [2]. This conditional excitation process (which in the present work occurs in the incoherent regime and can thus be described by a rate equation) competes with spontaneous decay and leads to a crossover between a stationary state with no excitations and one with a finite number of Rydberg excitations as a function of the driving strength [3] (see figure). We observe a characteristic power-law scaling of the Rydberg excitation density (inset of figure) as well as increased fluctuations close to the transition point (dashed line in the figure). Our study [4] paves the road towards future investigations into the largely unexplored physics of non-equilibrium phase transitions in open many-body quantum systems, both in the semi-classical (incoherent) and in the quantum (coherent) regime.

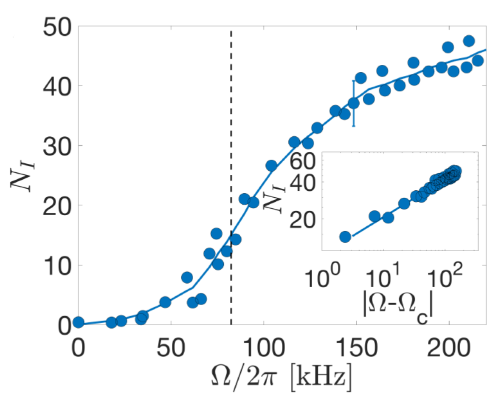

Figure 1. Number of Rydberg excitations N_I as a function of driving strength Ω.

[1] H. Hinrichsen, Adv. Phys. **49**, 815 (2000).
[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] M. Marcuzzi, E. Levi, W. Li, J. P. Garrahan, B. Olmos, and I. Lesanovsky, New J. Phys. **17**, 072003 (2015).
[4] R. Gutierrez, C. Simonelli, M. Archimi, F. Castellucci, E. Arimondo, D. Ciampini, M. Marcuzzi, I. Lesanovsky, and O. Morsch, arXiv:1611.03288 (2017).

Towards quantum simulation with circular Rydberg atoms

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We propose to realize a quantum simulator of spin arrays, based on laser-trapped circular Rydberg atoms. The atoms are protected from spontaneous emission decay, reaching lifetimes in the minute range. A defect-free chain of 40 atoms can be prepared thanks to an innovative technique, that bears resemblance with evaporative cooling, based on van der Waals interaction between the atoms. This strong dipole-dipole interaction emulates spin-1/2 XXZ Hamiltonian, all parameters of which are experimentally tunable over a wide range. The chain dynamics can be followed over one second, corresponding to more than 10^4 interaction cycles. The final state of each spin can be individually measured, and any spin-correlations between any atoms of the chain can be recovered. This enables the observation of adiabatic evolutions through quantum phase transitions, of sudden quenches, and fast modulations of the interaction parameters. The proposed circular-Rydberg-atom quantum simulator should open the way towards the simulations of systems and of their dynamics beyond the grasp of classical computation [1].

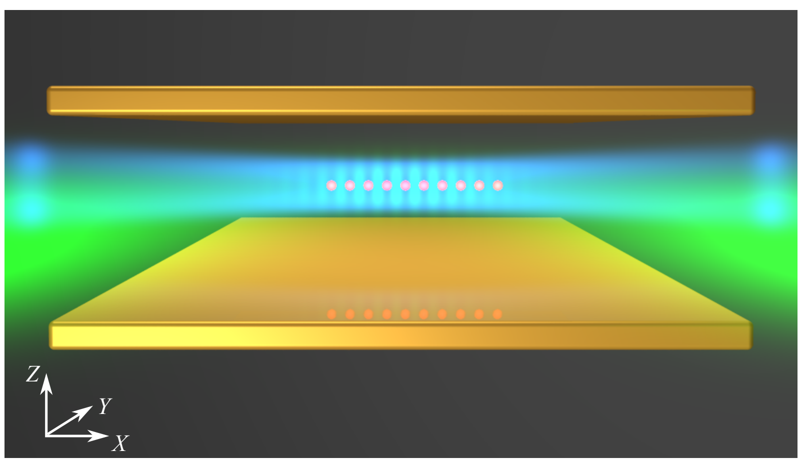

Figure 1. Circular Rydberg atoms are laser trapped in a plane-parallel capacitor that inhibits spontaneous emission. A chain of several tens of atoms can be deterministically prepared in the capacitor, and its dynamics observed over very long times.

[1] T. L. Nuyen, *et al.* (in preparation)

Non-equilibrium phase transitions and quench dynamics in dissipative Rydberg gases

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[2] Centre for the Mathematics and Theoretical Physics of Quantum Non-equilibrium Systems,
University of Nottingham, Nottingham NG7 2RD, UK

Cold atomic gases are a versatile platform for the study of quantum many-body phenomena. Especially atoms excited to highly-lying electronic states — so-called Rydberg atoms — offer rather intriguing possibilities for the exploration of strongly correlated dynamics of interacting spin systems.

The out-of-equilibrium behaviour of Rydberg gases is governed by emergent kinetic constraints [1]. In soft-matter physics these are often used to mimic dynamical arrest or excluded volume effects in idealised models of glass forming substances. The strong interactions among Rydberg atoms moreover leads to a remarkably rich physics including non-equilibrium phase transitions and localisation phenomena. Rydberg gases thus offer intriguing opportunities for the systematic exploration of emerging collective non-equilibrium effects. Beyond that they highlight a route towards a systematic generalisation of classical non-equilibrium processes into the quantum domain (see Fig. 1). This permits for example the experimental study of quantum absorbing-state phase transitions [2] and the implementation of quantum generalisations of population dynamics [3]. In this talk I will give an overview over our recent results on this research direction.

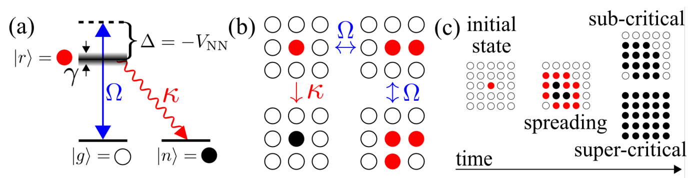

Figure 1. (a) Atoms are coherently excited from the ground state $|g\rangle$ to a Rydberg state $|r\rangle$ with a laser with Rabi frequency Ω. External noise broadens the state $|r\rangle$ (width γ) which decays to a third state $|n\rangle$ at rate κ. The laser is off-resonant with a detuning Δ that compensates the nearest-neighbor interaction V_{NN} ($V_{\mathrm{NN}} - \Delta = 0$). (b) The dominant processes are facilitation (top row and right column) and decay (left column). (c) An initial seed leads to the formation of clusters of Rydberg states (infected sites) which can either be converted to ground state atoms (healthy sites) or decay to the immune state $|n\rangle$. The relative strength of the dephasing rate γ with respect to Ω determines the nature of the transition. At fixed γ, depending on the ratio Ω/κ the stationary state is either an ever-expanding infection leaving a macroscopic fraction of immune sites (super-critical) or an infection that dies leaving the lattice partially filled (sub-critical).

[1] M. M. Valado *et al.*, Experimental observation of controllable kinetic constraints in a cold atomic gas, Physical Review A **93**, 040701 (2016).
[2] M. Marcuzzi *et al.*, Absorbing state phase transition with competing quantum and classical fluctuations, Physical Review Letters **116**, 245701 (2016).
[3] C. Pérez-Espigares *et al.*, Epidemic dynamics in open quantum spin systems, arXiv:1705.06994.

Many-body dynamics of excitation holes in a dissipative spin chain of Rydberg superatoms

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[2] Department of Physics, University of Kaiserslautern, D-67663 Kaiserslautern, Germany

Strong dipole-dipole interactions between atoms in high-lying Rydberg states can suppress multiple Rydberg excitations within a micron-sized trapping volume and yield sizable Rydberg level shifts at larger distances. Ensembles of atoms in optical microtraps can then form Rydberg superatoms with collectively enhanced transition rates to the singly excited state. The superatoms can represent mesoscopic, strongly-interacting spins (Fig. 1(a)).

We study a regular array of such effective spins driven by a laser field tuned to compensate the interaction-induced level shifts between neighboring superatoms. During the initial transient, a few excited superatoms seed a cascade of resonantly facilitated excitation of large clusters of superatoms. Due to spontaneous decay, the system then relaxes to the steady state having nearly universal Rydberg excitation density $\rho_{\mathrm{R}} = 2/3$. This state is characterized by highly-nontrivial equilibrium dynamics of quasi-particles – excitation holes in the lattice of Rydberg excited superatoms.

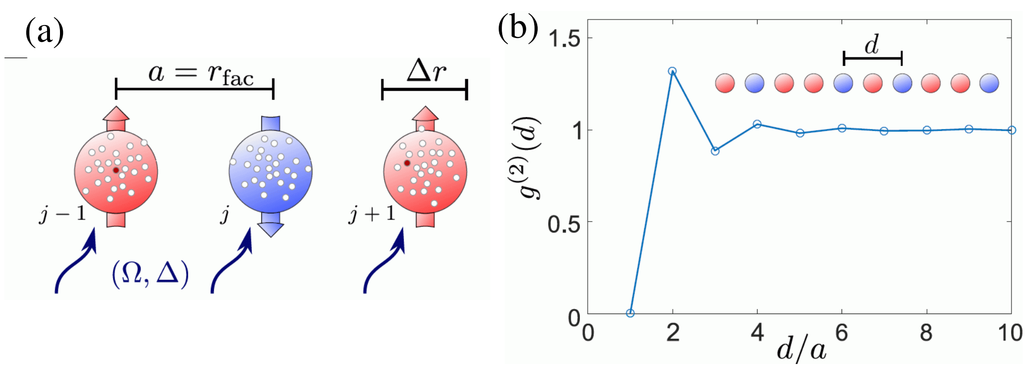

Figure 1. (a) A chain of effective spins is formed by Rydberg superatoms driven by a laser with Rabi frequency Ω and detuning Δ which facilitates excitation at distance $r_{\mathrm{fac}} = a$. (b) In the steady state, the typical two-particle correlation function $g^{(2)}(d)$ for the Rydberg excitation holes (blue circles) corresponds to a liquid of hard rods of length $2a$.

We derive an effective many-body model that accounts for hole mobility as well as continuous creation and annihilation of holes upon collisions with each other. Varying the parameters of the effective model, we find a cross-over from crystalline order of holes with period of three lattice sites to a nearly incompressible liquid of holes with density-density correlations peaked at the distance of two lattice periods (Fig. 1(b)). In both cases, the density of holes is $\rho_h \simeq 1/3$ (consistent with $\rho_{\mathrm{R}} = 2/3$) with highly suppressed number fluctuations.

[1] F. Letscher, D. Petrosyan, M. Fleischhauer, arXiv:1705.06532.

Observation of Roton Mode Population in a Dipolar Quantum Gas.

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[1] Institut für Experimentalphysik, University of Innsbruck (Austria)

The concept of a roton, a special kind of elementary excitation, forming a minimum of energy at finite momentum, has been essential to understand the properties of superfluid helium. In quantum liquids, rotons arise from the strong interparticle interactions, whose microscopic description remains debated. In the realm of highly-controllable quantum gases, a roton mode has been predicted to emerge due to magnetic dipole-dipole interactions despite of their weakly-interacting character. This prospect has raised considerable theoretical interest; yet roton modes in dipolar quantum gases have remained elusive to observations. Here we report experimental and theoretical studies of the momentum distribution in dipolar Bose-Einstein condensates of highly-magnetic erbium atoms, revealing the existence of the long-sought roton mode. The roton excitation manifests itself with the appearance of peculiar peaks at well-defined and large momentum that we trigger via an interaction quench. We observe that the value of the roton momentum follows the predicted geometrical scaling with the inverse of the confinement length along the magnetization axis. From the growth of the roton population, we probe in real time the roton softening of the excitation spectrum and extract the corresponding value of the roton gap. Our results provide a further step in the quest towards supersolidity in dipolar quantum gases.

Simulating polaron biophysics with Rydberg atoms

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Transport of excitations along proteins can be formulated in a quantum physics context, based on the periodicity and vibrational modes of the structures. Exact solutions are very challenging to obtain on classical computers, however, approximate solutions based on the Davydov ansatz have demonstrated the possibility of stabilized solitonic excitations along the protein. We propose an alternative study based on a chain of ultracold atoms. We investigate the experimental parameters to control such a quantum simulator based on dressed Rydberg atoms [1]. We show that there is a feasible range of parameters where a quantum simulator can directly mimic the Davydov equations and their solutions. Such a quantum simulator opens up new directions for the study of transport phenomena in a biophysical context.

[1] M. Płodzień, Tomasz Sowiński, and Servaas Kokkelmans, arXiv:1707.04120.

Cavity-enhanced transport of charge

Guido Pupillo[1]

[1] University of Strasbourg, France

We discuss the effects on charge conductivity in a molecular semiconductor of coupling intramolecular electronic transitions to the bosonic field of a cavity or of a plasmonic structure prepared in its vacuum state [1]. We present a proof-of-principle model where this coupling leads to a light-matter hybridization - the dressed fermionic bands interact via absorption and emission of dressed cavity-photons - that ultimately provides an enhancement of charge conductivity in the steady-state. We discuss the role of the finite electronic band-width in the dressing, and explain how this affects the current enhancement. We demonstrate that under certain experimentally relevant conditions the enhancement can reach orders of magnitudes and discuss the relevance of these results to recent experiments with organic semi-conductors, where a dramatic enhancement of charge conductivity was demonstrated [2]. We conclude with a discussion of open questions.

[1] *Cavity-enhanced transport of charge*, D. Hagenmüller, J. Schachenmayer, S. Schütz, C. Genes, and G. Pupillo, arXiv:1703.00803 (2017).
[2] *Conductivity in organic semiconductors hybridized with the vacuum field*, E. Orgiu et al., Nature Materials 14, 1123-1129 (2015).

Quantum algorithmic breakeven: on scaling up with noisy qubits

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As quantum computing proceeds from perfecting physical qubits towards testing logical qubits and small scale algorithms, an urgent question being confronted is how to decide that critical milestones and thresholds have been reached. Typical criteria are gates exceeding the accuracy threshold for fault tolerance, logical qubits with higher coherence than the constituent physical qubits, and logical gates with higher fidelity than the constituent physical gates. In this talk I will argue in favor of a different criterion I call "quantum algorithmic breakeven", which focuses on demonstrating an algorithmic scaling improvement in an error-corrected setting over the uncorrected setting. I will present evidence that current experiments with commercial quantum annealers have already crossed this threshold. I will also discuss our latest evidence for a limited quantum speedup with such devices. The lessons we have learned from experimenting with commercial devices with many noisy qubits will hopefully inform other approaches to quantum computing.

Thursday 16/11

Programmable superpositions of Ising configurations

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In this talk I will present a framework that allows one to prepare superpositions of bit strings, i.e., many-body spin configurations, with deterministic programmable probabilities[1]. The spin configurations are encoded in the degenerate ground states of the lattice-gauge representation of an all-to-all connected Ising spin glass[2]. In this model, the ground state manifold is invariant under variations of the gauge degrees of freedom, which take the form of four-body parity constraints. The protocol allows one to make use of these degrees of freedom to prepare programmable superpositions by quantum simulation of a transverse Ising model. The dynamics combines an adiabatic protocol with controlled diabatic transitions. I will present an effective model that allows one to determine the control parameters efficiently even for system sizes that cannot be simulated on a classical computer.

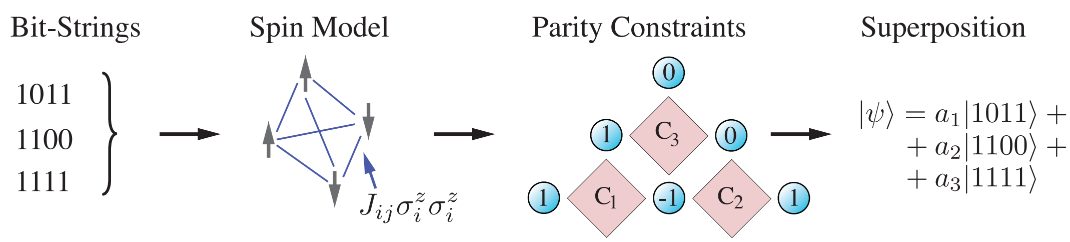

Figure 1. Illustration of the protocol that takes arbitrary bit-strings as input and puts out a superposition of these data with programmable amplitudes.

[1] L. M. Sieberer and W. Lechner, arXiv:1708.02533 (2017).

[2] W. Lechner, P. Hauke, and P. Zoller, Science Advances **1**, 1500838 (2015).

Non-destructive detection of ensembles of Rydberg atoms with microwave cavity transmission measurements

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Cavity quantum electrodynamics (QED) provides a powerful tool to realize quantum non-demolition measurements of either part of the system, emitter or photon, by observing the effect of the interaction on the other part. Such ideal projective measurements allow to detect, to prepare and to manipulate quantum states in a controlled and coherent manner. They are used with atomic or solid-state emitters in the optical or microwave domain. So far, Rydberg atoms in cavity QED systems have mainly been used to measure or create quantum states of light. Using a microwave cavity to determine the state of a single Rydberg atom or an ensemble thereof is less explored and constitutes a step towards the application of the long coherence time of Rydberg atoms as quantum memories for microwave-based quantum information processing. In our experiment, transmitting a weak probe tone through a 3D microwave cavity allows us to measure the dispersive shift induced by an ensemble of helium Rydberg atoms [1]. The system is quantitatively described by the dispersive Tavis-Cummings hamiltonian. We consistently observe maximal collective coupling strengths above 1 MHz with up to 3300 Rydberg atoms. We also determine the scaling of the collective dispersive shift with the atom-cavity detuning and the number of Rydberg atoms. The latter provides a non-destructive measurement of the number of Rydberg atoms (cf. Figure 1). We discuss the extension of this technique to non-demolition measurements of the pseudo-spin polarization of an ensemble of Rydberg atoms used as microwave frequency qubits.

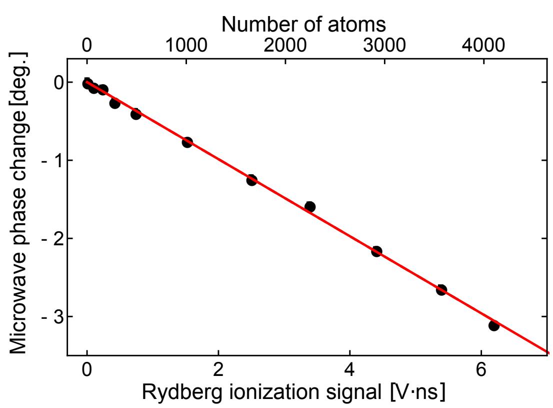

Figure 1. Phase change of the microwave probe as function of detected signal from ionization of Rydberg atoms : both detections signals are here proportional to the atom number, which is scaled on top axis from phase change and known atom-cavity coupling and detuning.

[1] M. Stammeier *et al.*, Phys. Rev. A, **95**, 053855 (2017).

A single Rydberg impurity coupled to a Bose-Einstein condensate

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Atoms prepared in highly excited Rydberg states constitute remarkable quantum objects with extreme properties. Among others, the electronic wavefunction may extend over mesoscopic distances easily reaching the micrometer scale. In our experiment, we explore single Rydberg impurities immersed in a Bose-Einstein condensate (BEC), for which thousands of groundstate atoms lie within the Rydberg wavefunction. Based on detailed spectroscopic studies of electron-neutral scattering in the ultracold, we report on the current status of our endeavor to employ the interaction of the Rydberg electron with the condensate atoms to imprint the Rydberg wavefunction onto the BEC density. In combination with high resolution optical addressing and readout, we aim for direct imaging of Rydberg orbitals.

[1] M. Schlagmüller, T. C. Liebisch, F. Engel, K. S. Kleinbach, F. Böttcher, U. Hermann, K. M. Westphal, A. Gaj, R. Löw, S. Hofferberth, T. Pfau, J. Perez-Rios, and C. H. Greene, Phys. Rev. X **6**, 031020 (2016).

Accurate Rydberg quantum simulations of spin-1/2 models

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[1] Institute for Theoretical Physics III and Center for Integrated Quantum Science and Technology, University of Stuttgart, 70550 Stuttgart, Germany
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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 quantum 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 the experimental parameters in order not to break the Rydberg blockade mechanism which underlies the mapping. By selecting appropriate experimental parameters, even in a large system of 49 Rydberg atoms, an excellent agreement is achieved between the measured time evolution and the numerically calculated dynamics of the Ising-like spin-1/2 model. This result opens exciting prospects for the realization of high-fidelity quantum simulators of spin Hamiltonians.

Simulating quantum spin systems using ultracold Rydberg atoms

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[2] Institut für Theoretische Physik, Universität Heidelberg, Philosophenweg 16, 69120 Heidelberg, Germany
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There is a currently growing interest in utilizing dipolar interacting Rydberg spin systems to study of non-equilibrium phenomena, like thermalization or relaxation of isolated quantum systems. The tunable strong, long-range interactions as well as the long lifetimes of highly excited Rydberg atoms also provide new opportunities for investigating the dynamics of strongly correlated many-body quantum systems with beyond nearest-neighbor coupling.

We present an experimental realization of a dipolar spin model by coupling two strongly interacting Rydberg states utilizing a microwave field. We study spin dynamics by letting spin systems evolve under designated interactions. The resulting magnetizations after the dynamics are extracted from the systems utilizing a state-tomography technique and a selective ionization. The result of the dynamics will be discussed in the talk.

[1] A. Piñeiro Orioli, A. Signoles, H. Wildhagen, *et al.*, arXiv:1703.05957 (2017).

Large Scale Quantum Simulations Using Ultracold Atomic Gases in Optical Lattices

Immanuel Bloch[1]

[1] Max Planck Institute of Quantum Optics, Germany
[2] Ludwig-Maximilians University, Germany

More than 30 years ago, Richard Feynman outlined the visionary concept of a quantum simulator for carrying out complex physics calculations. Today, his dream has become a reality in laboratories around the world. In my talk I will focus on the remarkable opportunities offered by ultracold quantum gases trapped in optical lattices to address fundamental physics questions ranging from condensed matter physics over statistical physics to high energy physics with table-top experiments. To date, ultracold atoms provide the only setting for quantum simulations in which 'quantum supremacy', i.e. the ability to simulate settings beyond the ability of classic supercomputers.

I will show how it has now become possible to image and control quantum matter with single atom sensitivity and single site resolution, thereby allowing one to directly image individual quantum fluctuations of a many-body system, to directly reveal antiferromagnetic order in the fermionic Hubbard model or hidden topological order and exotic forms of magnetic ordering that can now, for the first time, be directly detected in experiments. In addition, I will discuss our recent experiments on novel *many-body localised states of matter that challenge our understanding of the connection between statistical physics and quantum mechanics at a fundamental level. Finally, I will discuss our new experiments on Rydberg dressed quantum gases in which controlled coherent long-ranged interactions can be implemented.*

Circuit-QED based spectroscopies of quantum impurities

Javier Puertas Martinez[1], Sebastien Leger[1], Nicolas Gheeraert[1], Remy Dassonneville[1], Luca Planat[1], Farshad Foroughi[1], Yuriy Krupko[1], Olivier Buisson[1], Cecile Naud[1], Wiebke Guichard[1], Serge Florens[1], Izak Snyman[2], Nicolas Roch[1]

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Quantum impurity problems describe a localized quantum system with a few degrees of freedom (the impurity), that is non-perturbatively coupled to a large system (the bath). These impurities can exist in many different forms in solid-state materials and nanostructures, such as charged [1] or magnetic impurities [2], while the bath is typically constituted by a Fermi sea. However, understanding the quantum dynamics and the entanglement properties of these many-body electronic systems remains a tremendous challenge, both experimentally and theoretically. The main underlying reason to this complexity lies in the presence of entanglement between the impurity and many modes of the bath that extend on a wide energy range, which prevents a brute force diagonalization of the full problem. In addition, in metallic devices such as artificial quantum dots, it has proved difficult experimentally to resolve or address electronic bath modes individually, due to internal losses of metallic islands. I will present a unique architecture based on superconducting circuits to tackle this challenging problem. It offers two main advantages: first, it allows to reach the multi-mode ultra-strong coupling regime allowing to build a strong hybridization between the quantum system and its bath; second, high quality factors of superconducting circuits enable to monitor spectroscopically the qubit and its bath at the same time. Our approach consists in coupling a superconducting artificial atom (namely a transmon qubit) to a meta-material made of thousands of SQUIDs [3,4,5]. The latter sustains many photonic modes and shows characteristic impedance close to the quantum of resistance. We succeeded in performing the full spectroscopy of the impurity plus bath system, which revealed strong hybridization of the transmon qubit with as many as ten modes of the bath. In this coupling regime, the common techniques used in circuit-QED (rotating wave approximation, exact diagonalization...) break down. To describe quantitatively our experimental data, we had to borrow a tool usually reserved to strongly interacting systems: the Self-Consistent Harmonic Approximation [6]. In the future, we plan to use this circuit to perform non-linear quantum optics experiments with a many-body system [4,7].

[1] P. W. Anderson, Phys. Rev. Lett. **18**, 1049 (1967)
[2] J. Kondo, Prog. Theor. Phys. **32**, 37 (1964).
[3] K. Le Hur, Phys. Rev. B **85**, 140506(R) (2012).
[4] M. Goldstein et al., Phys. Rev. Lett. **110**, 017002 (2013).
[5] I. Snyman and S. Florens, Phys. Rev. B **92**, 085131 (2015).
[6] T. Giamarchi, "Quantum physics in one dimension" (Oxford 2003).
[7] N. Gheeraert et al., in preparation.

Quantum simulation in arrays of single-addressable traps: multi-layer configurations, qubit synchronization, and tunnel-coupled geometries

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Efficient quantum simulation requires scalable architectures that guarantee the allocation of large-scale qubit resources. In our work, we focus on the implementation of multi-site geometries based on microoptical systems. The use of microlens arrays allows for the creation of massive multi-site trap arrays with structure sizes approaching the wavelength of the light applied, yet the geometry being decoupled from the laser wavelength and therefore customizable. Large scale quantum simulation, quantum computing, and quantum error correction will be accessible.

We give an overview on recent progress and future directions: (a) We report on a novel technique for the optical creation of 3D multi-layer configurations of 2D periodic quantum registers based on the Talbot effect and demonstrate the trapping and imaging of individual atoms in integer and fractional Talbot planes [1]. This will increase the simulation speed by parallelizing different tasks within different planes. (b) The distribution of computational tasks over the full 2D architecture requires a high degree of synchronization of the qubit dynamics. We implemented a scheme for compensation of the differential Stark shift of hyperfine quantum states by adding a weak near-resonant field. This causes a suppression of dephasing and decoherence by more than an order of magnitude [2]. (c) In a novel approach for a bottom-up quantum simulator, we propose to combine site-controllable potential surfaces (Fig. 1) based on microlens arrays with the highly successful technique of tunnel-coupled quantum simulation [3].

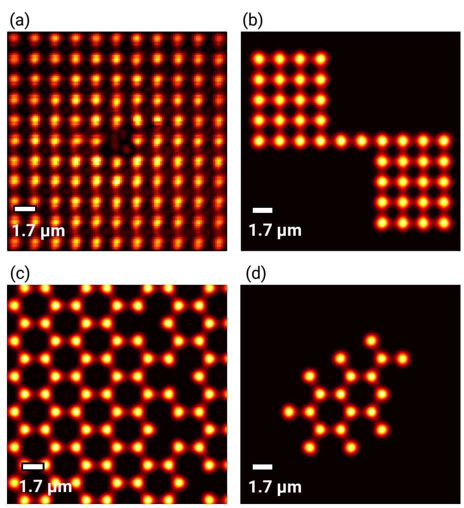

Figure 1. Measured (a) and simulated (b - d) optical potentials for a fully controllable quantum simulator based on tunnel-coupled arrays of independently generated potential wells.

[1] M. Schlosser et al., submitted (2017).

[2] J. Kruse, M. Schlosser, G. Birkl, submitted (2017).

[3] M. R. Sturm, M. Schlosser, R. Walser, G. Birkl, Phys. Rev. A **95**, 063625 (2017).

Quantum correlations: or how to turn a quantum simulator into a quantum sensor

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[1] Laboratoire de Physique, Ecole Normale Supérieure de Lyon, Lyon, France
[2] Institut Universitaire de France

In quantum systems correlations can take forms which are impossible in classical mechanics. The most famous, yet elusive form of quantum correlation is represented by entanglement, a property well defined and investigated for pure states, and envisioned as a resource for nearly all technological tasks harnessing quantum many-body physics. In the real life of mixed states, on the other hand, incoherent fluctuations appear in the game, making the distinction of quantum vs. classical correlations less sharp. Being able to discern the ?quantumness" of correlations in mixed states, and to identify many-body regimes in which correlations have a pronounced quantum character, represents a formidable question of both fundamental as well as technological nature.

We have recently introduced a statistical-physics definition of quantum correlations which reveals the existence of a fundamental emerging length (the quantum coherence length) beyond which correlations are purely of incoherent (classical) origin. This definition lends itself very naturally to large-scale numerical calculations in quantum many-body systems, as well as to experiments with quantum simulators - either via thermodynamic or spectroscopic measurements. Once quantified, quantum correlations unveil the metrological interest of quantum many-body states, as they represent the fundamental ingredient which allows interferometric protocols to beat the shot-noise limit. We apply our statistical physics analysis of quantum correlations to quantum phase transitions in models of atomic physics quantum simulators – quantum Ising transition in spin models for trapped ions, Rydberg atoms or ultracold binary mixtures. Our analysis reveals the impressive metrological potential of adiabatically prepared equilibrium states close to the quantum phase transition, owing to the quantum-critical enhancement of quantum correlations.

Scalable creation of long-lived multipartite entanglement

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We demonstrate the deterministic generation of multipartite entanglement based on scalable methods. Four qubits are encoded in $^{40}Ca^+$, stored in a micro-structured segmented Paul trap. Qubits are sequentially entangled by laser-driven pairwise gate operations. Between these, the qubit register is dynamically reconfigured via ion shuttling operations. We generate a four-ion GHZ state $|\psi\rangle = \frac{1}{\sqrt{2}}|0000\rangle + |1111\rangle)$ with a state fidelity of 94.4(3)% (see Fig. 1) and a storage time of 1.1 seconds [1].

To keep track of phase evolution of qubits shuttled in the inhomogeneous dc magnetic field, we use Bell states of the type $|\uparrow\downarrow\rangle + e^{i\varphi}|\downarrow\uparrow\rangle$ encoded in two $^{40}Ca^+$ ions stored at different locations. Undergoing linear Zeeman effect, the relative phase φ serves to measure the magnetic field difference between the constituent locations and we measure this over distances of up to 6.2 mm with accuracies of around 300 fT and sensitivities down to 12 pT/$\sqrt{\mathrm{Hz}}$ at a spatial resolutions down to 10 nm [2].

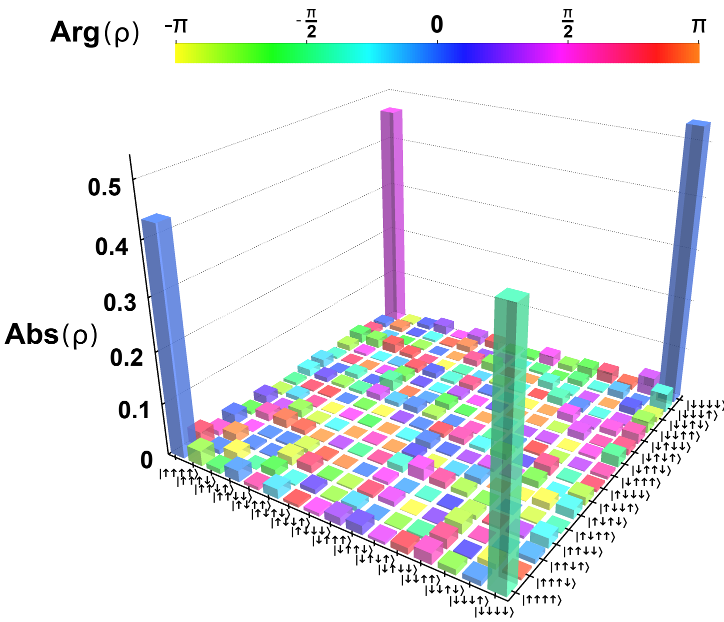

Figure 1. Absolut values of the four-ion GHZ state with 94.4(3)% fidelity.

[1] H. Kaufmann, T. Ruster, C. T. Schmiegelow, M. A. Luda, V. Kaushal, J. Schulz, D. von Lindenfels, F. Schmidt-Kaler, U. G. Poschinger, Phys. Rev. Lett. (2017), arXiv:1707.03695.
[2] T. Ruster, H. Kaufmann, M. A. Luda, V. Kaushal, C. T. Schmiegelow, F. Schmidt-Kaler, U. G. Poschinger, Phys. Rev. X 7, 031050 (2017).

Friday 17/11

Dual Bose-Fermi Superfluids

Christophe Salomon, Sébastien Laurent, Matthieu Pierce, M. Delehaye
Shuwei Jin, Tarik Yefsah, Frédéric Chevy

Laboratoire Kastler Brossel, Ecole Normale Supérieure, 24 rue Lhomond, 75005 Paris, France

We report on the production and study of a mixture of Bose and Fermi superfluids. Such a mixture has long been sought in liquid helium where superfluidity was achieved separately in bosonic ^{4}He and fermionic ^{3}He. However due to strong interactions between isotopes, phase separation occurs when the ^{3}He concentration exceeds 6%, which, so far, has prevented reaching simultaneous superfluidity for both species. Using dilute quantum gases where interactions can be tuned, we have produced a Bose-Fermi mixture where both species are superfluid [1]. By exciting center of mass oscillations of the mixture we probe the collective dynamics of the system. Coherent energy exchange between the Bose and Fermi gas is observed with very small damping below a certain critical velocity. We compare this critical velocity for superfluid counterflow to a recent theoretical prediction [2,3]. Raising the temperature of the system slightly above the superfluid transition reveals an unexpected phase-locking of the oscillations induced by dissipation. Finally the lifetime of the Bose-Fermi mixture is governed by a very simple formula involving the fermionic two-body contact [4].

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[2] Y. Castin, I. Ferrier-Barbut, and C. Salomon, The Landau critical velocity for a particle in a Fermi superfluid, Comptes Rendus Physique, 16, 241 (2015)
[3] M. Delehaye, S. Laurent, I. Ferrier-Barbut, S. Jin, F. Chevy, and C. Salomon, Critical Velocity and Dissipation of an ultracold Bose-Fermi Counterflow, Phys. Rev. Lett., 115, 265303 (2015).
[4] S. Laurent, M. Pierce, M. Delehaye, T. Yefsah, F. Chevy, C. Salomon, Connecting few-body inelastic decay to quantum correlations in a many-body system : a weakly coupled impurity in a resonant Fermi gas, Phys. Rev. Lett., 118, 103403 (2017)

Spontaneous avalanche dephasing in large Rydberg ensembles

Thomas Boulier[1], Eric Magnan[1], Carlos Bracamontes[1], James Maslek[1], Steve Rolston[1], and James Porto[1]

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Realizing efficient many-body quantum simulators requires an exquisite control over the coherence and the interactions between many particles. Rydberg atoms are emerging as a strong candidate [1] for achieving the coherent control of large interacting systems. However recently there has been concerns [1] due to the observation of giant inhomogeneous dephasing in large ensembles [2,3]. Hence the current difficulties encountered for realizing Rydberg dressing for atomic ensembles of ~ 100 atoms or more [1]. We provide experimental evidence confirming the hypothesis [3] that this phenomenon is due to the avalanche-like onset of off-diagonal dipole-exchange interactions, fueled by blackbody transitions. Using several time-resolved spectroscopic methods in a neatly controlled ensemble of ultracold Rydberg atoms held in a 3D optical lattice, we present the first dynamical description of this highly-correlated, many-body avalanche dephasing process. We also present ways to mitigate the decoherence in the context of current experiments, which should be immediately useful to the community. Finally, we argue that the avalanche process is an instance of interesting highly-correlated many-body excitation growth, which should also be studied for its own sake.

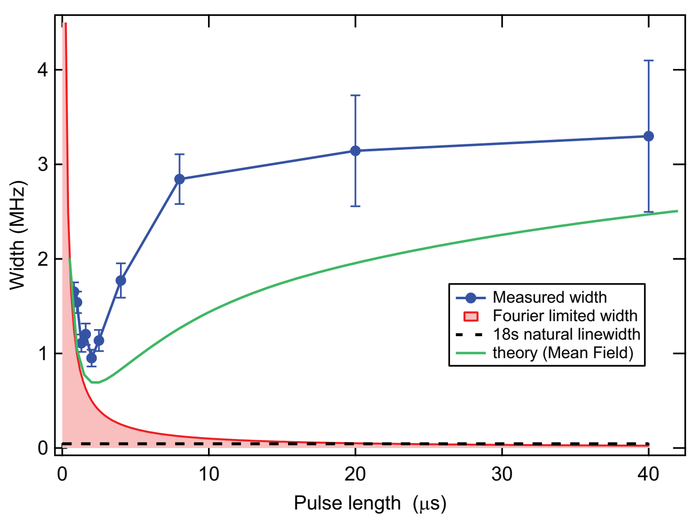

Figure 1. Observed broadening (blue) vs. excitation time. Fast excitations hinder the buildup of opposite-parity states: the dephasing is reduced. The natural linewidth (dashed line) cannot be recovered due to Fourier broadening (red). Mean-field approaches (green) are slower than the experiment, showing the high degree of correlations.

[1] M. Saffman, J. Phys. B **49**, 202001 (2016).
[2] J.A. Aman *et al.*, PRA **93.4**, 043425 (2016).
[3] E.A. Goldschmidt *et al.*, PRL **116**, 113001 (2016)

Exploring collective effects through Rydberg interactions on atom chips

J.J.M. de Hond[1], N. Cisternas[1], S.L.P. Charpignon, G. Lochead[1,*], R.J.C. Spreeuw[1], H.B. van Linden van den Heuvell[1], and N.J. van Druten[1]

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Rydberg states are a promising tool to control interactions in ultracold gases, making them relevant for quantum simulation. In our atom chip experiment we trap rubidium atoms in a highly elongated magnetic trap and excite them to Rydberg states. For typical parameters, the radial size of our cloud is smaller than the range of the Rydberg–Rydberg interactions, meaning we are effectively in a one-dimensional regime. The excitation coherence can be severely limited by stray electric fields, making it hard to see interaction effects. We are able to characterize all three vector components of these fields using an on-chip electrode [1]. Using a pair of lasers which are frequency-narrowed and stabilized to a cavity [2] we are able to observe Rydberg–Rydberg interactions; for instance, we see strong saturation of the Rydberg excitation fraction (i.e. Rydberg blockade, see Figure 1) and have observed asymmetric line broadening related to the Van der Waals interaction. Presently we are investigating these effects in the time domain.

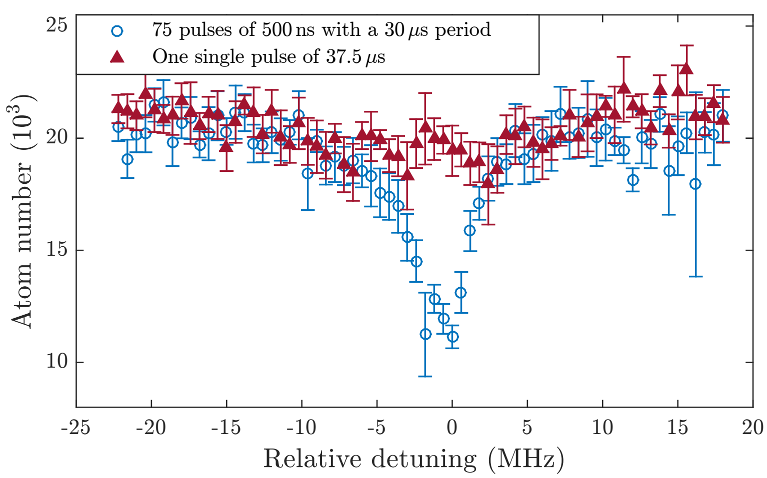

Figure 1. $28D_{5/2,5/2}$ state probed with either a single pulse (solid triangles) or multiple, separated pulses with the same total flux (open circles). For the single pulse, the losses from the Rydberg excitation are strongly reduced, indicative of Rydberg blockade.

[1] N. Cisternas, Julius de Hond, G. Lochead, R.J.C. Spreeuw, H.B. van Linden van den Heuvell, and N.J. van Druten, Phys. Rev. A **96**, 013425.

[2] Julius de Hond, Nataly Cisternas, Graham Lochead, and N.J. van Druten, Applied Optics, **56**, 5436–5443 (2017).

Fast thermalization of a frozen Rydberg gas in long-range interatomic dipole-dipole coupling

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In a cold, disordered and dense cesium Rydberg gas in a Förster resonance configuration, two atoms or a group of few atoms can exchange internal energy by a resonant way. We consider the two-atom reaction for the cesium atom

$$np + np \to ns + (n+1)s$$

We observe a saturation regime, characterized by an amazing behavior corresponding to the "thermalization" of the atomic sample, meaning an equal- distribution of the populations of the relevant level of the resonant reaction. The dynamics of the thermalization seems to be the result of few-body effects. The interplay between two-, few- and many-body regime in a dipole coupling will be discussed, as so well as the role of the diffusion scattering of the products of the reaction.

Programmable quantum simulator based on a 51-atom array with Rydberg interactions

Sylvain Schwartz[1,2,3], Hannes Bernien[1], Alexander Keesling[1], Harry Levine[1], Ahmed Omran[1], Hannes Pichler[1,4], Soonwon Choi[1], Alexander S. Zibrov[1], Manuel Endres[5], Markus Greiner[1], Vladan Vuletić[2] and Mikhail D. Lukin[1]

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Controllable coherent interactions between large numbers of particles are a key ingredient for the experimental realization of quantum simulators. We have developed a platform where we can create reconfigurable defect-free chains of up to 60 neutral atoms with Rydberg interactions [1]. Our technique is based on an array of 100 tightly focused optical tweezers stochastically loaded from an optical molasses with at most one atom per trap. We use site-resolved imaging to probe the atomic distribution without destroying it, and deterministically arrange the atoms into the configuration of interest, hence removing the entropy associated with probabilistic loading [2,3]. We implement strong tunable Ising-type interactions across the array by coupling the atomic ground state to a Rydberg state using a two-photon optical transition. By sweeping the frequency of one of the coupling lasers across the single-atom resonance, we induce phase transitions into Rydberg crystals [4,5], where the Rydberg excitations are spatially ordered across the array. These ordered states break various symmetries depending on the interaction strength, which we can tune by changing the interatomic distance. They can be prepared with high fidelity even for large system sizes, showing promise for the implementation of quantum optimization algorithms [6] with this system. We will also discuss the many-body dynamics of these ordered states when their adiabatic preparation is followed by a sudden quantum quench to single-atom resonance, leading to robust and persistent oscillations of the crystalline order.

[1] H. Bernien, S. Schwartz, A. Keesling, H. Levine, A. Omran, H. Pichler, S. Choi, A.S. Zibrov, M. Endres, M. Greiner, V. Vuletić, and M.D. Lukin, arXiv:1707.04344 (2017)
[2] M. Endres, H. Bernien, A. Keesling, H. Levine, E.R. Anschuetz, A. Krajenbrink, C. Senko, V. Vuletić, M. Greiner, and M.D. Lukin, Science, aah3752 (2016).
[3] D. Barredo, S. de Léséleuc, V. Lienhard, T. Lahaye, and A. Browaeys, Science **354**, 1021 (2016).
[4] T. Pohl, E. Demler, and M.D. Lukin, Physical review letters **104** (4), 043002 (2010).
[5] P. Schauß, J. Zeiher, T. Fukuhara, S. Hild, M. Cheneau, T. Macrì, T. Pohl, I. Bloch, and C. Groß, Science **347**, 6229 (2015).
[6] E. Farhi, and A.W. Harrow, arXiv:1602.07674 (2016).

Poster Sessions

MONDAY 13/11

		couloir Jaurès	Hall Lhomond
Frédéric Assémat	*Single shot quantum non demolition photon counting of microwave photons using Rydberg atoms*		X
Romain Bachelard	*Quantum cooperative effects in light scattering by atomic clouds*		X
Amaudric Boisse	*Nonlinear scattering of atomic bright solitons in disorder*		X
Sylvain De Léséleuc	*Experimental quantum simulation of spin models in 2d atomic arrays*		X
Johannes Deiglmayr	*Long-range Rydberg-Rydberg interactions: formation of macrodimers*		X
Tobias Grass	*Tailoring a spin system with synthetic fluxes by shaking a chain of ions*		X
Yara Hodroj	*SIRTEQ - Science and engineering in Ile-de-France Region for Quantum Technologies*	X	
Karina Jimenez Garcia	*One-dimensional spinor Bose gases: Magnetic order and giant spin-dipole polarizability*	X	
Matthew Jones	*A Rydberg-dressed magneto-optical trap*		X
Christiane Koch	*Fast circularisation of Rydberg atoms using optimal control theory*		X
Tommaso Macri	*Stabilization of droplet phases in Rabi-coupled BECs and dipolar gases in free space*	X	
Manfred Mark	*An Er-Dy mixture for quantum gas microscopy*	X	
Igor Mekhov	*Quantum optical lattices and weak measurements for strongly correlated bosons and fermions*	X	
Alexis Morvan	*Simulating artificial graphene in circuit-QED*	X	
Giuliano Orso	*2D Anderson transition of cold atoms with synthetic spin-orbit coupling in speckle potentials*	X	
Matteo Rizzi	*Exploring Interacting Topological Insulators with Ultracold Atoms: the Synthetic Creutz-Hubbard Model*	X	
Mariya Romanova	*Theoretical study of deep-center defects in some semiconductors*	X	
Carla Sanna	*Quantum simulators based on Rydberg atoms in magnetic nanolattices*		X
Jelena Sjakste	*Relaxation dynamics of highly excited electrons: mecanisms limiting the performance of electronic devices.*	X	
Yvan Sortais	*Light scattering by cold interacting two-level atoms*		X
Daniel Valente	*A propagating single-photon packet cannot always be mimicked by a low-intensity coherent packet*		X

WEDNESDAY 15/11

		couloir Jaurès	***Hall Lhomond***
Cécile Carcy	*Single-atom-resolved probing of lattice gases in momentum space*	X	
Nicola Carlon Zambon	*Probing a dissipative phase transition via dynamical optical hysteresis*	X	
Thomas Chalopin	*Ultracold dysprosium gas: optical cooling and coherent dynamics of a large spin atom*		X
Marc Cheneau	*A two-particle, four-mode interferometer for atoms*	X	
Hanning Dai	*Four-body ring-exchange interactions and anyonic statistics within a minimal toric-code Hamiltonian*	X	
Alexandre Dareau	*Cold-atom based implementation of the quantum Rabi model*	X	
Yara Hodroj	*SIRTEQ - Science and engineering in Ile-de-France Region for Quantum Technologies*	X	
Arthur La Rooij	*Towards a single-atom register in a fiber micro-cavity for generation of multi-particle entanglement*	X	
Henri Lehec	*Spectroscopy of the Rydberg states of ytterbium and isolated core excitation*		X
Ivan Marquez	*Topological effects due to the magnetic field in the Quantum Walk*		X
Guido Masella	*Numerical study of Bose-Hubbard models with finite-range interactions*		X
Kristian Nielsen	*Impurities in quantum gasses*		X
Matthew Rispoli	*Microscopy of the interacting Harper-Hofstadter model in the two-body limit*		X
Maximilian Schemmer	*Effect of losses in a 1D Bose gas: cooling to the ground state by quantum feedback and production of non thermal states*		X
Nithiwadee Thaicharoen	*Spatial imaging of strongly interacting Rydberg atoms*	X	
Jérôme Thibaut	*Entanglement properties of lattice bosons from a variational wave function*	X	
Laurent Vernac	*Spin mixing dynamics in chromium quantum gases*		X
Nicolas Vitrant	*Imaging and trapping cold atoms using a multimode fiber*		X
Lan Yin	*BCS pairing state of a Dilute Bose Gas with Spin-Orbit Coupling*		X
Yongchang Zhang	*Localized states induced by the spatially oscillating long-range interaction*		X

THURSDAY 16/11

		couloir Jaurès	Hall Lhomond
Manuel Andia	*A quantum-gas microscope for fermionic potassium-40*		X
Przemyslaw Bienias	*Photon propagation through dissipative Rydberg medium at large input rates*	X	
Raphaël Bouganne	*Clock spectroscopy of strongly interacting bosons in deep optical lattices*		X
William Burton	*Experimental realization of the spin Mott phase and progress toward the xy-ferromagnet and spin-superfluidity*		X
Ulysse Chabaud	*Continuous variable sampling from photon-added or photon-subtracted squeezed states*		X
Jian Cui	*Optimal control of Rydberg lattice gases*	X	
Mathieu De Goër De Hervé	*A 2D Bose gas in a ring trap*		X
Juan Pablo Dehollain	*A 2x2 quantum dot analogue simulator*	X	
Norman Ewald	*Trapped ions in strongly polarizable atomic media*	X	
Yara Hodroj	*SIRTEQ - Science and engineering in Ile-de-France Region for Quantum Technologies*	X	
Arthur Larrouy	*Quantum metrology based on a Schrödinger-cat state of a Rydberg atom*	X	
Eduardo Mascarenhas	*Simulating Nonequilibrium Quantum Systems*	X	
Uditendu Mukhopadhyay	*Capacitance spectroscopy of large quantum dot arrays for simulating Fermi-Hubbard physics*	X	
Callum Robert Murray	*Photon subtraction via controlled many-body decoherence*		X
Thanh Long Nguyen	*Phonon Lasing with Trapped Ions by Engineered Reservoirs*		X
Sabrina Patsch	*Quantum simulators for open quantum systems using quantum Zeno dynamics*		X
Matthew Rispoli	*Quantum thermalization through entanglement in an isolated many-body system*		X
Philippe St-Jean	*Topological lasing in the edge states of a 1D polariton lattice*	X	
Kris Van Houcke	*Controlled summation of diagrammatic series for the unitary Fermi gas: bold diagrammatic Monte Carlo, large-order asymptotics and conformal-Borel transformation*		X
Filippo Vicentini	*Critical slowing down in driven-dissipative Bose-Hubbard lattices*		X

Monday 13/11

Single shot quantum non demolition photon counting of microwave photons using Rydberg atoms

Frédéric Assémat[1], D. Grosso[1], S. Haroche[1], J.-M. Raimond[1], S. Gleyzes[1], and M. Brune[1]

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Light detection is usually a destructive process as photons are detected with photosensitive materials that absorb them. However, there exist quantum non-destructive (QND) strategies [1] that permit repeated measurements on the same system yielding identical results. Those non destructive strategies have been for instance experimentally implemented for photon fluxes [2]. Yet, single photon resolution requires an extremely strong light-matter coupling. In the context of cavity quantum electrodynamics, it is possible to achieve QND measurement of the number of photons trapped in a microwave cavity made of two superconducting mirrors by using Rydberg atoms as probes. The presence of n photons induces a light shift of the atomic levels proportional to n, that can be read by Ramsey interferometry. By measuring this light shift for several atoms, information is progressively extracted and the field-state collapses on a given number of photons [3].

We have developed a new experiment where the atoms used for the QND measurement are beforehand prepared from the laser-cooled atomic beam of an atomic fountain. The small velocity of the atom allows us to reach interaction times between the field and the atom up to 100 times longer than before. This long interaction time makes it possible to spectrally resolve the individual light shifts corresponding to different photon numbers. It is thus possible to induce a transition of the atomic state only when the cavity contains exactly n_0 photons. This corresponds to a single shot measurement of n_0 , which can be confirmed by another measurement done immediately afterwards.

This set up opens the way to the observation of interesting dynamics of the field, like quantum Zeno dynamics, where removing a single level from the accessible Hilbert space leads to the deterministic preparation of non-classical states such as Schrödinger cat states [4].

[1] V.B. Braginsky, Y.I. Vorontsov , "Quantum-mechanical limitations in macroscopic experiments and modern experimental technique", Physics-Uspekhi **17**, 644 (1975).
[2] P. Grangier et al. , "Observation of backaction-evading measurement of an optical intensity in a three-level atomic nonlinear system", Physical Review Letters **66**, 14182 (1991).
[3] C. Guerlin et al. , "Progressive field-state collapse and quantum non-demolition photon counting", Nature **448**, 889 (2007).
[4] J-M. Raimond et al. , "Quantum Zeno dynamics of a field in a cavity", Physical Review A **86**, 032120 (2012).

Cooperative fluorescence spectrum of strongly driven atomic clouds

Romain Bachelard[1,2], Tiago Santiago do Espirito Santo[2], Michael Kastner[3], Robin Kaiser[4]

[1] Departamento de Física, Universidade Federal de São Carlos, São Carlos, SP, Brazil
[2] Instituto de Física de São Carlos, Universidade de São Paulo, São Carlos, SP, Brazil
[3] National Institute for Theoretical Physics (NITheP), Stellenbosch, South Africa
[4]Université Côte dAzur, CNRS, INPHYNI, France

The scattering of light by dilute cold atomic clouds is a long-range problem by nature, as light induces an effective $1/r$ interaction between the particles. Furthermore, the relative absence of decoherence allows for classical and quantum correlations to be preserved over long distances. Examples of these effects include in dilute clouds include superradiance and subradiance, as well as modification of the linewidth. While most previous works in dilute clouds addressed classical scattering, we have studied the modifications of the fluorescence spectrum due to this long-range interaction. By using approximate numerical schemes, based on a truncation of the BBGKY hierarchy which keeps only the lowest-order quantum correlations [1], we show that the spectrum of strongly-driven dilute clouds presents new sidebands (higher-order Mollow sidebands) as well as an asymmetry that can only be captured by including the (quantum) coupling between the atoms [2]. The modifications of the fluorescence spectrum that we characterize thus correspond to a form of entanglement of the atoms over large distances (i.e., many wavelengths).

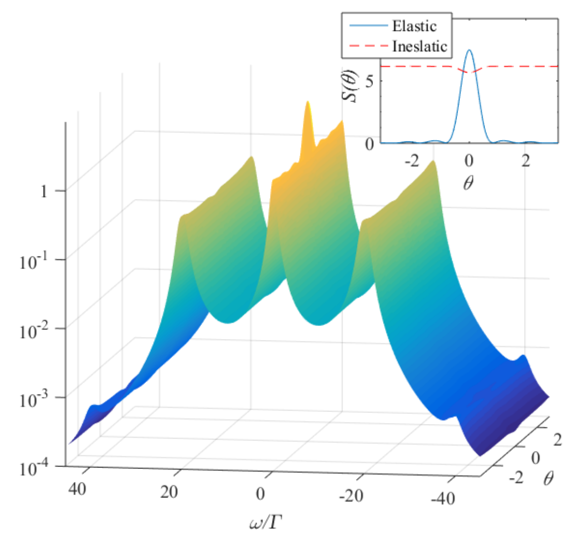

Figure 1. Angular dependence of the fluorescence spectrum of a cloud of $N = 72$ atoms, driven by a field of Rabi frequency $\Omega = 20\Gamma$ at resonance. The inset shows the elastic and integrated inelastic spectra.

[1] L. Pucci, A. Roy, and M. Kastner, Phys. Rev. B 93, 174302 (2016).
[2] L. Pucci, A. Roy, T. S. do Espirito Santo, R. Kaiser, M. Kastner, and R. Bachelard, Phys. Rev. A 95, 053625 (2017).

Nonlinear scattering of atomic bright solitons in disorder.

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We observe nonlinear scattering of ^{39}K atomic bright solitons [1] launched in a one-dimensional (1D) speckle disorder. We directly compare it with the scattering of non-interacting particles in the same disorder. The atoms in the soliton tend to be collectively either reflected or transmitted, in contrast with the behavior of independent particles in the singlescattering regime, thus demonstrating a clear nonlinear effect in scattering. The observed strong fluctuations in the reflected fraction, between zero and 100%, are interpreted as a consequence of the strong sensitivity of the system to the experimental conditions and in particular to the soliton velocity [2]. This behavior is reproduced in a mean-field framework by Gross-Pitaevskii simulations, and mesoscopic quantum superpositions of the soliton being fully reflected and fully transmitted are not expected for our parameters. We discuss the conditions for observing such superpositions, which would find applications in atom interferometry beyond the standard quantum limit [3].

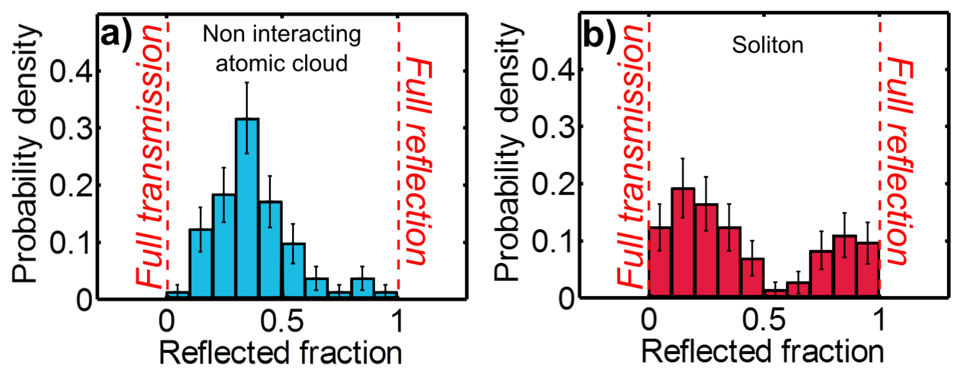

Figure 1. (Color online) Histograms of the experimentally measured reflected fractions of non-interacting atoms ((a) in blue) and solitons ((b) in red). The double-peak structure in (b) is a clear signature of nonlinear scattering.

[1] S. Lepoutre, L. Fouché, A. Boissé, G. Berthet, G. Salomon, A. Aspect, and T. Bourdel, Phys. Rev. A **94**, 053626 (2016).

[2] A. Boissé, G. Berthet, L. Fouché, G. Salomon, A. Aspect, S. Lepoutre and T. Bourdel, EPL **117**, 10007 (2017).

[3] Alexej I. Streltsov, Ofir E. Alon, and Lorenz S. Cederbaum, Phys. Rev. A **80**, 043616 (2009).

Experimental quantum simulation of spin models in 2d atomic arrays

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Laboratoire Charles Fabry, Institut d'Optique Graduate School,
*CNRS, Université Paris-Saclay, 91127 Palaiseau cedex, France**

Combining holographic arrays of optical traps with a fast moveable tweezers allows to assemble efficiently large 2d atomic arrays. On these cold matter samples, we can implement spin models (Ising, XY) using the strong dipole-dipole interaction when these atoms are excited to Rydberg states.

Large arrays of individually controlled atoms trapped in optical tweezers are a very promising platform for quantum engineering applications [1]. Recently we demonstrated a technique to prepare fully loaded, two-dimensional arrays of up to ~ 50 microtraps each containing a single atom, and arranged in arbitrary geometries [2, 3].

Starting from initially larger, half-filled matrices of randomly loaded traps, we obtain user-defined target arrays at unit filling. This is achieved with a real-time control system and a moving optical tweezers that performs a sequence of rapid atom moves depending on the initial distribution of the atoms in the arrays.

We can combine this new technique with previous works on implementing, e.g., the Ising model with Rydberg atoms interacting via the van-der-Waals energy $V_{ij} = C_6/r_{ij}^6$ [1] and study the properties of many-body interacting Hamiltonians on large arrays of up to 50 atoms. The flexibility of the atom-by-atom assembly technique allows to easily change between interesting configurations from 1d chains with or without periodic boundary conditions to 2d arrays with geometries that could lead to frustation phenomenas.

Our assembly technique can also be extended to work on 3d atomic arrays with the use of electro-tunable lenses whose focal distances can be quickly modified (~ 5 ms) to detect and move atoms at different positions along the optical axis.

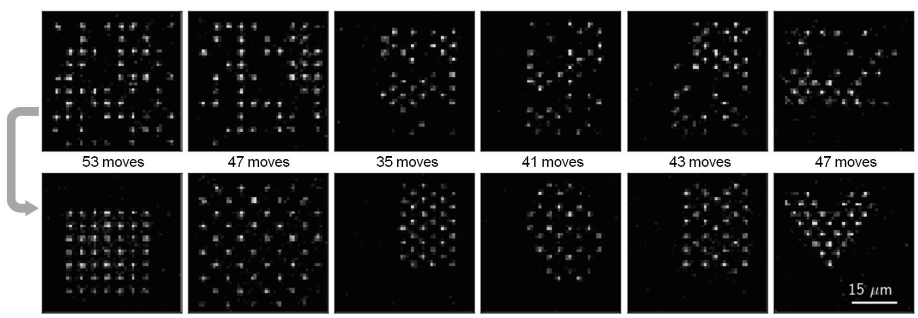

FIG 1: Gallery of fully loaded arrays (bottom images) obtained from the initial configurations shown in the top images. All images are single shots. The number of elementary moves needed to achieve the sorting are indicated.

* sylvain.leseleuc@institutoptique.fr

[1] H. Labuhn, D. Barredo, S. Ravets, S. de Léséleuc, T. Macrì, T. Lahaye, and A. Browaeys, Nature **534**, 667 (2016).
[2] D. Barredo, S. de Léséleuc, V. Lienhard, T. Lahaye, and A. Browaeys, Science **354**, 1021 (2016).
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Long-range Rydberg-Rydberg interactions: formation of macrodimers

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The large polarizability of atoms in highly excited Rydberg states leads to strong and long-ranging interactions between such atoms. Interacting pairs of Rydberg atoms represent an exotic molecular system, characterized by high internal excitation, high density of electronic states, internuclear separations exceeding one micrometer, and lifetimes beyond tens of microseconds. I will discuss the computational methods we have developed to determine the electronic structure of interacting Rydberg-atom pairs [1] and our spectroscopic approaches to verify these calculations [2]. Recently, we could observe the formation of macrodimers by detecting vibrational bound states of two interacting Rydberg atoms [3], as predicted in 2002 by Boisseau and coworkers [4]. This observation has important consequences, *e.g.*, for the implementation of Rydberg-atom-based quantum gates: because the relative translational motion of the two bound Rydberg atoms is frozen, quantum gates without motional decoherence can be realized [5]. The sequential photoassociation scheme and the validity of adiabatic approximations for these states will also be discussed.

The interaction of Rydberg atoms with ground-state atoms located inside the Rydberg orbit can lead to the formation of another class of exotic molecules, long-range Rydberg molecules [6]. Our experiments towards determining electron-atom-scattering phase shifts from high-resolution spectroscopy of long-range Rydberg molecules will be presented [7].

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[2] H. Saßmannshausen, F. Merkt, and J. Deiglmayr, Phys. Rev. A 92, 032505 (2015)
[3] H. Saßmannshausen and J. Deiglmayr, Phys. Rev. Lett. 117, 83401 (2016)
[4] C. Boisseau, I. Simbotin, and R. Côté, Phys. Rev. Lett. 88, 133004 (2002)
[5] D. Petrosyan and K. Mølmer, Phys. Rev. Lett. 113, 123003 (2014)
[6] C. H. Greene, A. S. Dickinson, and H. R. Sadeghpour, Phys. Rev. Lett. 85, 2458 (2000)
[7] H. Saßmannshausen, F. Merkt, and J. Deiglmayr, Phys. Rev. Lett. 114, 133201 (2015)

Tailoring a spin system with synthetic fluxes by shaking a chain of ions

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The Dicke model, describing the coupling of spins and bosons, gives rise to an effective long-range Ising model. In past years, this relation has been exploited for using trapped ions as quantum simulators of spin models. Here we suggest to gain additional control by applying a periodically driven potential to the Dicke model. Such 'shaking' can be used to enhance or suppress interactions between selected spins, or even to render spin-spin interactions complex-valued. The latter case allows for mimicking the presence of artificial magnetic fluxes, which can give rise to phenomena known from topological insulators, such as fractal energy spectra or end states located between bulk energy bands [1]. By simulating the dynamics in such shaken Dicke model, we show explicitly for few ions that synthesizing magnetic fluxes is feasible. Chiral spin flow serves as a direct hallmark of the flux. Surprisingly, the noisy effects of the phonons to the spin dynamics is reduced in the presence of synthetic fluxes [2].

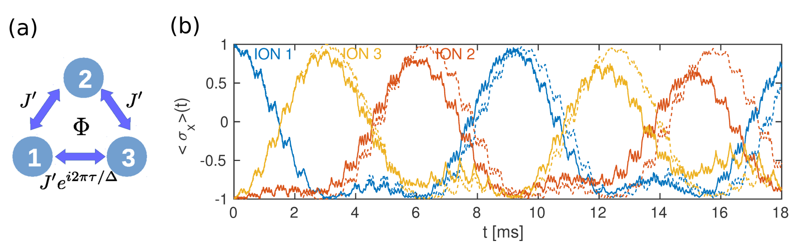

Figure 1. We shake a chain of three ions such that the system mimics a particle hopping on a triangle pierced by a flux Φ, as illustrated in (a). Shown in (b) is the time evolution of the three spins evaluated on the level of a pure Ising spin model (dashed lines) and on the level of a Dicke model with spin-phonon coupling (solid lines). The presence of the flux not only leads to chiral flow seen in both descriptions, but also makes the curves matching remarkably well.

[1] Tobias Grass, Christine Muschik, Alessio Celi, Ravindra W. Chhajlany, and Maciej Lewenstein, Phys. Rev. A **91**, 063612 (2015).
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SIRTEQ: Science and engineering in Ile-de-France Region for Quantum Technologies

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[1] Institut d'Optique Graduate School, Palaiseau (FR)

The SIRTEQ project labeled Major Interest Domain (DIM) is funded by the Ile-de-France Region. SIRTEQ brings together the largest European concentration of academic teams in the field of quantum technologies. Its main objective is to promote an excellent academic research in the field of quantum technologies in Ile de France, taking into account the actual current societal challenges and the importance of the transfer of knowledge and technologies.

The SIRTEQ project is focused on Quantum Technologies. When the level of individual quantum objects is reached, quantum properties such as entanglement or superposition become evident experimentally. They then pave the way for revolutionary methods to process and manipulate information carried by such objects. The general objective of SIRTEQ is to develop new ways of processing information or making ultra-precise measurements, using new physical supports quantum supports, rather than classical ones. It brings together computer scientists, physicists of condensed matter, cold atoms, optics and metrology in Ile-de-France who are paving the way for the second quantum revolution.

The DIM SIRTEQ has four main themes:
1- Quantum Sensors and metrology
2- Quantum simulations
3- Quantum communications
4- Quantum computing
To these four vertical themes structuring the DIM are added two horizontal ones:
5- Enabling science and technology
6- Scientific valorization and training

One-dimensional spinor Bose gases: magnetic order and giant spin-dipole polarizability

Karina Jiménez-García, Andrea Invernizzi, Bertrand Evrard, Camille Frapolli, Jean Dalibard and Fabrice Gerbier

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Spinor Bose gases —bosonic quantum systems with internal degree of freedom s— are excellent candidates to investigate the underlying physical mechanisms behind magnetic order. While ferromagnetism is favored in systems with $s = 1/2$, atomic quantum gases with $s > 1/2$ can support more complex magnetic phases, such as spin-nematics.

Spinor Bose gases in reduced dimensions are particularly interesting to study both the spatial organization of spins in equilibrium, as well as non-equilibrium dynamics after a quench across a magnetic quantum phase transition. Here we present the experimental study of one-dimensional $s = 1$ Bose gases of Na atoms across a magnetic quantum phase transition. We observe phase separation and the formation of spin domains purely driven by antiferromagnetic spin-exchange interactions. We measure a significant increase of the linear response to a magnetic field gradient —the so-called spin-dipole polarizability— for a partially polarized and phase-separated spinor gas compared to a completely polarized system. Finally, we discuss experimental progress toward the observation of the non-equilibrium dynamics of spin domains.

A Rydberg-dressed magneto-optical trap

Alistair D. Bounds, Niamh C. Keegan, Ryan K. Hanley, Riccardo Faoro, Elizabeth M. Bridge, Paul Huillery, Matthew P. A. Jones.

Joint Quantum Centre (JQC) Durham-Newcastle, Department of Physics, Durham University, South Road, Durham, DH1 3LE, United Kingdom

The strong dipolar interactions between Rydberg atoms have been exploited to perform numerous experimental studies of interacting many-body systems. A promising approach to create an interacting many-body quantum gas with tunable interactions is to off-resonantly couple a low-lying atomic state to a Rydberg state [1,2]. It has been shown that this so-called Rydberg dressing approach could facilitate the formation of interesting states of matter, such as supersolids [3,4]. Recently, experimental work has demonstrated the tunability of the Rydberg-dressed interaction in optical lattices [5,6], however the effect of these interactions in a randomly distributed ensemble are yet to be observed. Here we present a novel Rydberg-dressing experiment where the excited state of a narrow-line strontium MOT is coupled off-resonantly to a high-lying Rydberg state, producing an operational MOT with measurable Rydberg character, as shown in figure 1. This is supported by a quantitative Monte-Carlo model of the MOT. We are able to measure the Rydberg character of the MOT through its sensitivity to an applied electric field, which without the Rydberg admixture would be nonexistent. Here we present recent experiments which strive to observe a mechanical effect of the long-range dressed interactions in a laser-cooled gas.

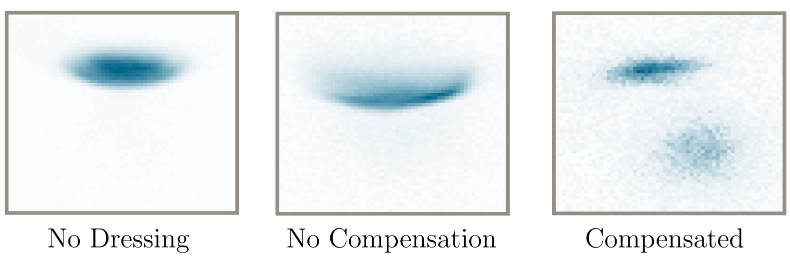

Figure 1. Rydberg dressing of a MOT. We start with a MOT operating on the 7 kHz wide intercombination line in Sr (left image). Applying an off-resonant UV laser to couple to the Rydberg state admixes Rydberg character into the excited state, and leads to an AC Stark shift that moves the MOT (centre image). By adjusting the MOT detuning to compensate the AC Stark shift (right image), Rydberg dressed atoms are magneto-optically trapped at the original position, while undressed atoms outside the UV beam fall away.

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[5] Y. Y. Jau *et al.*, Nat. Phys **12**, 71 (2015)
[6] J. Zeiher *et al.*, Nat. Phys **12**, 1095 (2016)

Fast circularisation of Rydberg atoms using optimal control theory

S. Patsch[1], D.M. Reich[1], S. Gleyzes[2], M. Brune[2], J.-M. Raimond[2], C. P. Koch[1]
[1] Theoretische Physik, Universität Kassel, Heinrich-Plett-Str. 40, 34132 Kassel, Germany
[2] Laboratoire Kastler Brossel, Collège de France, CNRS, ENS-PSL Research University, UPMC-Sorbonne Universités, 11, place Marcelin Berthelot, 75231 Paris Cedex 05, France

Circular Rydberg atoms have many remarkable and useful properties such as a long lifetime, a large polarisability and a high sensibility to magnetic fields due to their maximal magnetic quantum number. For use of circular states in quantum technologies such as quantum sensing [1] or quantum simulation [2], it is crucial that their preparation be as fast as possible in order to obviate decoherence. We use quantum optimal control [3] to construct RF pulses that achieve high fidelity in the shortest possible time, given current experimental limitations on peak amplitudes and spectral bandwidth. We also discuss the fundamental quantum speed limit for circularisation of Rydberg atoms when lifting these constraints.

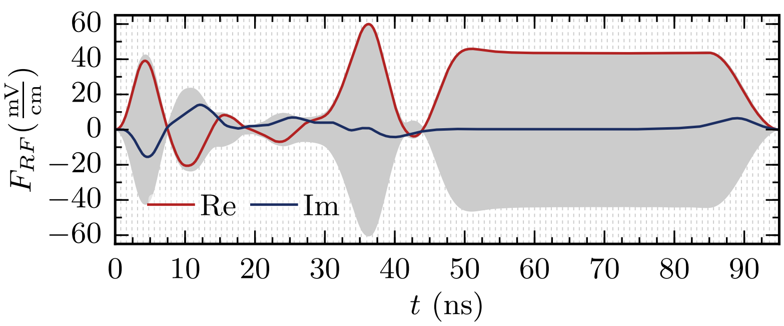

Figure 1. Optimized RF pulse reaching a state preparation fidelity of 99% (coarse-grained to match the experimental temporal resolution).

[1] T.L. Nguyen, J.M. Raimond, C. Sayrin, R. Cortiñas, T. Cantat-Moltrecht, F. Assemat, I. Dotsenko, S. Gleyzes, S. Haroche, G. Roux, Th. Jolicoeur, M. Brune, arXiv:1707.04397 (2017).
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Stabilization of droplet phases in Rabi-coupled BECs and dipolar gases in free space

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Droplets are very common in nature, from liquid water to superfluid Helium and nuclear matter. In the first part I will present the zero temperature phase diagram of bosons interacting via dipolar interactions in three dimensions in free space. Upon increasing the strength of the dipolar interaction and at sufficiently high densities we find a wide region where filaments are stabilized along the direction of the external field. Most interestingly by computing the superfluid fraction we conclude that superfluidity is anisotropic and vanishes along the orthogonal plane. In the second part I will focus on the case of two-component Bose condensates coupled via a laser field. We study the effects of quantum fluctuations on a Rabi-coupled two-component Bose gas of interacting alkali atoms. The divergent zero-point energy of gapless and gapped elementary excitations of the uniform system is properly regularized obtaining a meaningful analytical expression for the beyond-mean-field equation of state. In the case of attractive inter-particle interaction we show that the quantum pressure arising from Gaussian fluctuations can prevent the collapse of the mixture with the creation of a self-bound droplet. We characterize the droplet phase and discover an energetic instability above a critical Rabi frequency provoking the evaporation of the droplet. Finally, we suggest an experiment to observe such quantum droplets using Rabi-coupled internal states of ^{39}K atoms.

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An Er-Dy mixture for quantum gas microscopy

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Strongly magnetic atoms enable the study of few- and many-body effects arising from long-range and anisotropic dipole-dipole interactions. Here we present the status of our new experimental setup, which for the first time will combine the two highly magnetic lanthanide atoms, Erbium and Dysprosium. Both species, which have been brought singularly to quantum degeneracy recently, have similar atomic properties, which makes their combination in a single experiment favorable. Within the main experimental chamber, we plan to investigate various Bose-Bose, Bose-Fermi and Fermi-Fermi mixtures with unbalanced dipolar strength.
A separate chamber with electric field electrodes enables the preparation and detection of Rydberg atoms composed from lanthanide atoms. This will allow to investigate the possibilities which arise from the optical active core. Additionally alternative excitation schemes via the unfilled f-Shell structure for a direct excitation of large angular momentum Rydberg states seems feasible.
To allow the detection of exotic quantum phases predicted on 2D lattice geometries, we will additionally implement a quantum gas microscope in an additional science chamber, being able to detect and manipulate single atoms on individual lattice sites. With an additional passive and active magnetic shielding we aim to create an ultralow magnetic field environment, possibly enabling self-organization of the permanent magnetic dipoles in absence of an external quantization field.

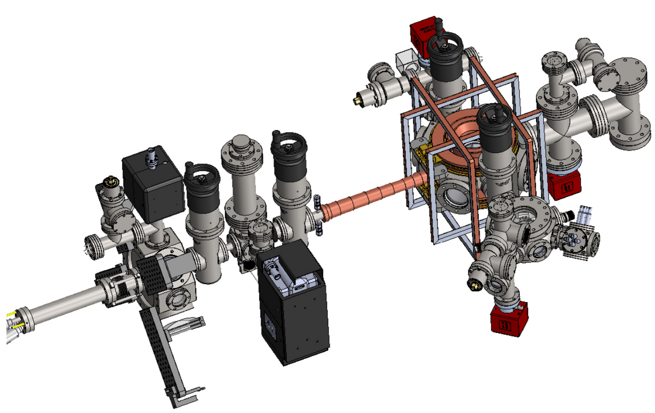

Figure 1. Experimental setup of the double-spezies Er-Dy experiment.

Quantum optical lattices and weak measurements for strongly correlated bosons and fermions

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[2] University of Oxford, Department of Physics, UK
[3] St. Petersburg State University, Russia

We show that the quantum backaction of weak global measurement constitutes a novel source of competitions in many-body systems (in addition to standard short-range tunnelling and interactions in lattices) [1,2]. This leads to novel dynamical effects: multimode oscillations of macroscopic superposition states, nonlocal non-Hermitian Zeno dynamics, long-range correlated pair tunnelling, protection and break-up of fermion pairs [2], as well as generation of antiferromagnetic states [3]. We demonstrate the generation of multipartite mode entanglement in this system, and feedback control of many-body states [4]. Quantization of optical lattice potentials enables quantum simulations of various long-range interacting systems unobtainable using classical optical lattices [5]. It leads to new quantum phases (dimers, trimers, etc. of matter waves similar to valence bond solids) beyond density orders (e.g. supersolids and density waves) directly benefiting from the collective light-matter interaction.

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Simulating artificial graphene in circuit-QED

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We present an experimental study of the eigenmodes and the dispersion relation of an artificial honeycomb lattice made of superconducting resonators. We image the spatial distribution of the modes using a low temperature laser scanning microscopy based on the variation of the microwave transmission of the lattice. (see Fig. 1.a and 1.b). This variation is induced by the absorbed laser power by a site of the lattice and is proportional to the weight of the probed mode on this site. In addition to mode labeling, mode imaging enables the reconstruction of the dispersion relation by Fourier transform. We were also able to investigate edges-states modes (see Fig. 1.b, bottom right image).

In order to model the lattice, we have developed an *ab initio* method to calculate its spectrum by simulating a few resonators on electromagnetic software. This modelization provides an effective tight-binding Hamiltonian that is in good agreement with experimental data (see Fig. 1.c).

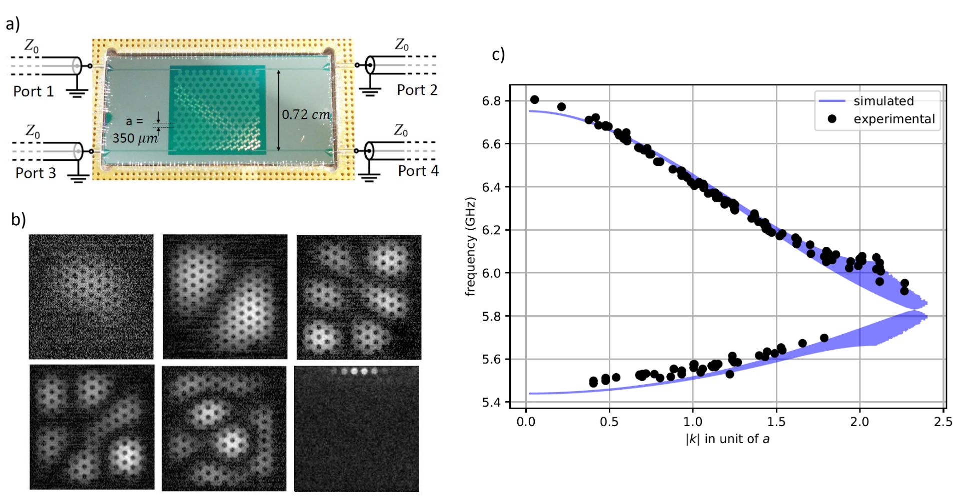

Figure 1. a) Image of the artificial graphene sample. b) Spatial distribution of a few modes. The one at the bottom right is one of the observed edge state. c) Comparison of experimental results and simulation for the dispersion relation of the lattice

2D Anderson transitions of cold atoms with synthetic spin-orbit coupling in speckle potentials

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We investigate the metal-insulator transition occurring in two-dimensional (2D) systems of non-interacting atoms in the presence of artificial spin-orbit interactions and a spatially correlated disorder generated by laser speckles. Based on a high order discretization scheme, we calculate the precise position of the mobility edge and verify that the transition belongs to the symplectic universality class. We show that the mobility edge depends strongly on the mixing angle between Rashba and Dresselhaus spin-orbit couplings. For equal couplings a non-power-law divergence is found, signaling the crossing to the orthogonal class, where such a 2D transition is forbidden.

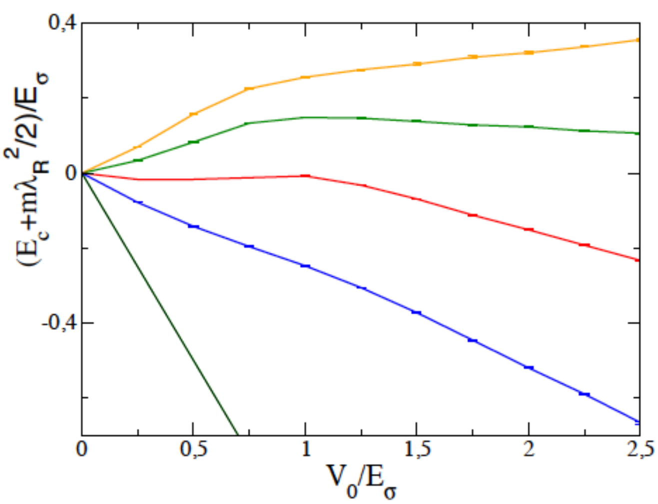

Figure 1. Mobility edge E_c of the 2D Anderson transition versus disorder strength V_0 for increasing values of the Rashba spin-orbit coupling λ_R (from top to bottom).

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Exploring Interacting Topological Insulators with Ultracold Atoms: the Synthetic Creutz-Hubbard Model

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Understanding the robustness of topological phases of matter in the presence of strong interactions, and synthesising novel strongly-correlated topological materials, lie among the most important and difficult challenges of modern theoretical and experimental physics. In this work, we present a complete theoretical analysis of the synthetic Creutz-Hubbard ladder, which is a paradigmatic model that provides a neat playground to address these challenges, including the generation of flat bands. We put special attention to the competition of correlated topological phases and orbital quantum magnetism in the regime of strong interactions. We predict topological quantum phase transitions for weak and intermediate interactions with different underlying conformal field theories (CFTs), i.e. Dirac versus Majorana CFTs. These results are furthermore confirmed and extended by extensive numerical simulations based on matrix product states (MPS). Moreover we propose how to experimentally realize this model in a synthetic ladder, made of two internal states of ultracold fermionic atoms in a one-dimensional optical lattice. Our work paves the way towards quantum simulators of interacting topological insulators with cold atoms [1].

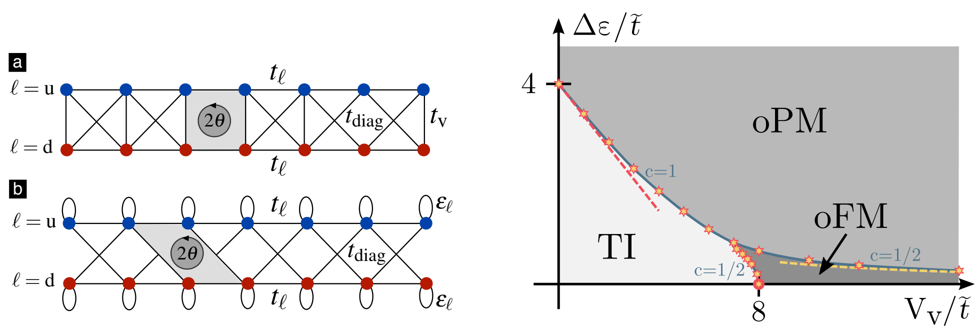

Figure 1. Left: standard vs imbalanced Creutz ladder scheme. Right: phase diagram with on-rung Hubbard interactions – tuning them and/or the Zeeman imbalance between legs, it is possible to drive the flat-band topological insulator into two different non-topological (magnetic) phases; the central charges of the critical lines are also indicated.

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Theoretical study of deep-center defects in some semiconductors

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The typical example of a deep-center defect is the nitrogen-vacancy (NV) center in diamond. The spin states of this defect can be optically manipulated at room temperature which makes it attractive for quantum applications. However, the fabrication of devices from diamond is quite difficult. The prospective material which is believed to have similar properties as diamond is SiC. Moreover, SiC growth and device engineering technologies are well established. The aim of this work is to obtain a reference method to model the electronic properties of the NV-center in diamond (C), and to transfer it to various defects in silicon carbide (SiC), so as to understand the photoconversion process in this material.

We first study the point defect consisting of one carbon atom substituted by one nitrogen atom in diamond with the density functional theory in the local density (LDA) and generalized gradient (GGA) approximations. Despite much work has been done on N substitutional center in diamond, there is still disagreement in results obtained with different theoretical methods, and between theory and experiment, for instance for the symmetry of the atomic structure of the point defect, and for the ordering of the electronic energy level(s) that appear in the band structure, and in particular in the band gap, due to the presence of the defect. To obtain these quantities, some calculation issues have to be resolved are discussed in this poster.

Firstly, the knowledge of the proper band gap edge is crucial in order to study defect levels. However, when used with traditional exchange-correlation functionals, the DFT systematically underestimates electronic bandgap of semiconductors. To go beyond DFT, quasiparticle correction can be introduced with the GW method [1]. Recently, it has been reported that the use of range-separated hybrid functional HSE06 within DFT can yield the band gap of diamond with an accuracy better than 0.1 eV [2].

Since defects we are going to study have charged states, the long-range interaction raises an important problem. By introducing a defect in the supercell, both electric and elastic deformations arise which have hardly reached the equilibrium at the boundary of the cell. This creates interactions between neighboring cells which must be carefully studied. We plan to perform ab initio calculations within DFT using the Quantum ESPRESSO package and the HSE06 exchange and correlation functional, and eventually to study the effect of quasi-particle corrections. Group theory will be used to develop analytical impurity wavefunctions of the defects in their ground and excited states. Finally, the role of electron-phonon coupling will be studied to understand the spin-decoherence time.

Supports from the ANR-10-LABX-0039-PALM program (Femtonic project), from DGA (France) and from the CEA-CNRS NEEDS-Matriaux program (France) are gratefully acknowledged. Computer time is granted by École Polytechnique through the LLR-LSI project and by GENCI (Project No. 2210).

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Quantum simulators based on Rydberg atoms in magnetic nanolattices

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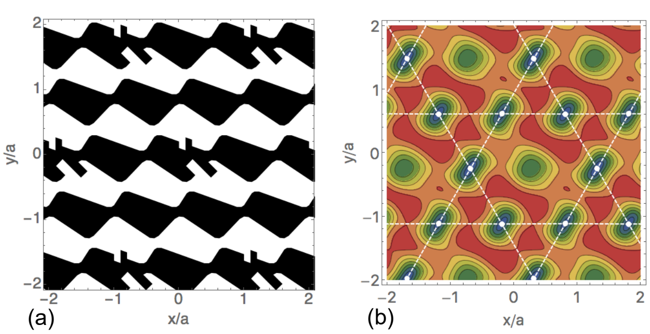
Lattices of ultracold atoms provide a versatile and tunable platform for the study of strongly interacting quantum many-body systems, including Hubbard and spin models. Our quantum simulator is based on ultracold ^{87}Rb atoms trapped in magnetic nanolattices. Our goal is to excite a single atom per site to the Rydberg state. In fact, due to their strong dipole-dipole interactions, Rydberg atoms are perfect candidates to study many body quantum systems. On one hand, our approach of using nanofabricated magnetic lattices offers the great opportunity to design a variety of geometries, allowing the investigation of new physical regimes in novel patterns like (super-)lattices with Kagome and honeycomb structure, combined on a single chip. On the other hand, we observe Stark shifts of Rydberg levels as well as line broadenings approaching the chip, due to stray electric field produced by adsorbates on the surface. For this reason, part of our work is dedicated to the characterization of adsorbates dynamics on the chip surface, in order to control and limit their interference with Rydberg interactions.



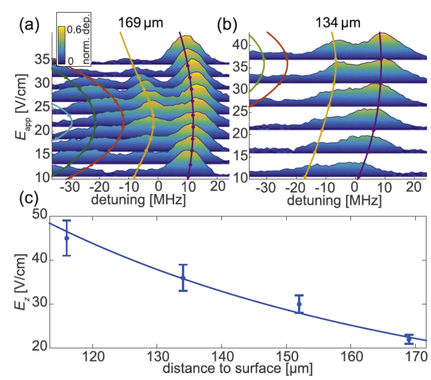


Figure 1. (a) Simulation of Kagome lattice and (b) respective potential.

Figure 2. Depletion spectrum of the $23D_{5/2}$ Rydberg state taken at distances of (a) 169 μm and (b) 134 μm from the surface, for different applied fields E_{app} in the z-direction (perpendicular to the surface.) Solid lines are theoretical predictions of peak positions, for stray field parameters that best match the observed spectral dependence on E_{app}. (c) Extracted stray field values in the z-direction, together with a fit assuming a Gaussian patch of Rb adatoms (Ref. [2]).

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Relaxation dynamics of highly excited electrons: mecanisms limiting the performance of electronic devices.

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Hot carrier relaxation mechanisms, such as electron-phonon and impurity scattering, determine the lifetimes of hot carriers and thus limit the performances of electronic devices, such as photovoltaic devices, single-photon avalanche diodes, devices based on deep-level impurities. In particular, electron-phonon coupling limits the spin coherence time of the of the deep defect levels in diamond and SiC, because of the possibility of phonon-mediated relaxation between excited state and ground state [1]. Detailed understanding of the hot carrier relaxation processes is thus necessary in order to make possible the device optimisation.

Although density functional theory (DFT) -based computational methods for the calculation of the electron-phonon coupling matrix elements in metals exist since the late nineties, DFT-based calculations of the electron-phonon coupling in semiconductors started much later [2,3]. We have calculated, in particular, the electron-phonon transition probability between shallow defect states in Si, by using an envelope-function description of the defect wave function and the electron-phonon matrix element of bulk material [4]. Very recently, we have developed a computational method for the calculation of the electron-phonon coupling in polar materials, based on the interpolation of the electron-phonon matrix elements in Wannier representation [5]. This method allowed us to successfully interpret the dynamics of hot electron relaxation in bulk GaAs, in excellent agreement with time- and angle- resolved photoemission experiment by the group of K. Tanimura (University of Osaka, Japan). The measured, and calculated, electron-phonon scattering times turned out to be surprisingly fast, of the order of a few tens of femtoseconds. Moreover, we have demonstrated, for the relaxation of hot carriers in GaAs, the existence of two distinct relaxation regimes, one related with the momentum, and the other with energy relaxation. Both regimes are shown to be almost entirely ruled by the electron-phonon interaction [6].

To conclude this presentation, we will show our first results on the modeling of the NV centers in diamond and SiC.

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Light scattering by cold interacting two-level atoms

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We have shown recently that when the inter-particle distance becomes small in comparison to the wavelength of light, resonant dipole-dipole interactions play an increasing role and modify the way the light is scattered. For instance, in the presence of interactions, the *incoherent* response of a wavelength-sized and dense atomic cloud is no longer proportional to the number of atoms but is rather strongly suppressed [1].

The near-resonance *coherent* optical response of cold atomic gases is also modified by dipole-dipole interactions and has been at the focus of recent investigations by several groups, both experimentally [2,3] and theoretically [4,5]. Partly to test the Lorentz local-field theory, which explains the recently measured cooperative Lamb-shift in hot vapor cells [6] but is predicted to break down when inhomogeneous broadening is absent [5]. Our recent measurements of the *coherent* optical response of a microscopic cloud of cold atoms [7] confirm this prediction. Qualitative agreement with the state-of-the-art coupled-dipole model was found, although discrepancies remain, possibly due to the multi-level structure of rubidium being improperly accounted for in the model.

Here, I will present our latest measurements using cold interacting *two-level* atoms. A model based on the Maxwell-Bloch equations (accounting for the propagation of light through the cloud of interacting atoms and the time-dependent evolution of the atomic coherences) shows good agreement with the data and confirms the approach of the coupled-dipole model.

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A propagating single-photon packet cannot always be mimicked by a low-intensity coherent packet

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The *Nature Physics Insight* edition of April 2012 [1] highlighted how electromagnetic fields are required to be as controllable as matter for Quantum Simulation purposes. Preparation and control of quantum states of the electromagnetic field is a key ingredient. However, under certain circumstances, a quantum state of the electromagnetic field can be mimicked by a classical field, as far as the quantum dynamics of matter is concerned, even at the single-quantum level. Identifying those circumstances is a central issue for Quantum Simulation. Single-quantum states of the electromagnetic field can be achieved, e.g., in optical and microwave cavities, in intensity-attenuated lasers, in nonlinear crystals and, more recently, in nanophotonic waveguides. Waveguide-based single-photon sources offer a novel regime: a truly single field excitation can be prepared on demand and it can also freely propagate, while maintaining strong atom-photon interaction at the single-photon level. Theoretically, one fundamental interest is on the fact that the single photon can be prepared as a broadband wavepacket formed by a quantum coherent superposition of different frequency modes. Depending on the wavepacket bandwidth, a single-photon packet may be either well simulated by a low-intensity coherent field state, as in the linear monochromatic limit [2,3], or badly simulated by it, as in the nonlinear large-bandwidth regime [4,5].

In this work, we present novel signatures that distinguish the effect of a propagating single-photon wavepacket from that by a low-intensity coherent wavepacket. These signatures appear even in the linear regime, achieved by a highly monochromatic field. For instance, we have recently found that a single-photon wavepacket can produce non-Markovianity in the reduced dynamics of a two-level system with which it interacts [6]. Here we show that such non-Markovianity has no classical analog. Another relevant feature we have also recently investigated is the time-dependent Stark shift induced by a single-photon wavepacket on the transition frequency of the two-level system [7]. Here we show that, although such a time-dependent Stark shift has indeed a classical analog, the way to experimentally access it is different from the classical situation.

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Wednesday 15/11

Single-atom-resolved probing of lattice gases in momentum space

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[2] Theoretical Physics, ETH Zurich, Zurich, Switzerland

Correlations between the degrees of freedom of individual quantum particles has been identified as a key ressource to solve open many-body problems. So far, a large experimental effort has been devoted to the building of apparatus capable of measuring spatial and spin correlations in one and two dimensions. We will present an experiment that provides access to multi-particle correlations between the momentum degree of freedom in three-dimensional lattice systems. We produce Bose-Einstein condensates of Helium-4 atoms in a metastable state [1, 2], whose internal energy (19.6 eV) is large enough to allow for an electronic detection of individual atoms in three dimensions [3, 4]. When released from a 3D optical lattice, we probe the gas in the far-field regime of expansion where the atom distribution can be exactly mapped on the in-trap momentum distribution. Comparison with ab-initio Quantum-Monte Carlo calculations in the Bose-Hubbard regime qualifies our apparatus as a single-atom probe delivering momentum distributions of strongly interacting systems as large as 60×60×60 sites. We also illustrate novel capabilities to access physical quantities of interest, like the condensed fraction, by investigating the superfluid-to-normal phase transition.

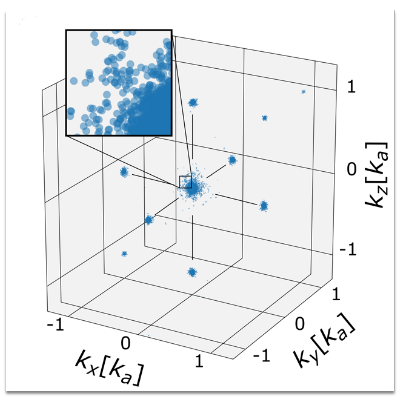

Figure 1. Three-dimensional atom distributions of lattice gases .

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Probing a dissipative phase transition via dynamical optical hysteresis

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Optical bistability -the existence of two stable states with different photon numbers for the same driving conditions- is a general feature of driven nonlinear systems described within the mean-field approximation (MFA). Beyond the MFA, a quantum treatment predicts that the steady-state of a nonlinear cavity is unique at any driving condition. The origin of this apparent contradiction can be ascribed to quantum fluctuations (neglected in MFA) which trigger switching between states [1]. When the average switching time is much greater than the measurement duration an apparent bistability is observed.

In the present contribution we explored the influence of fluctuations on bistability for constant and dynamical driving conditions with semiconductor microcavities operating in the exciton-photon strong coupling regime, gathering evidence of a dissipative phase transition [2]. When the drive amplitude is swept across the region where mean field approximation predicts bistability, the hysteresis area exhibits a double power law decay as a function of the sweep time. The experimentally retrieved exponents are in agreement with calculations [3]. By measuring the time-resolved cavity transmission at a constant drive amplitude we observed the switching events and deduced the scaling of the average switching time as a function of the laser-cavity detuning. Probing different laser-cavity detunings and photon-photon interactions, we show that the algebraic decay evolves towards a single power law when the photon number becomes very large, i.e. when approaching the thermodynamic limit. This algebraic behavior characterizes a dissipative phase transition, a class of phenomena which is receiving significant interest [4]. We are now studying the switching time distributions as a function of the driving conditions. Our results pave the way to the investigation of dissipative phase transitions in lattices of nonlinear resonators.

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Ultracold dysprosium gas: optical cooling and coherent dynamics of a large spin atom

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Lanthanide atoms, with their complex electronic configuration and large magnetic moment, make good candidates for the study of long-range anisotropic interactions or for the realization of artificial gauge fields. Here, we detail the behavior of our dysprosium narrow-line Magneto-Optical Trap (MOT). We show that optimal operation is reached in the spin-polarized regime, which is achieved through an interplay between gravity and optical forces [1]. The narrow-line transition can also be used to create strong spin-dependent dipolar potentials with reduced heating, yielding to the coherent manipulation of spin states. With adequat choice of the laser field's polarization, non-linear interaction can be achieved, leading to the generation of highly entangled spin states and spin squeezing [2]. These non-classical states can be used, for example, in quantum metrology [3, 4].

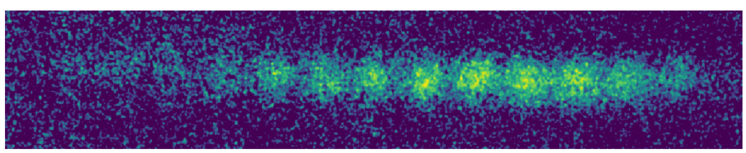

Figure 1. The spin dynamics are measured with a Stern-Gerlach detection scheme. In this absorption image, each cloud corresponds to a different spin state, populated after the interaction with the laser field. For bosonic dysprosium, up to 17 different clouds can be observed ($J = 8$).

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A two-particle, four-mode interferometer for atoms

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The demonstration of non-classical interference effects has been a crucial enterprise in the history of quantum optics. On the one hand, these observations have played a role in stimulating the field of quantum information, and on the other they have provided benchmarking experiments for important quantum protocols. Two archetypal examples are the violation of Bell's inequalities and the observation of the Hong–Ou–Mandel effect using photons. An essential element of these experiments is the light source which provides well characterized pairs of entangled photons. In the past few years, our group has been developing an analoguous source of atom pairs based on spontaneous four wave mixing in a Bose–Einstein condensate of metastable Helium-4 atoms. In a recent paper, we described our observation of the Hong–Ou–Mandel interference between the emitted atoms [1]. Here, we report on further experiments on two-particle interference in a four-mode interferometer. Our results support, if not yet prove, the presence of momentum entanglement in the emitted atom pairs sent at the input of the interferometer [2].

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Four-body ring-exchange interactions and anyonic statistics within a minimal toric-code Hamiltonian

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Ring exchange is an elementary interaction for modeling unconventional topological matter which hold promise for efficient quantum information processing. We report the observation of four-body ring-exchange interactions and the topological properties of anyonic excitations within an ultracold atom system. A minimum toric code Hamiltonian, in which the ring exchange is the dominant term, was implemented in disconnected four-spin plaquette arrays formed by two orthogonal superlattices. The ring-exchange interactions were resolved from the dynamical evolutions of the spin orders in each plaquette, matching well with the predicted energy gaps between two anyonic excitations of the spin system. A braiding operation was applied to the spins in the plaquettes and an induced phase $1.00(3)\pi$ in the four-spin state was observed, confirming 1/2 mutual statistics. This work offers a novel prospect for quantum simulation of topological phases by engineering many-body interactions.

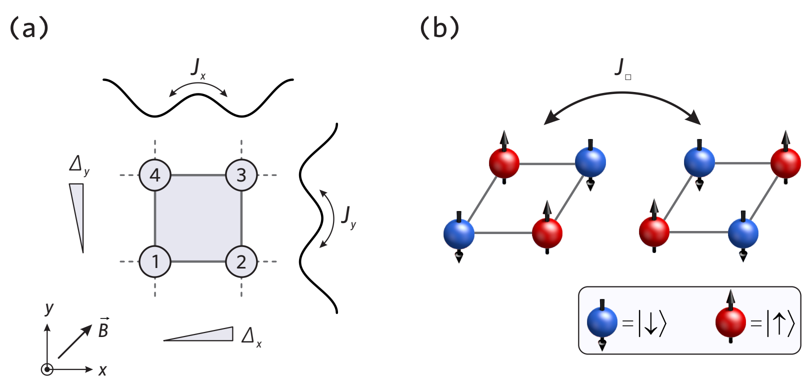

Figure 1. Experimental scheme and the ring-exchange process in disconnected four-site plaquettes.(a) An isolated optical plaquette with effective magnetic gradients are created by two orthogonal spin-dependent superlattices, and the sites of each plaquette are enumerated in a counter-clockwise fashion; (b) The ring-exchange driven oscillations take place between the two antiferromagnetically ordered states.

Cold-atom based implementation of the quantum Rabi model

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The interaction of a two-level system (TLS) with a single bosonic mode is one of the most fundamental processes in quantum optics. Microscopically, it is described by the quantum Rabi model (QRM). Here, we propose a versatile implementation of this model based on single trapped cold atoms [1]. Assuming realistic experimental conditions, we show that our approach is not restricted to the Jaynes-Cummings regime but also allows exploring the regimes of ultra-strong coupling, deep strong coupling, and dispersive deep strong coupling. In contrast to most other QRM platforms, all important system parameters, i.e., the emitter-field detuning and the coupling strength of the emitter to the mode, can be dynamically tuned over a wide range. The quantum state of the bosonic mode and the TLS can be prepared and read out using standard cold-atom techniques, enabling the study of the QRM and its dynamics with unprecedented control. Our scheme implements the TLS using atomic Zeeman states, while the atom's vibrational states in the trap represent the bosonic mode. The coupling is mediated by a suitable fictitious magnetic field pattern [2]. Finally, we show that our scheme also enables the implementation of important generalizations, namely, the driven QRM, the QRM with quadratic coupling as well as the case of many TLSs coupled to one mode (Dicke model).

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SIRTEQ: Science and engineering in Ile-de-France Region for Quantum Technologies

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The SIRTEQ project labeled Major Interest Domain (DIM) is funded by the Ile-de-France Region. SIRTEQ brings together the largest European concentration of academic teams in the field of quantum technologies. Its main objective is to promote an excellent academic research in the field of quantum technologies in Ile de France, taking into account the actual current societal challenges and the importance of the transfer of knowledge and technologies.

The SIRTEQ project is focused on Quantum Technologies. When the level of individual quantum objects is reached, quantum properties such as entanglement or superposition become evident experimentally. They then pave the way for revolutionary methods to process and manipulate information carried by such objects. The general objective of SIRTEQ is to develop new ways of processing information or making ultra-precise measurements, using new physical supports quantum supports, rather than classical ones. It brings together computer scientists, physicists of condensed matter, cold atoms, optics and metrology in Ile-de-France who are paving the way for the second quantum revolution.

The DIM SIRTEQ has four main themes:
1- Quantum Sensors and metrology
2- Quantum simulations
3- Quantum communications
4- Quantum computing
To these four vertical themes structuring the DIM are added two horizontal ones:
5- Enabling science and technology
6- Scientific valorization and training

Towards a single-atom register in a fiber micro-cavity for generation of multi-particle entanglement

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We present our new experimental platform where a high finesse fiber Fabry-Pérot cavity is combined with a single-atom microscope, see Fig. 1. Our experiment is aimed at extending the generation of multi-particle entanglement to 1D arrays of up to a 100 neutral atoms while maintaining control on a single particle level. In this experiment atoms will be trapped by an one-dimensional optical lattice ($\lambda = 1560\,\mathrm{nm}$) inside the cavity. A second wavelength in the cavity of 780 nm strongly couples the trapped atoms with a single-atom cooperative of $C_1 = 90$. The possibility to address the trapped atoms through the microscope with a Digital Micromirror Device will also be discussed. Our first measurements from interactions of untrapped atoms that couple to the cavity will be presented. At the conference we also hope to show the first measurements of trapped atoms inside the cavity.

This new experimental platform will provide an ideal test-bed to investigate multiparticle-entanglement generation in many different contexts. Our main interest are the application of Quantum Zeno Dynamics [1], quantum state carving [2] and the studying the superradiance quantum phase transition in the Dicke model [3].

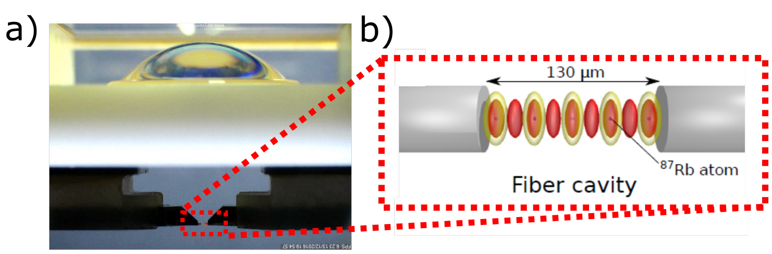

Figure 1. a) Photo of our all-in-vacuum setup. b) Schematic of our fiber Fabry-Perot cavity strongly coupled with a register of ≈ 100 single 87^Rb atoms.

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Spectroscopy of the Rydberg states of ytterbium and isolated core excitation

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Rydberg atoms offers an ideal platform for the study of strongly interacting systems. However, usual techniques for imaging or trapping atoms are unavailable in alkali Rydberg atoms. The aim of this experiment is to optically manipulate atoms in Rydberg states using a divalent atom: ytterbium.

We present our results of laser and microwave spectroscopy of highly excited Rydberg levels of ytterbium. We have improved the precision over previous absolute measurements [1] by two or more orders of magnitude, now reaching around 10 MHz, which opens new perspectives on two-electron atoms. Our analysis [2] based on Multichannel Quantum Defect Theory (MQDT) demonstrates a good understanding of the interactions between the two electrons in such levels. In particular, we need for the first time to include in the theory a channel with no bound state to account accurately for the level perturbations.

Once excited to the Rydberg state, the atom has still a valence electron to optically manipulate its external degrees of freedom. This can be a powerful tool to investigate ultra-cold interacting Rydberg gases. However, autoionization can occur when this 2nd valence electron is optically excited [3]. In the purpose of studying this process, we have recently performed ionic core spectroscopy. These results will also be presented.

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Topological effects due to the magnetic field in the Quantum Walk

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In this work, we analyze the properties of a quantum walk that simulates a particle subject to the combined action of a electric and magnetic field. Inspired by the idea of the integer quantum Hall effect (IQHE), the main purpose is to find the topological effects due to the magnetic field in the QW. One way to approach this result is by defining a discrete current in the QW. We make use of our definition to study its effects as the electric and magnetic fields are changed. As we know, in the continuous limit, the conductivity in the IQHE is quantized, as a function of the magnetic intensity. We analyze what happens in a discrete system. We also study the Bloch oscillations, and several properties related to the propagation of the walker as a function of the values of the electric and the magnetic field.

Numerical study of Bose-Hubbard models with finite-range interactions.

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We investigate, by means of various Quantum Monte Carlo techniques, the quantum phases of Bose-Hubbard models with finite-range interactions. These models are of direct interest for realization in ongoing experiments of Rydberg-dressed atoms. We demostrated numerically the existence of equilibrium and out-of-equilibrium phases including superfluid, supersolid and glassy ones [1].

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Impurities in quantum gasses

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I wish to present my work as a poster. The presented work is theoretical studies of impurities in quantum gasses. The primary focus will be topological superfluids in Fermi-Bose mixtures. The Fermi-Bose mixtures include one-dimensional identical fermions embedded in both three- and one-dimensional bosonic gasses. Similar work has previously been done on 2D-3D mixtures [1, 2]. An attractive induced interaction between the fermions mediated by the bosons is calculated and the resulting Cooper pairing of the fermions is studied on a mean field level. The systems show emerging edge states and are good candidates for experimental investigation, because the induced interaction can be tuned both in range and strength. This work has been done in collaboration with G. M. Bruun and Z. Wu, and with fruitful discussion with J. M. Midtgaard. Further, I will present novel work on a single impurity in a Bose gas using a master equation approach. In principle this lets us calculate the quantum dynamics of the impurity, including the formation of the polaron. The latter work has been done in collaboration with Thomas Pohl and L. A. Peña Ardila. The Bose polaron has received a lot of attention the last years, both theoretically and experimentally [3, 4, 5, 6].

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Microscopy of the interacting Harper-Hofstadter model in the two-body limit

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The combination of interacting charged particles and magnetic fields can to lead to exotic physics that exhibit both spatial entanglement and topological order. Using optical fields, ultracold neutral atoms can simulate the behavior of charged particles in magnetic fields. This capability has been used to study effects such as edge states, topological band structures, and the quantum hall effect. Thus far, however, these experiments have not yet incorporated inter-particle interactions. I will describe recent experimental results in which we apply microscopy to interacting atoms exposed to a synthetic magnetic field and are confined to a 2xN real-space ladder. We observe the chiral dynamics of both single-particle and two-particle systems with strong, finite interactions. We show the interactions for the two-particle system enable chiral dynamics where they would otherwise be absent. Our observation of a novel form of interaction-induced chirality illustrates the rich physics that can emerge with these ingredients even in the few particle limit. Realizing this combination of elements is essential to advance into the regime of fractional quantum hall physics, as well as to drive explorations for new phenomena with the microscopic tools of AMO systems [1].

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Effect of losses in a 1D Bose gas: cooling to the ground state by quantum feedback and production of non thermal states

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In [1] the effect of atom losses on a 1D quasi-condensate was investigated. The authors have shown that, within a linearized approach one expects the temperature of the low lying modes to decrease in time, in agreement with recent experimental results [3]. The fluctuations induced by the loss process due to the discrete nature of atoms is however responsible for a heating, limiting the temperature which can be achieved. More precisely, one expects that the temperature asymptotically converges towards $g\rho(t)$ where g is the coupling constant and ρ the linear atomic density [1]. We extend this work on the effect of atom losses in two directions.

First, we describe the dynamics using a Monte Carlo wavefunction approach [4]. More precisely, we assume that the losses are monitored with a spatially and temporally resolved detector and we calculated the evolution of the system conditioned by the result of the loss process, namely a given history of losses. This approach not only presents an alternative picture conveying more physical insight, but also opens the road to the realization of measurement based quantum feedback: controlled dynamics, conditioned on the monitored losses, allow to reach lower temperatures. We show how feedback could cool a given mode to its ground state.

Second, we investigate the realization of non-thermal states under the effect of atom losses [2]. For this purpose, we go beyond the linearized approach, describing the quasi-condensate within a classical field approach; the time-dependent Gross-Pitaevskii equation with an additional loss term. We believe that the realization of long-lived non-thermal states is related to the integrability of the system, supported by numerical simulations showing that the system thermalizes towards the Gibbs ensemble when integrability is violently broken. We then present numerical studies showing that long-lived non-thermal states are also produced if one incorporates the shot-noise associated with the discrete loss process, namely the quantum nature of the atomic field operator. Finally, we present experimental results with long-lived non-thermal states following atom losses.

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Spatial imaging of strongly interacting Rydberg atoms

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The strong interactions between Rydberg excitations can result in spatial correlations between the excitations. In this work, we investigate how the character of the Rydberg-Rydberg interactions affects the nature of the spatial correlations and the evolution of those correlations in time. We use direct imaging of the center-of-mass positions of the individual Rydberg atoms and pair-correlation analysis to observe the atom-pair kinetics due to binary dipolar forces. The Rydberg excitations are prepared with a well-defined initial separation, and the effects of van der Waals or dipole-dipole forces are observed by tracking the interatomic distance between the Rydberg atoms. The atom trajectories and thereby the interaction coefficient are extracted from the pair correlation functions of the Rydberg atom positions. The pair correlation results provide the first direct visualization of the electric-dipole interaction and clearly exhibit its anisotropic nature. We also demonstrates the ability to enhance or suppress the degree of spatial correlation in a system of Rydberg excitations, using a rotary-echo excitation process in concert with particular excitation laser detunings. The work demonstrates an ability to control long-range interactions between Rydberg atoms, which paves the way towards preparing and studying increasingly complex many-body systems.

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Entanglement properties of lattice bosons from a variational wave function

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Entanglement is a defining characteristic of many-body quantum systems, expressing the degree of non-locality required by the description of the state of the system, and quantifying the amount of classical information demanded to faithfully reproduce the reduced state of any subsystem. The ground states of many-body Hamiltonians with short-range interactions are generically characterized by area-law scaling of entanglement entropies of a subsystem, implying that the classical information required to store the reduced density matrix is exponential in the surface of the subsystem itself this aspect impairs scalable simulations with methods based on the explicit reconstruction of reduced density matrix, such as DMRG, in dimensions higher than one. A viable alternative is based on variational ground states explicitly exhibiting an area-law scaling of entanglement. Here we explore the entanglement properties of entangled plaquette states (EPS) [1] representing a systematically improvable variational Ansatz for lattice boson models, and lending itself to an efficient optimization based on variational Monte Carlo. We evaluate the explicit dependence of the entanglement entropy on the number of coefficients in the variational Ansatz, and contrast the entanglement properties of local vs. nonlocal plaquettes in the EPS structure. Applying the EPS approach to a lattice boson model (the spatially anisotropic pi-flux triangular lattice) which bridges 1d and 2d physics, we investigate how the entanglement scaling reveals the effective dimensionality of correlations

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Spin mixing dynamics in chromium quantum gases

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In spin 3 chromium quantum Bose gases, atoms interact through (short range, isotropic) Van der Waals, and (long range and anisotropic) dipole-dipole interactions. We experimentally study spin mixing dynamics in these spinor gases, in bulk or lattices, and compare our results with mean field simulations, or simulations taking into account quantum correlations [1].

In recent experiments we initiate spin mixing dynamics by tilting the spins by an angle θ with respect to the external magnetic field. In the BEC case, dynamics is induced by the interplay between long-range dipolar and short-range contact exchange interactions. While spin mixing is triggered by dipolar coupling, it is strongly influenced by contact interactions once started. For the particular case $\theta = \pi/2$, an external spin-orbit coupling term, induced by a magnetic gradient, is required to drive the spin dynamics. In that case, relatively strong spin-dependent contact interactions tend to locally preserve ferromagnetism, which disfavours beyond mean field physics [2]. In a Mott insulating state, with one atom per site, only intersite dipolar interactions are at play. While a mean field approach fails to reproduce the data, we obtain good agreement with simulations based on the Truncated Wigner Approximation, which indicates the emergence of quantum correlations: the pure dipolar spin dynamics has a beyond mean field character.

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Imaging and trapping cold atoms using a multimode fiber

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A high imaging resolution, or a tight focus of a laser beam impose a certain minimal numerical aperture (NA) of the optical system in question. Since a higher NA is usually achieved by placing larger lenses closer to the object, one can quickly be limited by spatial constraints on the experiment. This is true, amongst other scenarios, when imaging or trapping cold atoms inside a vacuum chamber. Multimode fibres, in conjunction with spatial light modulators, offer an interesting alternative to the standard approach of high NA lenses, as they are a flexible optical waveguide with very small transverse dimensions ($\sim 100\mu m$), and a reasonably high NA (up to 0.5). For those reasons, the use of multimode fibres for imaging purposes has been widely studied in the past years, especially with bio-medical applications in mind. I will present our work in progress, which aims at transferring this technique to the field of cold atoms. We will collect light from the atoms for imaging, and send light towards the atoms for trapping, all with a NA of 0.5. Inherent in this approach is a correction of optical aberrations, meaning that the spot size will attain the theoretical diffraction limit given by the NA ($\lesssim 1\mu m$).

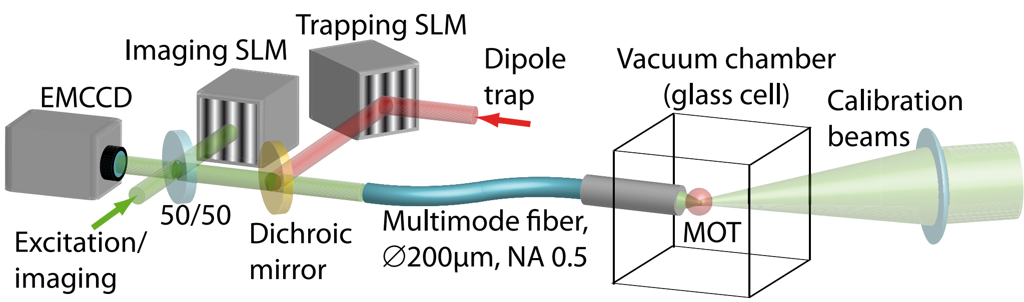

Figure 1. Trapping and imaging experimental setup.

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BCS pairing state of a Dilute Bose Gas with Spin-Orbit Coupling

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We study a two-component Bose gas with Rashba and symmetric spin-orbit couplings (SOC). Due to special density of states with SOC, two atoms can form a bound state with any intra-species scattering length in the case of Rashba SOC [1], and with any intra- or inter-species scattering lengths in the case of symmetric SOC [2]. Consequently, in the dilute limit, the Bardeen-Cooper-Shrieffer (BCS) pairing state of bosons can be formed with weakly-attractive interactions. The quasiparticle excitation energies are anisotropic due to spin-orbit coupling. This BCS paring state is energetically favored over Bose-Einstein condensation (BEC) of atoms at low densities. The superfluid transition temperature of this pairing state is less than the BEC tempature of ideal atoms with the same density [1, 3].

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[3] Dekun Luo and Lan Yin, to be published in Int. J. Mod. Phys. B.

Localized states induced by the spatially oscillating long-range interaction

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We derive an effective model in the light-atom coupling system placed in front of a reflecting mirror. Resulting from the feedback effect induced by the mirror, this effective model possesses an intriguing long-range interaction. This interaction oscillates more and more rapidly in space as the range increasing, however, its amplitude remains unchanged. We numerically demonstrate that this model hosts various ground states with rich localized structures as shown in the following figure, and further discuss how to observe the localized structures through the dynamical process. By considering the relevant physical parameters, we also illustrate that the interesting phenomena based on our effective model are realizable experimentally.

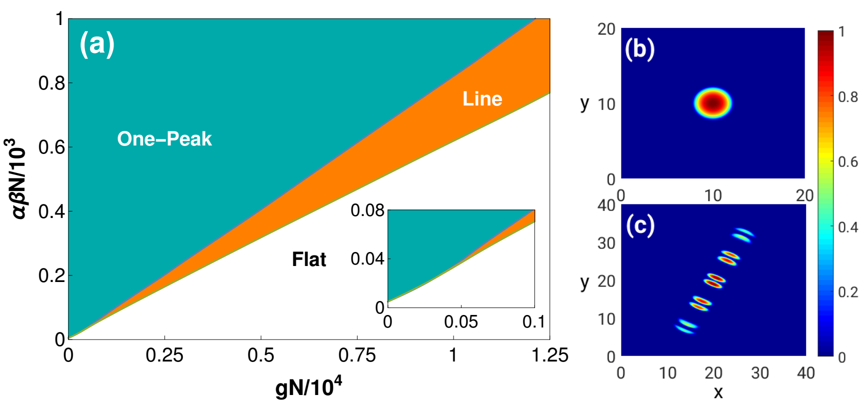

Figure 1. (a) Phase diagram of the effective model. Here, N is the total norm, $\alpha\beta$ is the strength of the long-range interaction, and g is the strength of the local interaction. (b) and (c) show the one-peak state and the line state respectively.

[1] Yong-Chang Zhang, Valentin Walther, and Thomas Pohl, Localized states induced by the spatially oscillating long-range interaction (in preparation).

Thursday 16/11

A quantum-gas microscope for fermionic potassium-40

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Single-atom-resolved detection in optical lattices using quantum-gas microscopes [1,2] has enabled a new generation of experiments in the field of quantum simulation. We achieve single-site-resolved imaging of individual atoms in an optical lattice with high fluorescence yield while maintaining a negligible particle loss rate, by simultaneously laser cooling the atoms to sub-Doppler temperatures while detecting the fluorescence photons emitted during this process. However, cooling of fermionic alkaline atoms in optical lattices is challenging, as their low mass and small excited-state hyperfine splitting make it more difficult to obtain low temperatures using the standard technique of polarization-gradient cooling.

We present how we achieved single-atom-resolved fluorescence imaging of ^{40}K using electromagnetically-induced-transparency (EIT) cooling [2]. This technique relies on the existence of a spectrally narrow, Fano-like line profile and dark resonances arising from quantum interference in a 3-level-like scheme. In confining potentials with quantized vibrational levels, as is the case in our optical lattice, the narrow absorption line can selectively excite red-sideband transitions that cool the atomic motion by removing one vibrational quantum, while carrier and blue-sideband excitations are suppressed. In our setup, we detected on average 1000 fluorescence photons from a single atom within 1.5s, while keeping it close to the vibrational ground state of the optical lattice.

We also demonstrate a new Raman gray-molasses cooling scheme which operates on the D2-line [4] using red-detuned lasers, in contrast to other schemes which operate on the D1-line. Our scheme allowed to reach sub-Doppler temperatures of 48(2) μK, which enables direct loading of $9.2(3) \times 10^6$ atoms from a magneto-optical trap into an optical dipole trap.

Our fermionic quantum-gas microscope will provide new possibilities to probe strongly correlated fermionic many-body systems at the single-atom level. It will allow the direct observation of spin-spin correlations, or, for example, the study of out-of-equilibrium dynamics and thermalisation of fermionic quantum systems.

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[3] E. Haller *et al.*, Nature Physics 11, 738 (2015).
[3] G. Bruce *et al.*, J. Phys. B: At. Mol. Opt. Phys. 50, 095002 (2017).

Photon propagation through dissipative Rydberg medium at large input rates

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Recently, the combination of slow light polaritons with the strong interactions between Rydberg atoms has emerged as a promising system for inducing a strong interaction between photons. Potential applications range from the implementation of phase gate for photons, to single photon sources, as well as the generation of strongly correlated states of photons. From theoretical point of view, the many-body setup of propagating Rydberg polaritons is hard to describe, especially when polaritons are strongly interacting.

We present a new approach to analyzing this challenging many-body problem with dissipative interactions in the limit of large optical depth per blockade radius [1]. In our approach, we separate the single-polariton EIT physics from Rydberg-Rydberg interactions in a serialized manner while using a hard-sphere model for the latter, thus capturing the dualistic particle-wave nature of light as it manifests itself in dissipative Rydberg-EIT media. Using this approach, we analyze the saturation behavior of the transmission through one-dimensional Rydberg-EIT media in the regime of non-perturbative dissipative interactions relevant to current experiments. Our serialized model agrees well with matrix product state (MPS) numerics. Moreover, our model is in good agreement with experimental data for low and intermediate input rates. For higher input rates the intensity of outgoing light is lower than from theoretical predictions which can be explained using simple pollutant-model.

[1] E. Zeuthen, et al., Correlated photon dynamics in dissipative Rydberg media, Phys. Rev. Lett. **119**, 043602 (2016)

Clock spectroscopy of strongly interacting bosons in deep optical lattices

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Two-electron atoms (such as ytterbium) have attracted great interest as quantum simulators. Indeed, due to their specific electronic structure, mainly the presence of a clock transition, they allow for the simulation of various interesting phenomena such as spin-orbit coupling [1] or artificial gauge fields [2]. Recently, large $SU(N)$ interactions were measured [3], which is very promising for the simulation of quantum impurity models [4]. In this context, we report on high-resolution optical spectroscopy of interacting bosonic ^{174}Yb atoms in deep optical lattices with negligible tunneling [5]. We prepare Mott insulator phases with singly- and doubly-occupied isolated sites and probe the atoms using a clock transition. Atoms in singly-occupied sites undergo long-lived Rabi oscillations. Atoms in doubly-occupied sites are strongly affected by interatomic interactions, and we measure their inelastic decay rates and energy shifts. We deduce from these measurements all relevant collisional parameters involving both clock states, in particular the intra- and inter-state scattering lengths [5, 6].

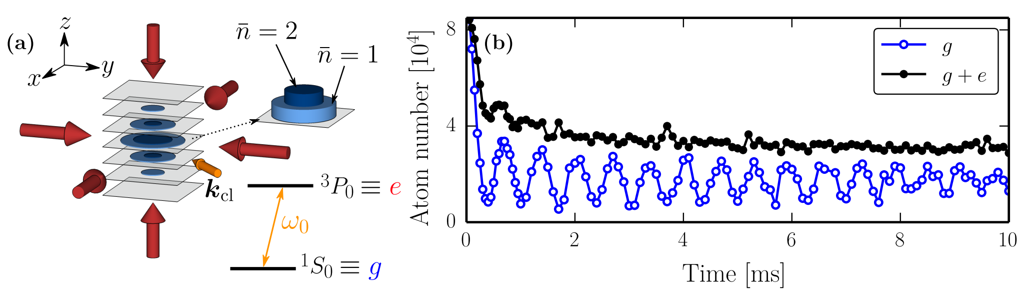

Figure 1. (a) Sketch of the three-dimensional lattice geometry. The drawing also illustrates the density profile of the Mott insulator and the level scheme of the ultra-narrow clock transition connecting the ground state g and the metastable excited state e. **(b)** Coherent driving on the clock transition in the deep Mott insulator regime. A coupling laser resonant on the clock transition is switched on at time $t = 0$ with a Rabi frequency $\Omega/(2\pi) \approx 1500\,\mathrm{Hz}$. Closed (respectively open) symbols represent the remaining total atom number (resp. the population in the ground state g).

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[4] L. Riegger et al, arXiv:1708.03810, (2017).
[5] R. Bouganne et al, accepted in New J. Phys., (2017).
[6] L. Franchi et al, arXiv:1707.04269, (2017).

Experimental realization of the spin Mott phase and progress toward the xy-ferromagnet and spin-superfluidity

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We experimentally demonstrate the high-fidelity realization of a spin-ordered state of bosonic atoms in a spin-dependent optical lattice. In the past, this has been experimentally difficult, since the required temperatures are given by the superexchange (second order tunneling) matrix elements, which are generally small. Instead, we ramp into a gapped phase known as the spin Mott phase, with exactly one spin-up and one spin-down atom at every site. The gap is given by the difference between the inter- and intra-spin interaction energies $U - U_{\uparrow\downarrow}$, whose relatively large magnitude allows us to populate the spin Mott state with high fidelity. In addition, the spin-dependence of the optical lattice allows for independent control of $U_{\uparrow\downarrow}$. Thus, the spin Mott phase provides a clean starting point for adiabatic preparation of other, possibly gapless, spin-ordered phases, including the xy-ferromagnetic phase [1], which demonstrates spin-superfluidity and spin-charge separation.

[1] J. Schachenmayer, D. M. Weld, H. Miyake, G. A. Siviloglou, W. Ketterle, and A. J. Daley, Phys. Rev. A **92**, 041602(R) (2015).

Continuous variable sampling from photon-added or photon-subtracted squeezed states

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We introduce a new family of quantum circuits in continuous variables and we address the corresponding sampling problem, that we call CVS [1]. We show that, relying on the widely accepted conjecture that the polynomial hierarchy of complexity classes does not collapse, their output probability distribution cannot be efficiently simulated by a classical computer. These circuits are composed of input photon-subtracted (or photon-added) squeezed states, passive linear optics evolution, and eight-port homodyne detection. We address the proof of hardness for the exact probability distribution of these quantum circuits by exploiting mappings onto different architectures of sub-universal quantum computers. We obtain both a worst-case and an average-case hardness result. Hardness of Boson Sampling with eight-port homodyne detection is obtained as the zero squeezing limit of our model.

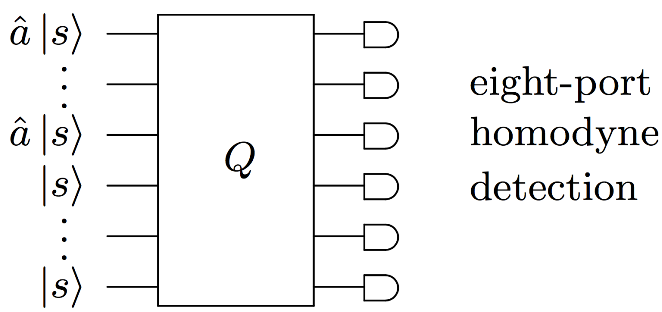

Figure 1. A CVS circuit: photon-subtracted squeezed states and squeezed states in input, a passive linear evolution described by the unitary matrix Q and eight-port homodyne detection.

[1] U. Chabaud, T. Douce, D. Markham, P. van Loock, E. Kashefi, and G. Ferrini, arXiv:quant-ph/170709245.

Optimal control of Rydberg lattice gases

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We present optimal control protocols to prepare different many-body quantum states of Rydberg atoms in optical lattices. Specifically, we show how to prepare highly ordered many-body ground states, GHZ states as well as some superposition of symmetric excitation number Fock states, that inherit the translational symmetry from the Hamiltonian, within sufficiently short excitation times minimising detrimental decoherence effects. For the GHZ states, we propose a two-step detection protocol to experimentally verify the optimal preparation of the target state based only on standard measurement techniques. Realistic experimental constraints and imperfections are taken into account by our optimisation procedure making it applicable to ongoing experiments [1]. The quantum speed limit time for preparing Rydberg GHZ state is also explored.

[1] J. Cui, R. v. Bijnen, T. Pohl, S. Montangero, T. Calarco, arXiv: 1702.07358.

A 2D Bose gas in a ring trap

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Ultracold atoms confined in ring-shaped traps are particularly suited for the study of superfluid flow, due to the presence of periodic boundary conditions [1,2]. As a consequence of superfluidity, the circulation of the velocity of the flow is quantized by multiples of h/m (m being the atomic mass). An annular, two-dimensional trap would thus be especially interesting to study the 2D superfluidity, governed by Berezinskii–Kosterlitz–Thouless physics [3].

I will present the setup we have realized that allows us to obtain such a trap. Combining a RF-dressed trap and a blue-detuned light sheet potential, we achieve a ring whose radius can reach values between 20 and 200 micrometers, and can be dynamically adjusted [4,5]. We have also developed schemes to create superflow in the ring: a focused laser beam whose position can be dynamically controlled to stir the superfluid, and a spatial light modulator to realize helices of laser intensity in order to phase-imprint a given state of circulation.

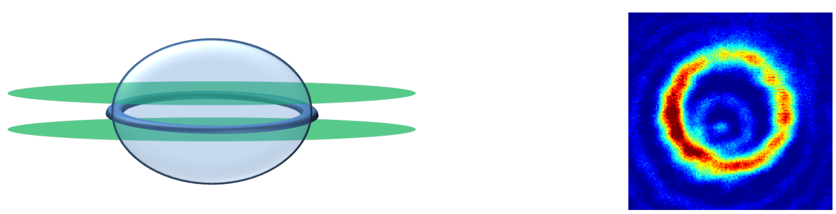

Figure 1. Left: Principle of the ring trap, at the intersection of a rf-dressed 'bubble' trap and blue-detuned light sheets. Right: example of a ^{87}Rb gas confined in such a ring (radius 40 microns).

[1] S. Moulder et al, Phys. Rev. A **86**, 013629 (2012).
[2] S. Eckel et al, Nature **506**, 200-203 (2014).
[3] C. de Rossi et al, New J. Phys. **18**, 062001 (2016).
[4] O. Morizot et al, Phys. Rev. A **74**, 023617 (2006).
[5] W.H. Heathcote et al, New J. Phys. **10**, 043012 (2008).

A 2x2 quantum dot analogue simulator

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The Hubbard model provides a description of interacting particles moving in a lattice [1]. Though seemingly simple, it uncovers strong quantum correlations which, on the one hand can explain striking phenomena such as superconductivity [2] and magnetism [3], but on the other hand make solutions to the model quickly intractable by classical methods as the number of particles in the lattice increases. The interaction between electrons in arrays of electrostatically defined quantum dots is naturally described by a Fermi-Hubbard hamiltonian; moreover, the high-degree of tunability that has been demonstrated in these systems [4] make them a perfect platform to explore different regimes of the Hubbard model through quantum simulations.

Here we present an array of 2x2 gate-defined quantum dots in a AlGaAs/GaAs heterostructure. This 2-dimensional quantum simulator presents symmetries not accessible in the more common linear arrays, which enable experimentally novel simulations such as mapping of the ferromagnetic to unpolarized phase transition in an almost-half-filled lattice [5]; and observation of resonating valence bond states, which have been predicted for high-temperature superconductors [2]. The device has been fabricated using a multi-layer gate technique, allowing us to make a vertical gate that increases the tunability of the tunnel coupling between the dots. Preliminary characterisation of the device is underway, showing good control of the simultaneous occupation of all four dots down to the single-electron regime; and individual control of the tunnel-couplings.

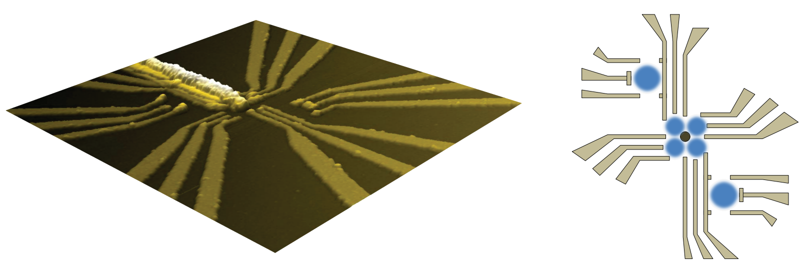

Figure 1. Atomic force microscope image of the gate structure of the 2x2 quantum dot device (left) and schematic top view of the gates (right). The 4 quantum dots are confined in the small region in the center, with 2 extra set of gates on the sides to form larger quantum dots used as charge sensors.

[1] J. Hubbard, P. Roy. Soc. Lon. A **276**, 238-257 (1963).
[2] P. W. Anderson, J. Phys. Conf. Ser. **449**, 012001 (2013).
[3] S. Sachdev, Nat. Phys. **4**, 173-185 (2008).
[4] T. Hensgens, *et. al.*, Nature, in print; arXiv:1702.07511 [cond-mat.mes-hall] (2017).
[5] Y. Nagaoka, Phys. Rev. **147**, 392-405 (1966).

Trapped ions in strongly polarizable atomic media

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We report on our experiment which will aim at studying ions trapped in a Paul trap interacting with ultracold atoms that are coupled to Rydberg states. Since the polarizability of the Rydberg-dressed atoms can be very large, the interaction strength between atoms and ions increases by many orders of magnitude as compared to the ground state case, and may be mediated over micrometers. Such interactions can be used to entangle an atom with the motional and/or internal state of an ion, to mediate spin-spin interactions between atoms via a bus ion, or to study spin-phonon couplings [1]. Simulations show that the scheme is to a large extend immune to imperfect ground state cooling of the ion or atom, and the ion's micromotion. Furthermore, we discuss how to employ Rydberg dressing on a dipole-forbidden transition to generate a repulsive atom-ion potential [2]. This prevents collision-induced heating of the ion due to its micromotion, typically limiting attainable temperatures in atom-ion hybrids. The system enables engineering of the atom-ion interaction, dynamic control, and offers a vast flexibility in manipulating the hybrid quantum states. Thus, our system should enable quantum simulation of few-body physics such as spin-spin interaction and atom-phonon coupling, solid-state physics such as quantum magnetism, and non-equilibrium dynamics in many-body systems such as relaxation and thermalization. We discuss our experimental approach for Rydberg dressing of Li atoms as well as a detailed theoretical analysis of Rydberg atom-ion interaction.

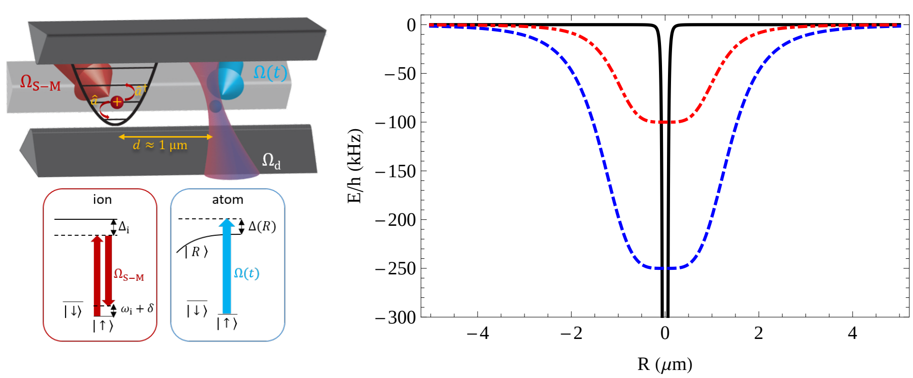

Figure 1. Sketch of the hybrid Rydberg-dressed atom-ion quantum system, its relevant energy level structures, and the adiabatic dressed atom-ion interaction potential for a set of realistic laser parameters. The solid black line corresponds to the ground state case. The interaction range can be tuned via the detuning from the Rydberg state used for dressing, while its strength can be tuned via both the detuning and the dressing transition's effective Rabi frequency [1].

[1] T. Secker, R. Gerritsma, A. W. Glätzle, and A. Negretti, Phys. Rev. A **94**, 013420 (2016).
[2] T. Secker, N. Ewald, J. Joger, H. Fürst, T. Feldker, and R. Gerritsma, Phys. Rev. Lett. **118**, 263201 (2017).

SIRTEQ: Science and engineering in Ile-de-France Region for Quantum Technologies

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The SIRTEQ project labeled Major Interest Domain (DIM) is funded by the Ile-de-France Region. SIRTEQ brings together the largest European concentration of academic teams in the field of quantum technologies. Its main objective is to promote an excellent academic research in the field of quantum technologies in Ile de France, taking into account the actual current societal challenges and the importance of the transfer of knowledge and technologies.

The SIRTEQ project is focused on Quantum Technologies. When the level of individual quantum objects is reached, quantum properties such as entanglement or superposition become evident experimentally. They then pave the way for revolutionary methods to process and manipulate information carried by such objects. The general objective of SIRTEQ is to develop new ways of processing information or making ultra-precise measurements, using new physical supports quantum supports, rather than classical ones. It brings together computer scientists, physicists of condensed matter, cold atoms, optics and metrology in Ile-de-France who are paving the way for the second quantum revolution.

The DIM SIRTEQ has four main themes:
1- Quantum Sensors and metrology
2- Quantum simulations
3- Quantum communications
4- Quantum computing
To these four vertical themes structuring the DIM are added two horizontal ones:
5- Enabling science and technology
6- Scientific valorization and training

Quantum metrology based on a Schrödinger cat state of a Rydberg atom

Arthur Larrouy[1], Eva-Katharina Dietsche[1], Adrien Facon[1], Dorian Grosso[1], Frédéric Assemat[1], Serge Haroche[1], Jean-Michel Raimond[1], Michel Brune[1], Sébastien Gleyzes[1]

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The sensitivity of quantum measurement is intrinsically limited by the projection noise. If the meter is a large angular momentum J, for instance, the quantum uncertainties limit the precision with which one can determine its precession frequency. Experiment using classical states of the meter, for which the quantum fluctuations are distributed isotropically, thus cannot achieve a precision lower than the standard quantum limit (SQL), which scales like $1/\sqrt{J}$. To go beyond the SQL, it is necessary to use non-classical states, like squeezed states or Schrödinger-cat states.

In our experiment, we use a rubidium atom in a Rydberg state as a quantum-enabled electrometer [1]. Rydberg levels are highly excited states with large dipoles, which makes them very sensitive to the electric field. By coupling the atom to a radiofrequency field of well-chosen polarization, we can restrict its evolution to a subspace of the Rydberg manifold, where it behaves as a large angular momentum J, whose precession frequency is proportional to the amplitude of the electric field. We have used this effective angular momentum to measure variations of the electric field with a precision that goes beyond the SQL. Instead of looking at the change of direction of the angular momentum induced by its precession, we prepare the system in a Schrödinger cat state and measure the quantum phase accumulated by the angular momentum during its evolution.

Using this method, we were able to reach a sensitivity 14dB beyond the SQL for our shortest measurement time. This highly sensitive, non-invasive space- and time-resolved field measurement extends the realm of electrometric techniques and could have important applications to charge detection.

[1] A. Facon, E.-K. Dietsche, D. Grosso, S. Haroche, J. M. Raimond, M. Brune, and S. Gleyzes, Nature **535**, 262-265 (2016).

Simulating Nonequilibrium Quantum Systems

Eduardo Mascarenhas[1]

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In the fist part of this talk I will discuss how quantum simulation may further our understanding and control of quantum transport. Specifically I will show classical state-of-the-art matrix-product-states based simulations addressing how interactions may induce conductor-insulating phase transitions [1]. Expanding the field of open systems I will also show how interacting quantum baths may induce novel emergent phenomena. In the second part of the talk we propose a protocol to simulate non-Markovian quantum environments through critical quantum systems at equilibrium [2]. Colorful quantum noise is generated by a collision process with many-body ground-states. Spatial correlations of the ground state are mapped into the time correlations of the noise process. Conversely, the protocol is an effective probe of quantum phase transitions determining the correlations of the many-body system by measuring the dynamics of a single observable of the probe. We simulate the system-bath dynamics with matrix-product-states and compare the system reduced dynamics with an approximate variational master equation which allows for the determination of the correlation length and estimating the back-action the probe exerts on the many-body system.

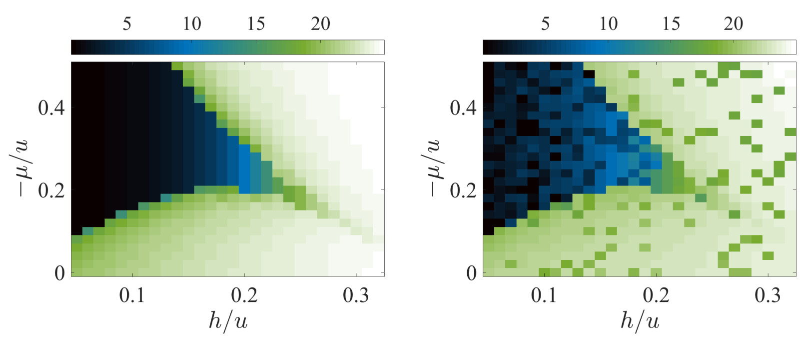

Figure 1. (Left) Direct MPS calculated correlation length $\xi^{(2)}$ and the (right) corresponding master equation probing of the correlation length for a Bose-Hubbard system of 50 sites with collision time steps of $dt = 0.02/\gamma$.

[1] Eduardo Mascarenhas, Giacomo Giudice, Vincenzo Savona, arXiv:1703.02934 [quant-ph].

[2] Eduardo Mascarenhas, Inés de Vega, Ulrich Schollwöck, Vincenzo Savona, in preparation.

Capacitance spectroscopy of large quantum dot arrays for simulating Fermi-Hubbard physics

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[2] Department of Physics, Purdue University, West Lafayette, Indiana 47907, USA
[3] Solid State Physics Laboratory, ETH Zurich, 8093 Zurich, Switzerland

In the last few years, quantum simulation experiments have started to probe problems in many-body physics that are not accessible to classical platforms, due to the exponential growth in complexity for highly-entangled systems. Here we report our progress on simulating fermionic Mott-Hubbard physics using two-dimensional arrays of quantum dots, which readily adhere to the same Hamiltonian. Such arrays would allow for emulations of the Mott insulator transition as well as band and Hofstadter physics[1]. By providing a voltage difference between two nanofabricated top gate layers on the sample surface, a periodic potential difference is created in the 2D electron gas (2DEG) underneath. Adding a doped back gate region and using capacitance spectroscopy [2], the global density of states in the 2DEG is measured as a function of Fermi energy. Although disorder levels are found to be sufficient for witnessing this transition, setting a sufficiently strong periodic potential proves difficult. A variety of different wafers and sample designs are tested to both lower disorder further and increase the periodic potential strength, which is needed to hit the ideal parameter regime.

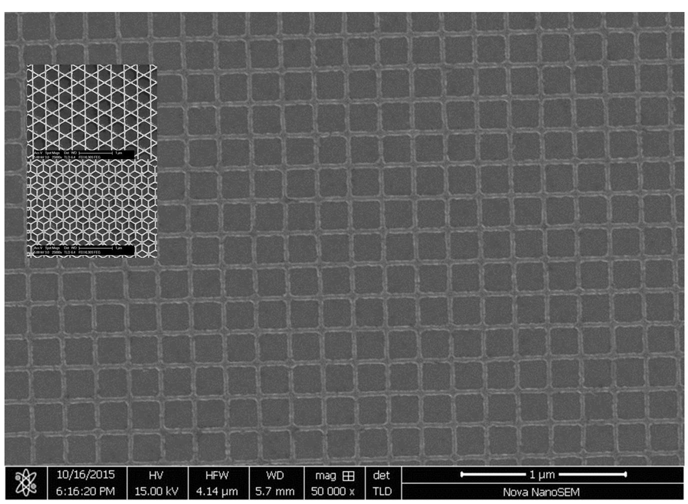

Figure 1. Nanofabricated grid-gate structures to create periodic potential in the 2DEG

[1] P. Barthelemy and L. M. K. Vandersypen, Annalen der Physik **525**, 808 (2013).
[2] R. Ashoori, J. Lebens, N. Bigelow, and R. Silsbee, Physical Review B **48**, 4616 (1993).

Photon subtraction via controlled many-body decoherence

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[2] 5. Phys. Inst. and Center for Integrated Quantum Science and Technology, Universität Stuttgart, Pfaffenwaldring 57, 70569 Stuttgart, Germany

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We present an experimental and theoretical investigation of the scattering-induced decoherence of multiple photons stored in a strongly interacting atomic ensemble. We derive an exact solution to this many-body problem, allowing for a rigorous understanding of the underlying dissipative quantum dynamics. Combined with our experiments, this analysis demonstrates a correlated coherence-protection process, in which the induced decoherence of one photon can preserve the spatial coherence of all others. We discuss how this effect can be used to manipulate light at the quantum level, providing a robust mechanism for single-photon subtraction, and experimentally demonstrate this capability.

Phonon Lasing with Trapped Ions by Engineered Reservoirs

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Quantum reservoir engineering (QRE), involving active control of the coupling of a quantum system to its environment, has recently been shown to be a resource for robust quantum state preparation and quantum computing. The implementation of QRE in our recent works allows us to stabilize squeezed states on the vibrational motion of a single trapped ion [1], and create superposition of these squeezed wave-packets such as the squeezed Schrödinger's cat [2] and GKP states useful for quantum error correction [3].

In addition, QRE provides the possibility to study quantum phase transitions driven by dissipation, in which a system abruptly changes its steady state as a function of the strength of the dissipation. We will explore such dissipative phase transitions using the vibrational motion of trapped ion chains, which are among the most precisely controlled quantum systems available to physics today. As a starting point for this research direction, we will realize both standard and squeezed phonon lasing deep in the quantum regime using newly available resources of mixed-species ion control and our pioneering works on QRE. This novel device can be applied for ultra-sensitive metrology, with the potential enhancement due to squeezing.

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Quantum simulators for open quantum systems using quantum Zeno dynamics

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A watched quantum arrow does not move. This effect, referred to as the quantum Zeno effect, arises from a frequent measurement of a quantum system's state. In more general terms, the evolution of the quantum system can be confined to a subspace of the system's Hilbert space leading to quantum Zeno dynamics. Resulting from the measurement process, a source of dissipation is introduced into the systems dynamics. However, different than for a common open quantum system, we can choose the strength of the dissipation by changing the parameters of the Zeno measurement.

We capitalise on the property of tunable dissipation to create a quantum simulator for open quantum systems. Due to the formal analogy of the measurement process and the theory of open quantum systems, we can derive a Lindblad master equation to describe the evolution of the open quantum system. Moreover, we extend the picture to enable also non-Markovian evolution in the quantum simulator.

The considered quantum system are photons inside a cavity being subject to a indirect measurement using circular Rydberg atoms. The setup is inspired by Zeno experiments proposed in the framework of cavity quantum electrodynamics [1].

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Quantum thermalization through entanglement in an isolated many-body system

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Quantum and classical many-body systems appear to have disparate behavior due to the different mechanisms that govern their evolution. The dynamics of a classical many-body system equilibrate to maximally entropic states and quickly re-thermalize when perturbed. The assumptions of ergodicity and unbiased configurations lead to a successful framework of describing classical systems by a sampling of thermal ensembles that are blind to the systems microscopic details. By contrast, an isolated quantum many-body system is governed by unitary evolution: the system retains memory of past dynamics and constant global entropy. However, even with differing characteristics, the long-term behavior for local observables in quenched, non-integrable quantum systems are often well described by the same thermal framework. We explore the onset of this convergence in a many-body system of bosonic atoms in an optical lattice. Our systems finite size allows us to verify full state purity and measure local observables. We observe rapid growth and saturation of the entanglement entropy with constant global purity. The combination of global purity and thermalized local observables agree with the Eigenstate Thermalization Hypothesis in the presence of a near-volume law in the entanglement entropy [1].

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Topological lasing in the edge states of a 1D polariton lattice

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Recently, the exploration of topological physics in photonic structures has triggered considerable efforts to engineer optical devices that are robust against external perturbation and fabrication defects [1]. However, due to the difficulty of implementing topological lattices in media exhibiting optical gain and/or nonlinearities, these realizations have been mostly limited so far to passive devices. Hence, cavity polaritons formed from the strong coupling between quantum well excitons and cavity photons are particularly appealing: their photonic part allows for engineering topological properties in lattices of coupled resonators [2,3], while their excitonic part gives rise to Kerr-like nonlinearities and to lasing through stimulated relaxation [4].

In this work [5], we demonstrate lasing in the topological edge states of a 1D lattice. This lattice emulates an orbital version of the Su-Schrieffer-Heeger (SSH) Hamiltonian by coupling the 1st excited states ($l = 1$) of polariton micropillars arranged in a zigzag configuration (Fig 1 (a) shows a SEM image of the lattice and a schematic representation of a micropillar, and (b) shows a real-space image of the emission from the orbital bands where we can observe the spatial distribution of the topological mode). Then, taking profit of the nonlinear properties of polaritons, we evaluate the robustness of this lasing action by optically shifting the on-site energy of the edge pillar, thus breaking the chiral symmetry of the lattice. Under this perturbation, we observe that the localization of the topological mode is not significantly affected, leading to an immunity of the lasing threshold. The most exciting perspective of this work is to extend the results to 2D lattices where we envision, in systems with broken time-reversal symmetry, topological lasers in chiral edge states allowing unidirectional transport of coherent light.

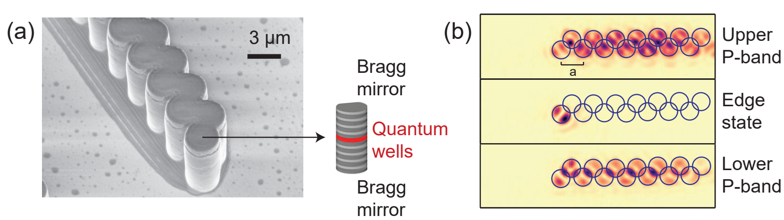

Figure 1. (a) SEM image of a zigzag lattice (a schematic image of a pillar is shown). (b) Real space images of the PL from the edge of the lattice at the energies of the two p-bands (formed from the coupling of the 1st excited states of each pillar), and of the topological edge state.

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Controlled summation of diagrammatic series for the unitary Fermi gas: bold diagrammatic Monte Carlo, large-order asymptotics and conformal-Borel transformation

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We consider the unitary Fermi gas (spin 1/2 fermions with contact interactions in 3D, which describes cold atomic gases at a Feshbach resonance) in the normal phase. Thanks to a diagrammatic Monte Carlo algorithm, we accurately sample all skeleton diagrams (built on dressed single-particle and pair propagators) up to order ≈ 8 [1]. The diagrammatic series is divergent and there is no small parameter so that a resummation method is needed. Previously we used Abelian resummation methods, which are applicable under the assumption that the diagrammatic series has a non-zero radius of convergence; this led to good agreement with experimental data for the equation of state [2] and Tan's contact coefficient [3]. Here we compute the large-order asymptotics of the diagrammatic series, based on a functional integral representation of the skeleton series [4] and the saddle-point method. We find that the radius of convergence is actually zero, and our new numerical results and analytical arguments show that the series is resummable by an generalised conformal-Borel transformation that incorporates the large-order asymptotics. This demonstrates that one can obtain controlled results for a strongly correlated fermionic field theory based on diagrammatic series with zero convergence radius.

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Critical slowing down in driven-dissipative Bose-Hubbard lattices

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In this work [1] we theoretically explore the dynamical properties of a first-order dissipative phase transition in the driven-dissipative Bose-Hubbard model, that can be experimentally investigated in photonic semiconductor or superconducting platforms [2]. Through stochastic trajectory calculations based on the truncated Wigner approximation [3], we investigate the dynamical behaviour as a function of system size for 1D and 2D square lattices in the regime where mean-field theory predicts nonlinear bistability [4,5]. We compute the Asymptotic Decay Rate (Liouvillian Gap), that is the inverse of the relaxation time towards the steady state. We show that a critical slowing down emerges for increasing number of sites in 2D square lattices, while it is absent in 1D arrays, and we characterise the peculiar properties of the collective phases in the critical region.

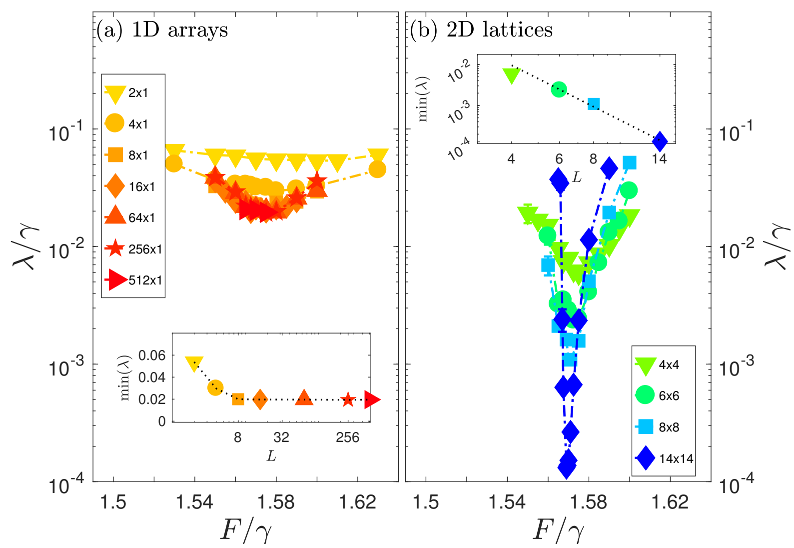

Figure 1. Rescaled Asymptotic Decay Rate λ versus the driving amplitude for several $L \times 1$ arrays (a) and $L \times L$ lattices (b). The insets show the minimum of λ as a function of the size L, fitted with a power law $\min(\lambda) \propto L^{-\alpha}$ in the 2D case. Notice the log scale.

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