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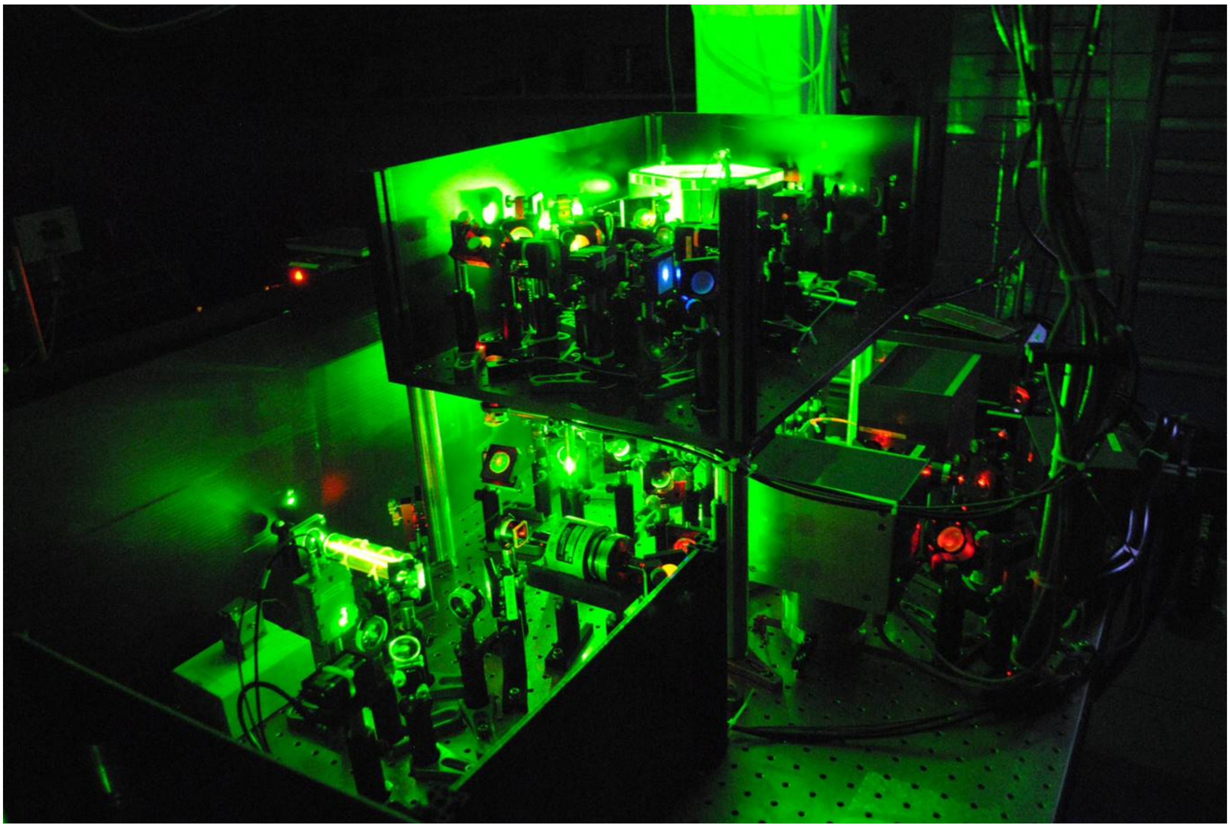

[1] stands for **O**pen **S**ystem **C**ontrol of **A**tomic and Photonic Matte**R;** funded by the Deutsche Forschungsgemeinschaft since July 01, 2016

Quantum spin dynamics of individual neutral impurities coupled to a Bose-Einstein condensate

Felix Schmidt, Daniel Mayer, Quentin Bouton, Daniel Adam, Tobias Lausch, Nicolas Spethmann, Artur Widera

Phys. Rev. Lett. 121, 130403 (2018)

Individual impurities interacting with a quantum system form a paradigmatic model system of quantum physics with numerous applications in probing, quantum state engineering or quantum simulation. Experimentally, ensembles of impurities have been studied, for example, in imbalanced quantum gas mixtures or for the study of polarons, i.e. the coherent dressing of impurities with fluctuations in the host medium. However, most experiments so far focussed on very dilute mixtures rather than individual particles. The limit of individual impurity atoms is experimentally challenging but is sensitive to individual trajectories and rare events. Experiments with individual impurities immersed into BEC has – for experimental convenience – often addressed somewhat exotic impurities such as trapped ions or as quasi-free charged particles in Rydberg atoms. The experiment of the Widera studies for the first time individual, thermalized impurities with a spin-degree of freedom in a Bose-Einstein condensate, thereby realizing the coupling of a very small quantum system to well-controlled environment, see Figure 1.

In this challenging experiment, Schmidt et al. prepare individual neutral Cs impurities inside a Bose-Einstein condensate (BEC) of Rubidium atoms. They start from a BEC of about 10^4 atoms at 300 nK with a typical condensate fraction of about 0.3 in a crossed-beam optical dipole trap. Single or up to ten Cs atoms are cooled and trapped in a high-gradient magneto-optical trap and transferred into a the partially shared trap. The interaction between the impurities and the BEC is initiated by transporting Cs atoms into the BEC with a one-dimensional, species-selective conveyor belt lattice.

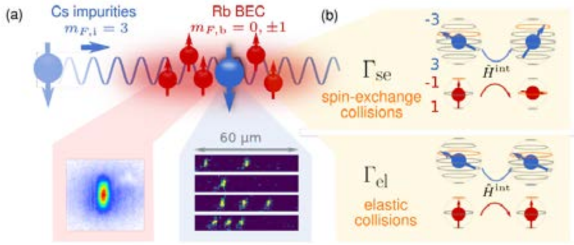

Fig. 1 *(a) Sketch of Cs impurities (blue dots and fluorescence images), immersed in a Rb BEC (red dots and time-of-flight image) by a species-selective optical lattice (blue). (b) Sketch of possible interaction paths: elastic and spin-exchange collisions.*

Upon contact between the Cs atoms and the Rubidium BEC, Schmidt et al. indeed manage to observe the spin dynamics of individual atoms coupled to an ultracold bath. In particular, they study spin-exchange collisions, i.e., collisions in which the spin state of the impurity, $m_{F,i}$, and the spin state of the environment atom, $m_{F,b}$, exchange quantum numbers whereas the total spin remains conserved. This is opposed to elastic collisions in which the internal states remain unchanged. While the present work shows a dissipative spin-exchange process, it can be tuned into resonance by, e.g., microwave dressing. This will realize the basic building block for the bosonic analogue of the Kondo effect, which could be interesting route for future investigations within OSCAR. Additionally, it will be interesting in the future to study the thermalization dynamics of the impurity in both motional and spin degrees of freedom, as the local relaxation of the impurity is faster than the global relaxation of the bath due to a strong difference in intra- versus inter-species scattering lengths.

Time-resolved collapse and revival of the Kondo state near a quantum phase transition

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Nature Physics 14, 1103 (2018)

When looking at the matter around us, the importance of the quantum many-body problem is evident: all matter is composed of interacting particles. In order to understand and calculate the properties of atoms, molecules as well as ensembles thereof in gases, liquids, and solids, we have to understand the role which interactions play for the many-body state. This is particularly interesting since interacting many-body systems exhibit intricate phenomena such as phase transitions, or – as discussed in this paper, the Kondo effect. However, treating interacting quantum systems of more than a few particles in the same way is a notoriously difficult problem.

In many systems we can find a simplified description by so-called ``quasiparticles''. Let's start by a simple classical analogue: the motion of two masses interacting with each other. This could be two balls tied together with a spring or earth and moon with their gravitational attraction. In the lab frame, the dynamics of the problem is rather complex, however, there is a trick to tremendously simplify the complexity of the solution. One introduces a new coordinate system of relative motion and center-of-mass motion. These coordinates are decoupled, which means that they don't influence each other and we can treat them and their dynamics independently of each other. In the concrete example, the center-of-mass moves on a trajectory of an effective particle with mass m_1+m_2 and the relative motion is that of a different effective particle with a reduced mass $m_r=m_1m_2/(m_1+m_2)$ and spring constant k. This is a fairly simple example of how a coordinate transformation greatly simplifies the description of an interacting problem: instead of considering two interacting particles, we transform into a frame of non-interacting fictitious particles -- these fictitious particles are called quasiparticles. At first, one may be tempted to find this merely a mathematical trick but, actually, the solution is physically meaningful and exact. It was in fact pointed out by Landau that a similar concept leads to a particularly simple description of interacting quantum many-body systems, such as metals, superconductors and weakly-interacting Bose-Einstein condensates. If a system is amenable to description in terms of non-interacting quasiparticles we can gain an excellent intuitive understanding of the ground state and the excitation spectrum.

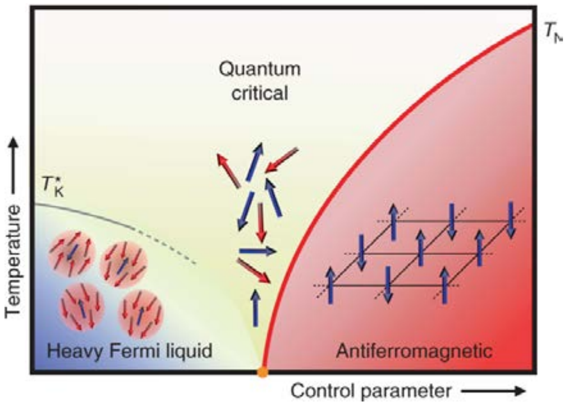

Figure 2: Behaviour of the heavy-fermion material $CeCu_{6-x}Au_x$ near the quantum critical point where it transitions into an antiferromagnet. The relative stochiometric composition between Cu and Au is the tuning parameter.

However, when a system's ground state undergoes a qualitative change, for example at a quantum critical point, the quasiparticles may disintegrate and give way to an exotic quantum-fluid state of matter, see Figure 2. As a consequence, non-Fermi-liquid behaviour, frustrated magnetism or unconventional superconductivity may emerge around the associated QCP. Experimentally, the quasiparticles in the heavy-fermion material (with various stochiometric compositions) are disrupted by a

THz pulse. When quasiparticles recovered after the excitation, the material responds by sending out a delayed THz reflex with a time delay and with a remarkably long coherence time. Even though the quasiparticle weight reduced towards the quantum critical point, as expected, the quasiparticle formation temperature remains constant, which is inconsistent with previous understanding of quantum criticality. J. Kroha proposed this experiment and contributed theory calculations for the analysis of the experimental findings.

The dynamic structure factor in impurity-doped spin chains

Annabelle Bohrdt, Kevin Jägering, Sebastian Eggert, Imke Schneider

Phys. Rev. B 98, 020402(R) (2018).

Spin chains have been the center of attention as prototypical quantum many body systems ever since the early days of quantum mechanics. Their low-lying excitations are slow rotations of the spin orientations, see Figure 3a. These so-called spin waves exhibit a linear excitation spectrum for low momenta that means they propagate at a constant velocity v, see Figure 3b. More interesting, however, is the situation at the wave vector π/d, where d denotes the lattice spacing. The spectrum becomes continuous over a certain range of energies and it is an important question how the spectral weight of excitations with different energies is distributed. This can be quantified by the dynamic structure factor

$$S(\omega,k)=\frac{1}{L}\sum_{j,j'}e^{-ik(j-j')}\int_{-\infty}^{\infty}dt\,e^{i\omega t}\langle S^z_j(t)S^z_{j'}(0)\rangle$$

which measures the correlation function of the magnetization at different wavevectors and different times.

A novel direction of interest concerns the effects of impurities in spin-1/2 Heisenberg chains. This system is a paradigmatic toy model of impurity physics.

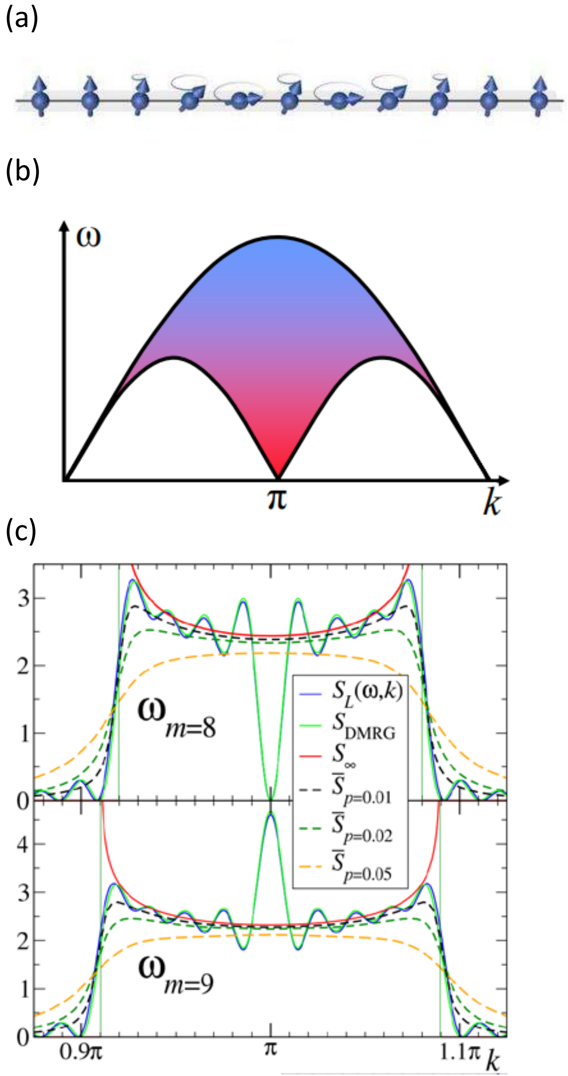

Figure 3. (a) Spin wave excitation in spin chain (source: MPQ). (b) Schematics of the excitation spectrum of a one-dimensional spin chain. (c) Dynamic structure factor near k=▯, for two different energies ▯m. The results show the comparison between different numerical techniques.

In one dimension, the underlying physics is well understandable: qualitatively speaking, the impurities effectively cut the chains into finite segments with a discrete spectrum and characteristic correlations. Bohrdt and coauthors analyse the behavior by calculating the dynamic structure factor using different theoretical approaches such as bosonization and DMRG. The authors find that doping of the spin chain leads to a significant shift of spectral weight from lower momenta to regions with $v|k-\pi/d| > \omega$. This novel effect could be observed in neutron scattering experiments or using ultracold atomic gases in optical lattices.