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Press Release

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Quantum magnets moving along

LMU/MPQ-team of scientists observes coherent propagation of a single spin impurity in a chain of ultracold atoms.

Many discoveries in physics came as a big surprise – for example the phenomenon, that some materials loose almost all their electrical resistance at low temperatures, or that others become superconductors at unexpectedly high temperatures. In the past it was mainly due to theoreticians to develop models explaining these unusual properties. Unfortunately it is not possible to have a direct look into a solid state crystal and follow up the motion of charge carriers as this process happens at extremely short time and length scales. A team around Professor Immanuel Bloch (Chair for Experimental Physics at the Ludwig-Maximilians-Universität Munich and Director at MPQ) has now observed the coherent propagation of single spin excitations in an ultracold quantum gas of strongly correlated atoms (Nature Physics, Advance Online Publication, 24 February 2013).This is one of the most fundamental processes in the magnetism of quantum systems. In close collaboration with theoretical physicists from the Ludwig-Maximilians-Universität Munich and the University of Geneva the scientists were able to demonstrate that the propagation of the spin wave in less strongly correlated systems is being slowed down by the emergence of quasi-particles, so-called polarons.

Properties of condensed matter such as magnetism, electrical conductivity, or superconductivity are the result of the behaviour of electrons in the periodic crystal of the solid. In this respect, the intrinsic angular momentum, i.e. the spin of the electrons, is playing a key role. For example, the high-temperature conductivity exhibited by a class of cuprates is thought to go back to the spin coupling of strongly correlated electrons. Ultracold atoms in an optical lattice are ideally suited to investigate such quantum magnetic phenomena under controlled experimental conditions.

The experiment starts with cooling rubidium atoms down to temperatures near absolute zero. The ensemble is then kept in a light field which divides it into several parallel one-dimensional tubes along which the atoms are allowed to move. Now the tubes are superimposed with yet another light field, a standing laser light wave. By the periodic sequence of dark and bright areas an optical lattice builds up in which each site is occupied with exactly one atom fixed to its position. This highly ordered state is called a Mott insulator (named after the British physicist Sir Neville Mott). After all, an array of several chains of atoms each containing around 15 atoms is formed.

The atoms in the optical lattice take the role of the electrons in a solid state crystal. They are in a similar way characterized by an intrinsic angular momentum (a spin). However, in this case the scientists have control over the spins which can – as if they were little magnetic needles – align in two opposite directions. In the beginning, all spins are pointing into the same direction. Then, one single atom in the centre of each chain is picked out by a laser beam, and its spin is flipped by irradiating microwave pulses. Afterwards the motion of this

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deterministically generated spin impurity through the chain is followed up (see figure 1).

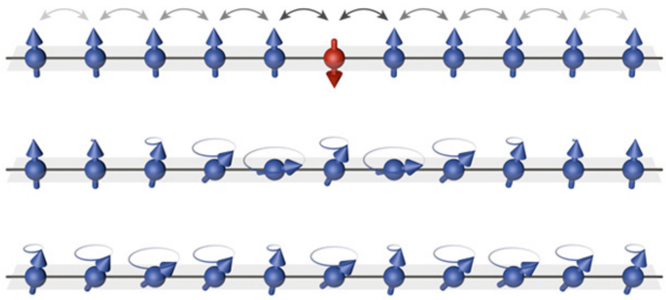

Figure 1: Illustration of the propagation of the spin impurity (red) through a chain of atoms with initially opposite spin. Graphic: MPQ, Quantum Many Body Systems Division

An imaging technique developed in the group makes it possible to visualize each atom on its particular lattice site with very high resolution. Using this method the position of the spin impurity can be precisely determined for various evolution times. This measurement is performed on all atomic chains at the same time. The emerging distributions exhibit a structure that is characteristic of an interference pattern, as it is expected from the interference of coherent waves. “Our model describes the process of spin propagation by a mechanism called ‘correlated super exchange’,” Dr. Christian Groß explains, scientist at the experiment. “The same instance the spin impurity moves one site to the right the neighbouring atom takes its place. As this exchange takes place in the opposite direction at the same time and with the same probability the observed interference pattern results. If the system was a classic one only a broadening of the distribution would have been observed over time. Thereby we have proved that the spin wave propagates coherently.”

In the insulating Mott phase the barriers between the lattice sites are very high, and the atoms are tightly bound to their position, except for the case of the correlated super exchange mentioned above. When the height of the barrier, i.e. the intensity of the laser beams, is lowered below a certain threshold, the atoms are allowed by the rules of quantum mechanics to ‘tunnel’ through the barrier and reach a neighbouring site. In this ‘superfluid phase’ the mobility of the atoms is enhanced, however, the motion of the impurity gets slowed down, as was demonstrated in the measurement. “The tunnelling happening everywhere in the lattice increases the complexity of the interaction of the spin impurity with the background atoms,” Dr. Takeshi Fukuhara points out, who works on the experiment as a postdoctoral researcher. “In the end, the interaction is repulsive, creating a hole in the distribution of the background atoms.” On its way through the chain the spin impurity has to drag this hole all along, that way getting kind of heavy. “This is quite similar to passing a crowd on a subway station: it will take a long time since one has to create the necessary space on each step,” Fukuhara says. “The motion of the impurity observed in our experiment is in good agreement with the forming of quasi particles in the lattice, so-called polarons, as they are known from solid state physics.”

The results obtained in this series of measurements are of high interest: on the one hand, the experiments demonstrate the outstanding control of ultracold quantum systems that can be achieved at present. This is a precondition for the simulation of collective solid state excitations, which give, for example, rise to quantum magnetic phenomena. On the other hand the measurements give a direct insight into the propagation of charge carriers and impurities in solid state crystals, which in the end determine the macroscopic properties of materials.

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