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Breakdown of correlated tunneling

MPQ-LMU scientists together with scientists from the Weizmann Institute in Israel show, how quantum-mechanical tunneling through a barrier can be altered drastically due to the interplay of many particles in low dimensions

Quantum systems do often behave differently from what we would expect intuitively and from our daily experience. One example is provided by the so-called Landau-Zener problem. It describes e.g. the tunneling of a quantum particle between two potential wells with an initial difference in potential energy that is gradually reversed over time. The Russian physicist Lew Landau and the American physicist Clarence Zener have tackled this problem in a more general context in 1932. They found that the quantum particle would be transported from one well to the other, provided that the reversal in potential energy is carried out slow enough. This is true no matter whether the particle started out in the well which was higher or lower in potential energy. In this respect, the result differs much from the expectation for a classical fluid, which will always find its way into the well lower eventually in energy. MPQ-LMU scientists around Prof. Immanuel Bloch in collaboration with theoreticians from the Weizmann Institute of Science in Rehovot, Israel have experimentally investigated a Landau-Zener scenario in a system of one-dimensional quantum gases in two coupled potential tubes. They found that the collective tunneling of the many particles is drastically altered from the single-particle case, ultimately leading to a breakdown of the transfer to the opposite side (Nature Physics, AOP, 17.10.2010, DOI: 10.1038/NPHYS1801).

In their experiments, the scientists cool down a small cloud of “bosonic” rubidium atoms to only a few nanokelvin above absolute zero – that is about minus 273 degree Celsius. At such low temperatures, all atoms gather in a single quantum state, forming a new state of matter known as the Bose-Einstein condensate. This ultracold quantum gas is subsequently loaded into a so-called two-dimensional “optical lattice”. This optical lattice is created by the interference of two orthogonal pairs of counter-propagating laser beams which results in a two dimensional pattern of bright “lines of light”. The interaction between light and atoms forces the latter to arrange in a matching regular pattern of thousands of elongated quantum gases, each consisting of up to 110 atoms.

Now, the scientists add another pair of counter-propagating laser beams forming an optical lattice with just half the period along one of the initial directions. This leads to a splitting of each of the potential tubes trapping the orthogonally elongated quantum gases into two. The full control of the relative phase between this additional optical lattice and the initial one allows the scientists to only populate one of the potential tubes of each pair by lifting the other one higher in potential energy during the splitting. Furthermore, they are able to change the difference in potential energy between the tubes of each pair by controlling the relative phase in real-time. Therefore, they can rapidly set an arbitrary initial difference in potential energy and then gradually reverse the potential energy difference as in the original Landau-Zener problem. The physicists are especially interested in the

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question, how the one-dimensional geometry and the many-body nature of the quantum gas would alter the findings from those for a single quantum particle.

Already in the conceptually simple case where all atoms start in the potential well initially lower in energy showed some significant deviations from the single particle physics. For slow enough changes of the potential energies – or "sweeps" – all particles ended up in the opposite tube as it would also be the case for a single quantum particle. The speed of the sweep, however, could be faster in the case of the one-dimensional quantum gases. Here, the repulsive interaction forces the atoms to line up for the transfer and to move to the opposite potential tube one-by-one, rather than all at once. Since each of these single-particle transfers can be carried out faster in the many-body system, the rate at which the potential energy is changed can be higher. The total time needed for a successful sweep however, is approximately the same as in the case of a single particle, since all particles have to move over and the advantage of the faster transfer of a single particle is lost.

Even more striking is the difference if all particles start out in the potential tube which is initially higher in potential energy. Here, the scientists found that not all particles would reach the opposite tube, no matter how slow the sweep is carried out. Actually, the transfer efficiency was decreasing for slower and slower Landau-Zener sweeps. This result strongly resembles the expectation for a classical fluid which would always flow into the lower tube – here the one that the atoms started from. In the classical case, the potential energy is converted into kinetic energy. Eventually, this kinetic energy will be given to the environment as the fluid comes to rest.

In a closed quantum system, such an energy exchange with the environment is not possible: the excess energy cannot leave the system and the relaxation of the quantum gas into the lower-energy tube is blocked. In a one-dimensional system, however, there are low-energy excitations which are often referred to as "phonons" due to their similarity to the lattice vibrations in solids. These phonon excitations provide an "inner environment" in which the excess energy can be stored in arbitrary portions. As a result, the quantum gas will relax towards the potential tube lower in energy while heating up. This relaxation mechanism is strongest for small differences in the potential energy of the two tubes. The slower the Landau-Zener sweep is carried out, the longer the system will reside in this region and the more effective will be the relaxation.

The work described here provides for the first time an experimental study of a Landau-Zener problem generalized to a one-dimensional many-body setup. The dynamics of such systems still holds a number of open questions. Especially the understanding of whether and how low-dimensional quantum gases far from equilibrium relax and eventually thermalize in closed quantum systems remains an unsolved problem. Furthermore, such generalized Landau-Zener experiments hold the prospect of detecting many-body quantum phase transitions at which the excitation spectra of the quantum gases are drastically altered. The measurements described here allow for a deep analysis of non-equilibrium phenomena in coupled one-dimensional systems and opens the way for the detailed study of their intrinsic sound-wave like excitations. *Stefan Trotzky*

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