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1. Testing of Bell's inequalities in a system of Josephson qubits

Researchers at the University of California, Santa Barbara experimentally confirmed that Bell's inequalities are violated in a macroscopic (solid-state) system composed of a pair of Josephson phase qubits (quantum bits) implemented using superconducting Josephson contacts. Violation of Bell's inequalities had already been tested in a number of quantum processes, which excluded the possibility of the 'hidden-variables' interpretation. In the new experiment, two Josephson qubits acting as spin-1/2 particles were transferred to the entangled quantum state (*Usp. Fiz. Nauk* **176** 1092 (2006) [*Phys. Usp.* **49** 1111 (2006)]) using an electromagnetic resonator, after which quantum correlations between the states of the qubits were measured in a single-shot manner. For this particular experiment, Bell's inequality can be written out in the form $S < 2$, where S depends on the states of the qubits. Measurements showed that $S = 2.0732 \pm 0.0003$, i.e., Bell's inequality is violated at the level of 244 standard deviations and therefore the state of the qubits in this experiment cannot be classically described, thus providing further strong evidence that a macroscopic electrical system is really a quantum system.

Source: *Nature* **461** 504 (2009)
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2. Persistent current in a ring

J Harris (Yale University, USA) and his colleagues indirectly measured for the first time the persistent electric current in metallic (nonsuperconducting) rings. The persistent ring current predicted theoretically by M Buttiker, Y Imry, and R B Landauer in 1983 is an element of the equilibrium quantum state of electrons in the ring. It was predicted that the persistent current in micron-sized rings at temperatures $T < 1$ K may reach approximately 1 nA. The external magnetic field breaks the time-reversal symmetry, which forces one of the possible current directions to be selected, plus this current is a periodic function $I(\Phi)$ of the magnetic flux Φ across the ring (due to the Aharonov–Bohm effect). Attempts had been made earlier to use superconducting quantum interferometers (SQUIDs) for measuring the magnetic field generated by the persistent current, but the sensitivity of this method proved insufficient owing to, among other factors, the feedback to the ring current from oscillations of the superconducting current in SQUIDs. J Harris and his team measured the effect induced by the magnetic field of the current in a micromechanical silicon cantilever probe. Aluminium rings were attached to the end of the probe and the system measured the shift of the resonance frequency of mechanical vibrations of the cantilever due to the interaction between the magnetic moments of ring currents and the external magnetic field. The vibrations of the cantilever were caused by a piezo-mechanical vibrator and were observed using a laser interferometer. This technique has the sensitivity (~ 20 pA Hz$^{-1/2}$), approximately an order of magnitude better than the approach based on SQUIDs. The results of measurements both with a single aluminium ring and with arrays of rings are in good agreement with theoretical predictions based on a model of noninteracting electrons. It was found that current oscillations $I(\Phi)$ in different rings of the arrays had uncorrelated phases in both the first and the second harmonics. Measuring persistent currents in microscopic rings can help in studying quantum phase transitions and quantum coherence at low temperatures.

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3. Splitting of Cooper pairs

Two independent groups of researchers created efficient sources of electrons entangled in spin states (EPR pairs); they act by splitting Cooper pairs of electrons tunneling through a superconductor. The difficulty that faced earlier attempts to generate EPR pairs stemmed from the fact that electrons in metals reside below the Fermi surface, so that releasing them immediately destroys entanglement. The ground state in superconductors is composed of the condensate of Cooper pairs in a spin-singlet state, so that these pairs can be separated from the superconductor by way of tunneling. L Hofstetter (University of Basel) and his colleagues in Switzerland, Hungary, and Denmark solved the remaining problem of splitting Cooper pairs into individual electrons by using the Coulomb repulsion of those electrons that went through tunneling into two quantum dots. Quantum dots were created in the region where the nanowire made of indium arsenide intersected with the central superconductor and two metal contacts in the normal (nonsuperconducting) state. Control electrodes make it possible to vary the depth of the potential well of quantum dots in such a way that only one electron passes through each quantum dot at any instant of time. The electrons of a Cooper pair are inherently quantum-correlated (entangled) along the direction of spin, and this entanglement of electrons survived after the pair was split. The experiment by L G Herrmann and colleagues in France, Spain, and Germany generally resembles the one described above, but it used carbon-nanotube-based Cooper pair splitter instead of nanowires. New sources of EPR pairs of electrons may find important applications in fundamental research, such as the study of the Einstein–Podolsky–Rosen paradox.

Sources: *Nature* **461** 960 (2009)
http://dx.doi.org/10.1038/nature08432,
http://arXiv.org/abs/0909.3243v1

4. Bose–Einstein condensate of calcium atoms

S Kraft (Federal Physical-Technical Institute, Braunschweig, Germany) and his coworkers were able to achieve for the first time the Bose–Einstein condensation of atoms of the alkaline-earth element: ^{40}Ca. At the initial stage of the experiment, atoms were laser-cooled in a magneto-optical trap using the transitions $^1S_0 - {^1P_1}$, $^1S_0 - {^3P_1}$, and some others. The main process that restricted the effectiveness of cooling was loss via three-particle atomic interactions. At the last stage, the atomic cloud was loaded into an optical dipole trap and cooled evaporatively. The transition of about 2×10^4 atoms to the Bose–Einstein condensate state at 170 nK was identified using the characteristic Gaussian density profile. The formation of the condensate was also confirmed by the large chemical potential of the gas, which was calculated on the basis of the measured rates of anisotropic expansion of the cloud. Quantum intercombination transitions $^1S_0 - {^3P_1}$ with very narrow spectral lines (only 370 Hz in width) are possible in ^{40}Ca atoms. Consequently, Bose–Einstein condensates of ^{40}Ca atoms are very promising for highest-precision measurements, for example, of gravitational fields. Furthermore, ^{40}Ca atoms in the nondegenerate ground state have no magnetic moment, which additionally increases the accuracy of measurements in view of the absence of interactions with external magnetic fields.

Source: *Phys. Rev. Lett.* **103** 130401 (2009)
http://dx.doi.org/10.1103/PhysRevLett.103.130401

5. Magnetism of carbon

Researchers in the Czech Republic and the Netherlands, J Červenka, M I Katsnelson, and C F J Flipse, have clarified the mechanism of formation of the ferromagnetic properties of specimens of polycrystalline graphite at room temperature. A number of experiments established that various forms of carbon manifest magnetism (see, e.g., *Usp. Fiz. Nauk* **174** 106 (2004) [*Phys. Usp.* **47** 102 (2004)]), but its nature remained unclear. Hypotheses were advanced that carbon owes the observed magnetism either to metal impurities or to defects of crystal structure. The new experiment used a magnetic force microscope, a SQUID magnetometer, and an atomic force microscope for measurements; this made it possible to study simultaneously and at high spatial resolution both magnetic and electron properties of samples. The obtained microscopic images provide direct evidence supporting the second hypothesis: the graphite magnetism arises owing to defects in the structure of atomic layers and that impurities do not play a significant role. A two-dimensional network of defects (only 2 nm thick each) is formed along atomic planes of carbon in highly oriented pyrolitic graphite; these networks confine homogeneous regions, i.e., grains of the polycrystal. Ferromagnetism originates with unpaired electrons localized on defects at the grain boundaries. Magnetic carbon may find applications in spintronic devices and in medical fields for designing biological sensors.

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