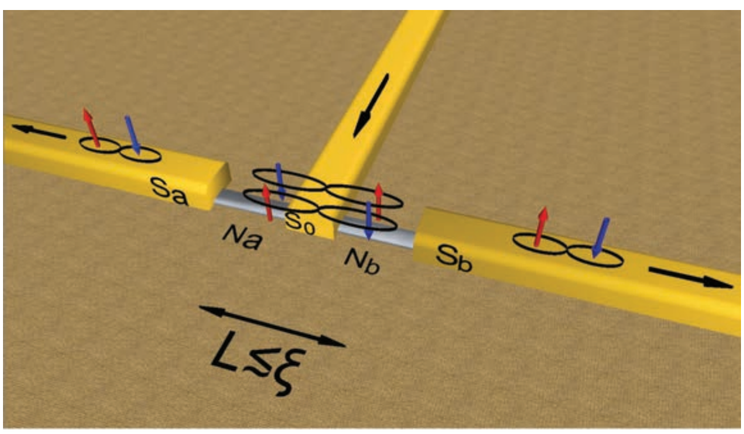
When electrons perform in quartets

Superconductivity is due to the condensation of a fraction of the electrons into Cooper pairs. A Josephson junction is a short bridge between two superconductors which allows a coherent transfer of Cooper pairs. Connecting three superconductors in a narrow region realizes a "bijunction". In such bijunctions, part of the superconducting currents must flow as correlated Cooper pairs, which are referred to as "electron quartets". New quantum correlations could be revealed in a bijunction, which is characterized by two phase variables coupled together, instead of one.

A superconductor is characterized by a mutual attraction between electrons at the Fermi surface, due to lattice phonons. This results in the formation of the famous Cooper pairs, which condense into a phase-coherent collective state at low temperature. In the classical superconductors used in nanofabrication (such as a Aluminium or Niobium), this collective state is well described by the Bardeen-Cooper-Schrieffer (BCS) theory of superconductivity.



Schematics of a bijunction consisting of three superconducting leads (yellow), separated by two, narrow non-superconducting regions N_a, N_b (grey) at the size scale of the Cooper pair ξ (at most a few hundred nm). The "quartet" component of the current flows from the central lead S_0 via the splitting of two singlet Cooper pairs, each into a spin up and a spin down electron. The spin of the electrons is indicated by blue and red arrows. Subsequently the quartet recombines into one Cooper pair exiting in lead S_a and another in S_b. A phase-coherent quartet current can flow even in presence of voltage biases, if $V_a = -V_b$.

Josephson discovered 50 years ago that two BCS superconductors separated by a thin oxide layer can exchange Cooper pairs. This maintains phase coherence and leads to a dissipationless dc supercurrent tunneling through the junction. This current exists only at zero voltage across the junction. A Josephson junction is characterized by the two Josephson equations, one for the relation between the current and the phase-difference across the junction at zero voltage and the other for the linear time dependence of the phase difference at constant voltage.

We have proposed that in a "bijunction" (see the Figure), where two side current leads S_a, S_b are fed by a central lead S_0 at a scale $L \leq \xi$ the Cooper pair size, a new microsocopic mechanism leads to the formation of electronic "quartets". A first Cooper pair entering from lead S_0 splits virtually into two electrons, one exiting in lead S_a and one in S_b. A second Cooper pair immediately splits in the same way, and the so-formed "quartet" of electrons eventually redistributes into one Cooper pair in S_a and one Cooper pair in S_b (see Figure), with a remarkable sign change of the quartet current compared to an ordinary junction. The quartets are transient states and can be understood as a four-particle resonance in the bijunction.

Strikingly, our calculations show that phase-coherent dc resonances can occur even in the presence of non-zero applied voltages V_a, V_b, with $V_0 = 0$. This is due to the quartet process in which two Cooper pairs from S_0 are transmitted simultaneously as one pair in S_a and one pair in S_b. The energy of the final state is $2e(V_a + V_b)$ and the energy of the initial state is 0. Then the energy is conserved if $Va = -Vb$. By the Josephson equations, this implies that a dc current of quartets appears just at the resonance condition $V_a = -V_b$. This current is phase-coherent, just like the ordinary zero-voltage DC Josephson current. Higher order resonances are also expected when $nV_a + mV_b = 0$, where n, m are integers. They are currently being tested experimentally.

In the future, nanoscale interference devices for the supercurrent inspired from the Superconducting Quantum Interference Devices (SQUIDs) will be an appropriate tool for probing these quartets because they have very specific signatures in the Josephson relationship linking the currents to the phase differences.

Josephson bijunctions are new objects, and the correlations between four electrons in a quartet open perspectives in the study of four-electron entanglement. They should also lead to nonlinear parametric amplification at microwave frequencies, if microwave lines are coupled to the bijunction.

CONTACTS

Régis MELIN
regis.melin@grenoble.cnrs.fr

Denis FEINBERG
denis.feinberg@grenoble.cnrs.fr

FURTHER READING

PRODUCTION OF NONLOCAL QUARTETS AND PHASE-SENSITIVE ENTANGLEMENT IN A SUPERCONDUCTING BEAM SPLITTER
A. Freyn, B. Douçot, D. Feinberg and R. Mélin
Phys. Rev. Lett. 106, 257005 (2011).