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 Sarrus Cooper pairs, which condense into a phase-coherent collective state at low temperature. In the classical superconductors used in nanofabrication (such as a Alumina or Niobium), this collective state is well described by the Bardeen-Cooper-Schrieffer (BCS) theory of superconductivity.

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 $\lambda$ $\leq 1$, the Cooper pair size, a new microscopic mechanism leads to the formation of electronic “quartets”. A first Cooper pair entering from lead $S_0$ splits virtually into two electrons, one entering $S_a$ and one in $S_b$. A second Cooper pair immediately splits in the same way, and the second “quartet” of electrons eventually recombines 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 $V_a = -V_b$. 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 bi-junctions are new objects, and the correlations between four electrons in a quartet open perspectives in the field of four-electron entanglement. They should also lead to nonlinear parametric amplification at microwave frequencies, if microwave lines are coupled to the bijunction.

The enormous progress in the control of the microwave environment in superconducting quantum circuit experiments over the last ten years now makes it possible to study coherence in large multi-junction circuits experimentally. In particular, this project aims, by novel experiments on Josephson junction chains, to understand the crucial question of external charge dynamics and dissipation that originates from the many-body effects present in these chains. Sizable up to the number of Josephson junctions in a circuit automatically implies the presence of low-frequency plasma modes, which lead to internal dissipation in the system and make these experiments very challenging.

By using Josephson junction chains with a disordered or fractal pattern it should be possible to localize plasmon wave functions that do not couple to the quantum states of the Josephson crystal and simultaneously keep the coherence intact. In addition, a first systematic study will be done of the external charge dynamics occurring in Josephson junction chains, in particular noise correlations.

A final aim of the project is to use the coherent superposition of quantum phase slips in a Josephson crystal to realize a frequency-to-current converter. If successful, this project will lead to a definition of the electrical current with an unprecedented precision.

Frequency-to-current conversion with coherent Josephson crystals

This project will explore quantum mechanical coherence in Josephson crystals and apply it for frequency-to-current conversion. A Josephson “crystal” can be realized by repeating a single Josephson junction or SQUID in space to form a one-dimensional ladder structure. This crystal can show a macroscopic coherent behaviour due to the coherent superposition of the quantum “phase-slip” (2$\pi$ phase differences) occurring on each single junction. The coherent superposition gives rise to a novel, global non-linearity which turns the Josephson crystal into an effective “single junction” described by the dynamics of the global charge.

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Hybrid quantum nano-optomechanics

It has recently become possible to cool macroscopic mechanical oscillators down to their quantum ground state of motion. Various kinds of mechanical oscillators, ranging in mass from picograms to micrograms have now been prepared at ultralow mean phonon occupancy by combining traditional cryogenic and active cooling techniques. It is now time to envision even more challenging experiments aiming at "engineering" the quantum mechanical state of the oscillator. This can be achieved by coupling the ultracold oscillator to a second system whose quantum state can be independently controlled and transferred onto the mechanical oscillator. The combination of these two components defines a “hybrid” mechanical system.

This project aims at exploring the emerging field of hybrid quantum nano-optomechanics in a setting where both components of the system can be monitored and controlled simultaneously. The goal is to investigate the hybrid coupling between a nanomechanical oscillator and a Nitrogen Vacancy defect in diamond. The electronic spin state of the defect represents a unique quantum system, of exceptional quality, which can be readout and manipulated by optical means. The nanoresonators will be probed by exploiting the ultra-sensitive optical techniques developed in the context of cavity optomechanics. When combined with the intrinsic, extremely high force sensitivity innate to nanomechanical oscillators, this approach promises to give unprecedented sensitivity for exploring the subtle signatures of the hybrid interaction. The goal of the project is to enter the quantum regime of hybrid nano-optomechanics and investigate unexplored phenomena, at the interface between the classical and quantum worlds.