Quantum computation with superconducting quantum point contacts

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We present a new type of superconducting flux qubit, which consists of a highly transmissive atomic-size quantum point contact (QPC) embedded in a low-inductance rf-SQUID (see Fig. 1). In this qubit, the quantum information is stored in the microscopic quantum two-level system, the Andreev bound levels in QPC. The number of Andreev bound levels is limited to one pair of levels per conducting electronic mode, thus the superconducting QPC may be viewed as a kind of quantum dot which contains a finite number of localized quantum states. This is similar to non-superconducting solid state qubits (e.g. localized spins on impurities or quantum dots). Coherent coupling of the Andreev levels to the supercurrent flowing through the QPC makes the Andreev levels accessible for manipulations and for measurements. The qubit is manipulated by applying resonant rf flux pulses or by flux ramping, read-out is achieved by monitoring the circulating current in the SQUID or the induced flux, similar to the conventional superconducting flux qubits.

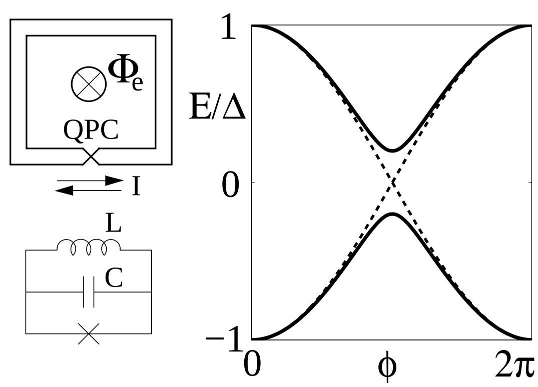

Figure 1: Left: Sketch of the Andreev level qubit - a non- hysteretic rf-SQUID with a quantum point contact (QPC), and the equivalent circuit containing the Josephson junction and LC- oscillator. Right: The energy spectrum of the QPC with finite reflectivity ($R = 0.04$) (solid line), appears as a hybridization of the current states ($R = 0$) (dashed line).

The energy of the Andreev levels is given by equation,

$$E_a(\phi) = \Delta\sqrt{\cos^2(\phi/2) + R\sin^2(\phi/2)}, \tag{1}$$

where R is the contact reflectivity, and ϕ is the phase difference across the QPC. In highly transmissive QPCs and at $\phi \approx \pi$, the Andreev levels lie deep within the superconducting gap and are well decoupled from the continuum quasiparticle states in the electrodes.

To maintain the current variations during evolution of the Andreev levels, and also to provide fidelity of the Andreev levels read-out, the plasma frequency of the loop LC-oscillator is to be much larger than the qubit evolution frequency. We estimate the upper bound for the qubit operation frequency $2E_a/\hbar \sim 10^{10}\text{sec}^{-1}$, assuming the loop plasma frequency $\omega \sim 10^{11}\text{sec}^{-1}$ (loop inductance $L \sim$0.1nH, and junction capacitance $C \sim 0.1$pF), and the QPC critical current $I_c \sim 400$nA (for Nb) for one open conducting mode with reflectivity $R \leq 0.01$.

The key difficulty is to extend a theory of quantum fluctuations in Josephson junctions [1], originally developed for tunnel junctions, to highly transmissive QPC. This is done by incorporating the electron scattering matrix of the contact in the QPC action [2]. Integration over fast fermionic variables, corresponding to extended quasiparticle states above the superconducting energy gap, leads to a spin- oscillator model describing a slow quantum dynamics of the coupled Andreev levels and superconducting phase,

$$\hat{H} = -\Delta\left(\cos\frac{\phi_e}{2}\,\sigma_z + \sqrt{R}\sin\frac{\phi_e}{2}\,\sigma_x\right) + \frac{\mathcal{I}(\phi_e)}{2}\,\phi\sigma_z + \hat{H}_{osc}(\phi). \tag{2}$$

Here ϕ_e is the bias phase, $\mathcal{I} = \Delta D\sin(\phi_e/2)$ is the current eigenvalue, and $\hat{H}_{osc} = -(\hbar\partial_\phi)^2/2M + M\omega^2\phi^2/2$, is the Hamiltonian of the loop LC-oscillator, $M = \hbar^2 C/4e^2$.

The averaging over the oscillator ground state fluctuations yields dressing of the bare reflectivity of the contact, $R \to R^*$, with the factor, $\exp\left(-\mathcal{I}^2/4M\hbar\omega^3\right)$, in the qubit Hamiltonian, $\hat{H}_q = -\Delta\left(\cos(\phi_e/2)\,\sigma_z + \sqrt{R^*}\sin(\phi_e/2)\,\sigma_x\right)$,

Inductive coupling is the most relevant interaction for multiple qubit configurations. It is included in the theory by adding the mutual inductance terms into the oscillator Hamiltonians. This will introduce hybridization of the loop oscillators, then the averaging over phase fluctuations, using the oscillators normal modes, will lead to the qubit Hamiltonians with slightly different dressing factors, and to a Hamiltonian of direct qubit-qubit interaction having the form, $H_{int} = -(e/c\hbar)^2(\mathcal{M}\mathcal{I}_1\mathcal{I}_2)\,\sigma_{z1}\sigma_{z2}$, where $\mathcal{M}$ is the mutual inductance.

The interaction of the Andreev levels with microscopic degrees of freedom in the contact, primarily with the phonons, is important specific mechanism of decoherence and relaxation of Andreev level qubits. We investigate this decoherence mechanism by considering quasiparticle interaction with acoustic phonons, and including the Frülich Hamiltonian in the QPC action. The interaction leads to both the dephasing and relaxation. Averaging over fast phase fluctuations will dress the electron-phonon coupling constant, $\lambda_{ph} \to \lambda^*_{ph}$, similar to the contact reflectivity, leading to the relaxation rate (dephasing rate is the two times smaller),

$$\Gamma = \Gamma^*_{ph}(\Delta)\frac{E_a^{*2}(\phi_e)}{\Delta^2}R^*|\sin(\phi_e/2)|, \tag{3}$$

where $\Gamma_{ph}(E)$ is the electron-phonon relaxation rate in normal metal at energy E. For $R^* < 0.01$ and at the degeneracy point, $\phi_e = \pi$, this relaxation rate is smaller than the qubit operation frequency by at least a factor of 10^4.

[1] V. Ambegaokar, *et al.,*, Phys. Rev. Lett. **48**, 1745 (1982).

[2] A. Zazunov, *et al.,*, Phys. Rev. Lett. **90**, 087003 (2003).