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# Spectroscopy of mesoscopic Josephson junction using inelastic Cooper-pair tunneling

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**Abstract**

We have measured the energy levels of a mesoscopic, nearly classical Josephson junction using the method of inelastic Cooper-pair tunneling. The tunneling in an ultrasmall Josephson junction causes transitions in the junction environment and provides a method of doing spectroscopy with a simple DC measurement. A classical Josephson junction can be thought of as an LC-circuit, which quantum mechanically corresponds to the harmonic oscillator. We find that the simple model agrees with the range of $E_J/E_C$ ratios down to about 35.



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The quantum mechanical behavior of the phase difference across a Josephson junction has been under considerable study during recent years [1]. The conjugate nature of the charge and phase gives the mesoscopic Josephson junction properties that differ from the classical case. The quantization of the Josephson potential have earlier been measured either with an RF-field [2] or rapid current ramping [3] but we are using a different approach, namely a small voltage-biased Josephson junction. In the subgap region, where for a voltage biased classical junction there would be no current, there is an inelastic Cooper-pair current, which depends on the impedance of the junction environment. This scheme has previously been used to measure the resonances of a transmission line [4].

According to the $P(E)$-theory, the tunneling in mesoscopic junctions is correlated via phase fluctuations with transitions in the electromagnetic environment [5]. The probability that a tunneling electron exchanges an energy $E$ with the environment is given by the function

$$P(E) = \frac{1}{2\pi\hbar} \int_{\infty}^{\infty} \mathrm{d}t \exp\left[J(t) + \frac{\mathrm{i}}{\hbar} Et\right]. \tag{1}$$

The phase–phase correlation function $J(t) = \langle[\varphi(t) - \varphi(0)]\varphi(0)\rangle$ depends on the impedance of the environment. For Cooper-pair tunneling, the IV characteristic assumes a simple form

$$I_S(V) = \frac{\pi e E_J^2}{\hbar}[P(2eV) - P(-2eV)], \tag{2}$$

where the last term can be ignored at low temperatures when the environment is only absorbing energy. Hence, the IV characteristic of a small Josephson junction in the subgap region will reflect the energy levels in the environment.

In our measurement we connected two SQUIDS, one to each side of a probe junction. Both the SQUIDs and the probe junction were made of aluminum. The SQUID behaves effectively as a single junction with a tunable critical current. For a classical junction we get from the Josephson relations a nonlinear inductance that can be used in the linear regime for currents $I \ll I_C$. The inductance and the critical current of the junction are related by $L = \hbar/2eI_C$. Together with the junction capacitance we find that the LC-oscillator mode, or plasma frequency of the junction is $\omega_p = 1/\sqrt{LC} = \sqrt{8E_J E_C}/\hbar$. A quantum mechanical treatment of the classical junction, i.e. one for which the phase is localized, results in the usual energy levels of the harmonic oscillator $E_n = (n + 1/2)\hbar\omega_p$.

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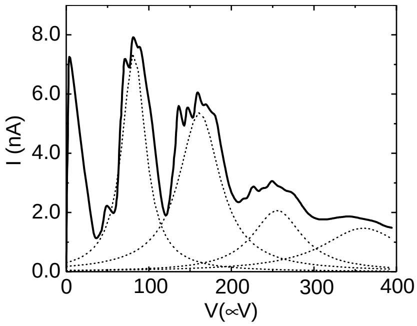


Fig. 1. IV-curve in the subgap region for the maximum value of $E_J/E_C = 50$. The dotted curves show the resonances fitted to the series of peaks. The measurements were carried out at 100 mK.

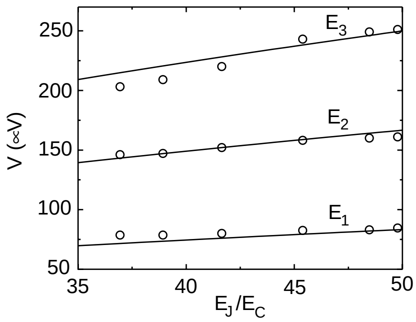


Fig. 2. Position of the resonance peaks as a function of $E_J/E_C$ together with the theoretical fit. Shown are the first three transitions. An asymmetry of $a = 0.7$ was used for the theoretical curves.

Due to the series coupling of the detector and SQUIDs, the parameters cannot be measured independently but have to be deduced from the overall behavior of the circuit. The detector junction had a resistance of $R_{\rm det} = 11$ kΩ and a capacitance of $C_{\rm det} = 1.0$ fF, which means that its $E_C/E_J$ ratio is around 1.5. The two SQUIDs had a resistance of $R_{\rm SQUID} = 1.4$ kΩ each and a capacitance of $C_{\rm SQUID} = 10$ fF, resulting in an $E_J/E_C$ ratio of 50, which means that we are in the classical regime where charging effects are negligible.

An IV-curve for the maximum value of the ratio $E_J/E_C$ is shown in Fig. 1. The equally spaced resonances consist of more than one peak due to a difference in the critical currents of the two SQUIDs and due to resonances from the measurement leads, which act as transmission lines at high frequencies. The transitions are identified from IV-curves by fitting each set of peaks by a single peak, representing an average over the two SQUIDS. Thus, by measuring IV-curves at different magnetic fields we can change the $E_J/E_C$ ratio and the spacing of the energy levels $E_n$. The three first transitions as a function of $E_J/E_C$ are depicted in Fig. 2. The energy levels as a function of the externally applied magnetic flux $\Phi$, are given by the expression

$$E_n = n\sqrt{8E_C E_{J,1}[1 + a^2 + 2a\cos(2\pi\Phi/\Phi_0)]^{1/2}}, \qquad (3)$$

where $a = E_{J,2}/E_{J,1}$ describes the asymmetry associated with one SQUID.

The agreement with the harmonic oscillator model is good over the range of values shown in Fig. 2. This simple model seems to brake down for lower values of the ratio, where charging effects and the corresponding delocalization of the phase is expected to lead to the formation of energy bands [6,7].

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