Fluctuation Dominated Josephson Tunneling with a Scanning Tunneling Microscope

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We demonstrate Josephson tunneling in vacuum tunnel junctions formed between a superconducting scanning tunneling microscope tip and a Pb film, for junction resistances in the range 50-300 kΩ. We show that the superconducting phase dynamics is dominated by thermal fluctuations, and that the Josephson current appears as a peak centered at small finite voltage. In the presence of microwave fields (f = 15.0 GHz) the peak decreases in magnitude and shifts to higher voltages with increasing rf power, in agreement with theory.

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Scanning tunneling microscopy (STM) has been extensively used in the study of high-T_c superconductors (HTSC), providing a spectroscopic tool with unparalleled energy and spatial resolution. Yet, while superconducting tips have been demonstrated in the past [1] all STM studies so far have been performed using normal-metal tips, thus probing only the single-particle excitation spectrum, the gap structure which is a consequence of superconductivity, but not the superconducting (SC) ground state itself. Results from STM measurements of HTSC show excitation gaps in situations where superconductivity is believed to be absent (pseudo-gap), such as in vortex cores [2] and above T_c in underdoped samples [3], as well as inhomogeneities in the gap structure in reportedly high quality BiSrCaCuO crystals [4]. These results, due to the nature of the measurements, do not remove the ambiguity with respect to the existence of a finite SC pair amplitude in the situations studied. In light of this outstanding problem, it seems desirable to have a way to directly probe the SC pair amplitude with high spatial resolutions on the order of ξ, the coherence length. This can be achieved by performing STM experiments with SC tips [5], measuring the contribution from Josephson pair tunneling to the total tunneling current. In this Letter we report on the observation of fluctuation-dominated Josephson tunneling in vacuum tunnel junctions formed between a SC tip and a conventional SC Pb film at T~2 K.

The present authors have recently developed a method for the reproducible fabrication of SC STM tips [6]. Tips made by deposition of Ag(30 Å)/Pb(5000 Å) proximity bilayer onto conventional Pt0.4Ir0.2 STM tips exhibit a well developed BCS gap at low temperatures. From \( \Delta(T) \) measurements, \( \Delta_0 \) and \( T_c \) were estimated to be 1.33 meV and 6.8 K respectively [6]. Here we use these tips to form superconductor/insulator/superconductor (S/I/S) vacuum tunnel junctions against a Pb film (Fig. 1) grown in situ on a graphite substrate.

\[
E_J = \frac{\pi \hbar}{4e^2} \frac{\Delta(T)}{R_N} \tanh \frac{\Delta(T)}{2k_BT}
\]

is vanishingly small compared to \( k_BT \). For example, for a typical junction of 100 MΩ, \( E_J/k_BT \sim 0.5 \text{ mK} \). Here \( T \) is the temperature, \( \Delta \) is the SC gap, \( R_N \) is the junction resistance, and all other symbols have their usual meaning.

As the junction resistance is decreased, \( E_J \) increases. When \( E_J \) becomes larger than \( k_BT \),

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FIG. 2. Normalized $dI/dV$ curves for a high resistance ($R_N = 100$ MΩ) S/I/S junction at various temperatures. Curves offset for clarity, horizontal lines correspond to zero conductance of each curve.

A supercurrent of magnitude $I = I_{c,0} \sin \phi$ can flow across the junction at zero voltage [3]; here $I_{c,0} = 2eE_J/\hbar$ and $\phi$ is the relative phase. When a finite voltage $V$ is applied across the junction, $\phi$ oscillates according to $\dot{\phi} = 2eV/\hbar$. These are the well known Josephson equations and the Josephson effect in low resistance junctions with macroscopically sized electrodes is well understood and well studied [9].

The present situation is different- we note that the tip electrode area is at most 1-2 nm$^2$, thus the very small junction capacitance $C$ leads to large charging energies of the junction, $E_C = e^2/2C$. In addition, the junction resistance cannot be made arbitrarily small and there are two factors limiting the range of this parameter. First, because of the small junction area, the current densities are high and a rough estimate suggest that junction resistances below few tens of kΩ will result in current densities sufficient to destroy the superconductivity in the tip. A second limit on the resistance is the transition from vacuum tunneling to a point contact regime which was observed to occur around $R_N \sim 10$ kΩ [10]. Experimentally we have been able to achieve resistances as low as 40 kΩ.

Figure 3 shows typical data from measurements of the current-voltage characteristics at our base temperature 2.0 K for various junction resistances.

FIG. 3. Low bias current-voltage characteristics for various junction resistances at $T = 2.0$ K. The data (points skipped for clarity) is represented by symbols, and the lines represent two-parameter fits to theory. Inset- $I_{c,0} \times \sqrt{e/k_BT}$ vs. $G_N$ (see text).

Note that the data is drawn for voltages below the sum of the energy gaps on a magnified current scale. The full $I-V$ curves show a well-defined gap feature at $\pm(\Delta_{\text{tip}} + \Delta_{\text{Pb}}) = 2.6$ meV. The location of the gap feature does not change with decreasing resistance, and the high bias part of the curves falls on the same line when the curves are scaled by $R_N$. The low bias part of these curves, however, does not reduce to the same line upon scaling. We observe a current peak centered at finite voltage near zero bias, the height of which grows when $R_N$ is decreased. Since the SC gap is temperature dependent, the fact that the gap-edge feature appears at the same voltage regardless of the junction resistance is an indication that there is no self heating of the junction (see also Ref. [11]). The current peak observed in Fig. 3 cannot, therefore, be attributed to enhanced quasiparticle thermal excitations across the gap, and must be a signature of pair tunneling.

One can model the dynamics of the phase $\phi$ in such a loosely coupled Josephson junction by a point particle moving in a periodic washboard-like potential landscape $U(\phi) = E_J(1 - \cos \phi)$ [12], and subject to a stochastic force due to thermal noise [13]. For very high junction resistances (very shallow potential) the motion of the phase is completely randomized by thermal fluctuations as $k_BT \gg E_J$. But as the resistance decreases the phase
spends on average more and more time near the minima of $U(\phi)$. We note that even at the lowest resistance achieved in this work $E_J/k_B \sim 1$ K, thus $E_J$ is comparable to, but still smaller than the thermal energy in the system. In this case the phase motion can be viewed as diffusive, and the $I-V$ characteristics of such a junction have been calculated using this approach by Ivanchenko and Zil'berman [13] and Harada et al. [13] (and also by Ingold et al. [14] using a perturbative approach) to have the form

$$I(V) = \frac{I_{0}^2 Z_{env}}{2} \frac{V}{V^2 + V_p^2}, \quad (2)$$

where $V_p = (2e/h)Z_{env}k_BT_n$, considering the thermal fluctuations as Johnson noise generated by a resistor $Z_{env}$ at temperature $T_n$. The solid lines in Fig. 2 represent fits of our data to Eq. (2) with $V_p$ and $A = I_{0}^2 Z_{env}/2$ the only fitting parameters. Using Eqs. (2) and (1), a plot of $\sqrt{(4e/h)A/V_p}$ vs. $G_N = 1/R_N$ (Fig. 3 inset) is expected to be linear with zero intercept and slope $\pi \Delta / 2e \sqrt{k_BT_n}$. We obtain from a linear fit $T_n = 5.8 \pm 0.6$ K, and $Z_{env} = 1.5 \pm 0.2$ kΩ. The value of $Z_{env}$ is consistent with our experimental setup. The value of the noise temperature $T_n$ is higher than the actual temperature of the junction, which is not surprising as the isolation of the junction from room temperature circuitry is not perfect. It is also consistent with values reported from similar measurements on ultra-small, high resistance planar junctions [13,14].

Since our data agrees very well with theory, and it is extremely difficult to explain our results using a quasiparticle-only picture, especially once self-heating is ruled out [14], we are led to the conclusion that this is a fluctuation dominated dc Josephson effect. This effect was previously observed in ultra-small planar junctions and is well documented [13,19]. Furthermore, we confirm that this effect stems from Josephson tunneling by measuring the response of the junction in the presence of microwave fields with frequency $f = 15.0$ GHz, fed into a cylindrical cavity containing the STM by a semi-rigid coaxial cable antenna [21].

In the absence of fluctuations, when $E_J \gg k_BT, E_C$, a voltage source driven Josephson junction exhibits phase locked Shapiro current spikes at voltages corresponding to integral multiples of $h\omega/2e$, where $\omega = 2\pi f$ is the angular frequency of the rf field [20], and the height of the k-th order spike $I_k$ at voltage $V_k$ is proportional to the Bessel function of order k of the reduced ac voltage induced on the junction. When strong thermal fluctuations dominate the phase dynamics, and especially in our case where the typical frequency of phase-slip events $f_{\text{slip}} \sim k_BT_n/h \sim 1.2 \times 10^{11}$ Hz is much greater than the frequency of the applied microwave field $f = 1.5 \times 10^{10}$ Hz, phase locking cannot be achieved and the $I-V$ characteristics will exhibit a broad peak instead of discrete spikes.

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shift linearly to higher bias voltages with increased ac voltage as predicted by Eq. (3). At higher bias voltages (not shown) we observe the expected quasiparticle tunneling current with a gap edge that smears, due to photon assisted tunneling, with increasing microwave power.

To summarize, we have demonstrated an STM based Josephson probe. We have shown that the tunneling characteristics obtained in this experiment are in good agreement with the model of fluctuation-dominated Josephson tunneling. While the fluctuation-dominated dc Josephson effect has been observed previously in ultrasmall planar junctions [15,18,19], this is to our knowledge the first observation of the corresponding ac effect in the presence of microwave fields. We expect that a Josephson STM will prove useful as a probe of the SC pair amplitude on length scales of the order of the coherence length in high- $T_c$ materials. In addition, the ease with which the junction resistance in an STM configuration can be controlled, makes this system favorable for studying the effects of thermal fluctuations and the Coulomb blockade (at low enough temperatures) [22] on the Josephson phase dynamics.

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