d-Wave Induced Zero-Field Resonances in dc π-Superconducting Quantum Interference Devices

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A dc π SQUID consists of a superconducting ring interrupted by two Josephson junctions, one of which carries in equilibrium a π phase difference, caused, for example, by the d-wave pairing symmetry of the high-T_c cuprates. If this phase shift is maintained in the voltage state, anomalous resonance currents are expected in the SQUIDs transport characteristics. Here we report the observation of such resonances for high-T_c dc π SQUIDs, providing evidence for the influence of the d-wave symmetry on the voltage state of a Josephson junction for frequencies of several tens of GHz.

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The predominantly $d_{x^2-y^2}$ symmetry of the order parameter [1–5] of high-T_c superconductors influences fundamental properties of Josephson junctions and Josephson junction-based devices, such as superconducting quantum interference devices (SQUIDs). Notably, it offers the possibility to fabricate Josephson junctions which in equilibrium are biased by a phase shift of π, and dc π SQUIDs which consist of such a π-Josephson junction and a conventional junction connected in a loop [1–8]. The electrical characteristics of these d-wave devices provide detailed insight into the symmetry of the superconducting order parameter, tracing, for example, possible admixtures of subdominant symmetry components. Furthermore, the devices present novel building blocks for superconducting (quantum) electronic applications.

Up to now, investigations of the order parameter symmetry and its influences on the properties of Josephson devices were focused on the zero-voltage state. In particular, it has been shown that complementary to standard SQUIDs, small magnetic fields enhance the critical currents of π SQUIDs. Further, circulating currents and magnetic flux may spontaneously appear in structures containing π junctions. In contrast to this, to our knowledge the influences of an unconventional order parameter symmetry on the voltage state of Josephson devices have never been investigated experimentally.

Such studies are of interest for scientific as well as practical reasons. They will reveal, for example, whether characteristic properties related to the symmetry of the superconducting quantum state, such as the π phase shift in a dc π SQUID, are maintained in the dissipative voltage state of the junctions, up to the high corresponding Josephson frequencies at which superconducting quantum-electronic devices are to operate. Prominent features in the voltage states of dc SQUIDs are predicted to arise from the LC resonances in the SQUIDs, leading to current enhancements in the current-voltage $I(V)$ characteristics around the resonance voltage [9–12]. Recently, the theories describing the effects of LC resonances on the current-voltage characteristics of conventional SQUIDs have been extended, accounting for a possible complex mixed symmetry $\varepsilon s + i(1-\varepsilon)d_{x^2-y^2}$, $0 < \varepsilon < 1$ of the order parameter [13]. It was predicted that, as a result of the spontaneous generation of circulating ac currents [14], anomalous zero-magnetic-field current enhancements are to appear in the transport characteristics of symmetric π SQUIDs around the resonance voltage [13]. Here we report the observation of these zero-field resonances and analyze their properties.

A dc SQUID acts in the voltage state as a tank circuit [9] biased by the two radiating Josephson junctions. If a phase difference of π exists between the two junctions, caused either by an applied magnetic flux or by the intrinsic π phase shift in a dc π SQUID, the ac Josephson currents are out of phase. In this case, the two Josephson currents are coupled to the tank circuit, causing a current enhancement [9–13]. By altering the applied magnetic field an additional phase difference is induced, leading to a reduction of this resonance current. In the special case that the total phase difference between the junctions equals a multiple of 2π, the ac currents are in phase and no current enhancement occurs. The maximum of the resonance current thus arises if the complete phase difference equals π. For standard SQUIDs, this π-phase difference is caused by an applied magnetic flux of $(n+\frac{1}{2})\Phi_0$, where $\Phi_0 = 2 \times 10^{-15}$ T m^2 is the quantum of magnetic flux. For π SQUIDs a π-phase difference is provided already intrinsically, and application of a magnetic field is thus not needed to generate a resonance.

For symmetric dc π SQUIDs incorporating two identical junctions, the magnetic field dependence of the amplitude $I_{nr}(\phi)$ of the nth harmonic of the resonance is described in parametric form by [13]

$$\begin{cases} \sin\left[\phi\left(\frac{1}{2} - l\right) - \frac{(1-\varepsilon)\pi}{2}\right]F(\phi) = \frac{1}{\Gamma}\frac{\delta}{[J_{n-1}(\delta) + J_{n+1}(\delta)]} \\ \frac{I_{nr}}{I_c} = \frac{\delta^2}{n\Gamma} \end{cases} \quad \text{for } n \text{ odd,} \tag{1}$$

in which the dimensionless parameter δ is proportional to the amplitude of the ac Josephson voltage oscillations across the junctions. For even values of n, the sine dependence on the left hand side of the first equation in Eq. (1) has to be replaced by a cosine. Here $\phi = 2\pi\Phi/\Phi_0$ is the normalized applied flux, I_c is the critical current of one junction, $\Gamma = I_cR/V_r$ is the damping parameter, R is the junction's shunt resistance, V_r is the resonance voltage, J_{n-1} and J_{n+1} are Bessel functions of the first kind of order $n-1$ and $n+1$, respectively, and l is a parameter that describes the SQUID geometry. The function F describes the $I_c(\Phi)$ dependence of the individual junctions in the SQUID. In the one-dimensional model used in [13], $l = s/[2(s+d)]$, with s the junction width and $s+d$ the size of the entire SQUID (the two junctions and the SQUID hole). In practice, one deals with a two-dimensional system, so that l equals half the ratio of the effective junction area to the effective SQUID area.

Further, the voltage dependence of the current enhancement $I_{nr}(V/V_r)$ in the π SQUID's $I(V)$ characteristics is given in the parametric form [11,13,15]:

$$\begin{cases} \left[\frac{1-(V/V_r)^2}{\pi\beta_L/2}\right]^2\left[\frac{\delta}{J_{n-1}(\delta) - J_{n+1}(\delta)}\right]^2 + \left[\frac{V/V_r}{\Gamma}\right]^2\left[\frac{\delta}{J_{n-1}(\delta) + J_{n+1}(\delta)}\right]^2 = 1, \\ \frac{I_{nr}}{I_c} = \frac{\delta^2}{n\Gamma}(V/V_r), \end{cases} \tag{2}$$

where $\beta_L = 2LI_c/\Phi_0$ is the SQUID screening parameter. Equations (1) and (2) are valid for frequencies ω larger than, or at least comparable to, the Josephson plasma frequency of the device $\omega_p = (2\pi I_c/C\Phi_0)^{1/2}$, with C the junction capacitance.

The above equations predict $d_{x^2-y^2}$-wave induced zero-field current enhancements due to resonances to appear in the $I(V)$ characteristic of π SQUIDs with small Josephson junctions, which have widths below $4\lambda_J$, where $\lambda_J = [\Phi_0/(2\pi\mu_0(2\lambda + t)J_c)]^{1/2}$ is the Josephson penetration depth; here J_c is the junction's critical current density, λ the effective London penetration depth in the two superconductors, t the barrier thickness, and μ_0 the vacuum permeability. In conventional junctions and standard dc SQUIDs, zero-field resonances are observed [16–19] only if the lengths of the junctions are larger than $4\lambda_J$. These resonances result from self-field effects [18]. Measurements of zero-field resonance currents can thus be used to determine whether the unconventional order parameter symmetry is maintained up to high Josephson frequencies in the voltage state of Josephson circuits.

To analyze experimentally the behavior of π SQUIDs in the frequency range of tens of GHz, two π-SQUID samples ($\pi1$ and $\pi2$) and a standard SQUID (used as a reference sample) have been fabricated according to the design shown in Fig. 1 [8]. In these SQUIDs, the two bicrystalline Josephson junctions are provided by superconducting bridges crossing symmetric 45° ± 1° [001]-tilt grain boundaries. The widths of the junctions are 8 μm for $\pi1$, 5 μm for $\pi2$, and $w_{st} = 7$ μm for the standard SQUID. The approximately 100 nm thin c-axis oriented $YBa_2Cu_3O_{7-\delta}$ films were grown by pulsed-laser deposition under standard conditions [8]. All measurements were performed in a magnetically shielded system, with an upper limit to background magnetic fields of 0.02 μT.

In Fig. 2, a typical $I(V)$ characteristic of a π SQUID (sample $\pi1$) is shown for two different values of an applied magnetic field. From the maximum of the junction critical current of 7.5 μA and from the London penetration depth of $YBa_2Cu_3O_{7-\delta}$ (bulk, 4.2 K), $\lambda \sim 150$ nm, the Josephson penetration depth of the

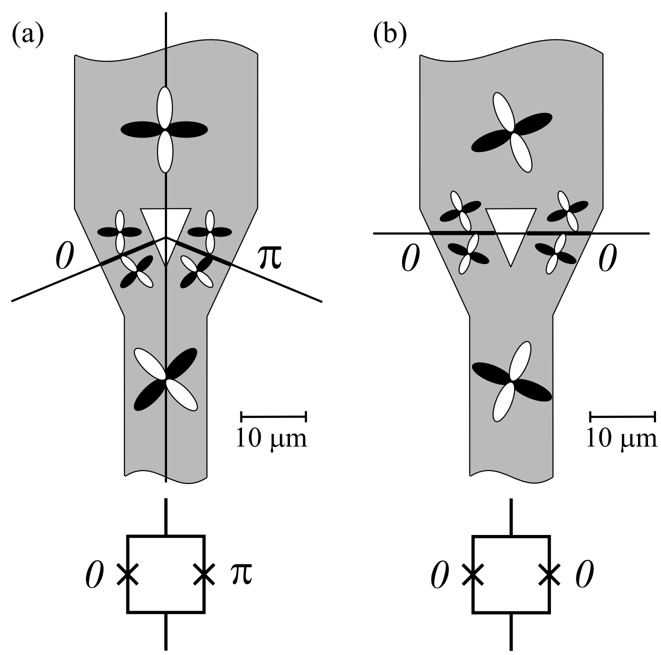

FIG. 1. Schematics of (a) the π SQUIDs and (b) the standard SQUID investigated. For both, the junctions straddle symmetric 45° [001] tilt boundaries (from [8]).

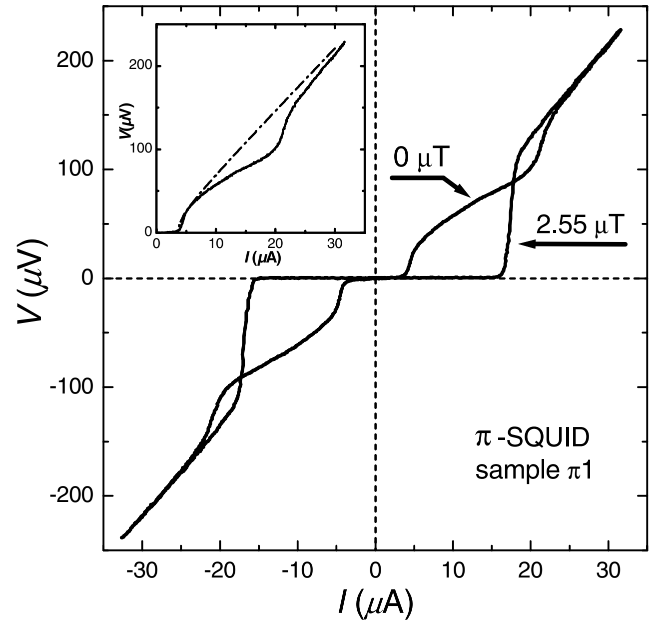

FIG. 2. Current-voltage characteristics measured at 4.2 K of a π-SQUID at zero field and for the smallest magnetic field which causes a maximum of I_c. The inset shows a measured characteristic together with a fit based on the RSJ model.

junctions in the films is calculated to equal $\lambda_J \sim 5\ \mu$m. In zero magnetic field, the characteristic displays a pronounced dc-current enhancement, which has a maximum at $V_r \cong 100\ \mu$V. For the standard SQUID, in contrast, such a resonance current is observed only if an external magnetic field is applied. Because the SQUID is composed of small Josephson junctions, this self-induced resonance has to be attributed to the π shift in these SQUIDs. In Figs. 3a and 3b, the measured magnetic field dependencies of the self-induced resonances and of the critical currents at 4 K are presented for the π SQUID ($\pi 1$) and for the standard SQUID. The maximum magnitude of the current resonance and the resonant voltages are taken as the values of maximal deviation of the experimental data from the fit based on the resistively shunted junction (RSJ) model [20]. As expected, for both types of SQUIDs the magnetic-field dependence of the resonance currents is out of phase with respect to the $I_c(\phi)$ dependence. The resonance currents of the conventional dc SQUID and of the dc π SQUID are therefore shifted by π.

Assuming a symmetric configuration of the devices, $I_{c,\pi 1} = 7.5\ \mu$A and $R_{\pi 1} = 14.9\ \Omega$, $I_{c,\pi 2} = 28\ \mu$A and $R_{\pi 2} = 17.9\ \Omega$, $I_{c,\mathrm{st}} = 96\ \mu$A and $R_{\mathrm{st}} = 9.5\ \Omega$ are obtained for the individual junctions. From the known dependence of the critical current modulation on β_L [21] we obtain $\beta_{L,\pi 1} = 0.49$, $\beta_{L,\pi 2} = 2.3$, and $\beta_{L,\mathrm{st}} = 4.9$, which compares well with the values obtained from $\beta_L = 2LI_c/\Phi_0$, presuming a SQUID inductance of 65 pH. Since the resonances occur at $V_r = (\omega/2\pi)\Phi_0 = v_r\Phi_0 = \Phi_0/2\pi(LC/2)^{1/2} \cong 100\ \mu$V for the standard SQUID as well as for π SQUID $\pi 1$, and at 105 μV for $\pi 2$, the junction capacitances of the standard and π SQUIDs are calculated to equal $C_{\mathrm{st}} = 0.4$ pF and $C_{\pi 1} = 0.3$ pF, $C_{\pi 2} = 0.25$ pF, respectively. The values of the capacitances can be deduced independently from the measured hysteresis in the $I(V)$ characteristics. Using the RCSJ model [22], values of the McCumber parameter $\beta_c = 2\pi I_c R^2 C/\Phi_0$ of $\beta_{c,\mathrm{st}} \approx 4$ and $\beta_{c,\pi 1} < 0.6$,

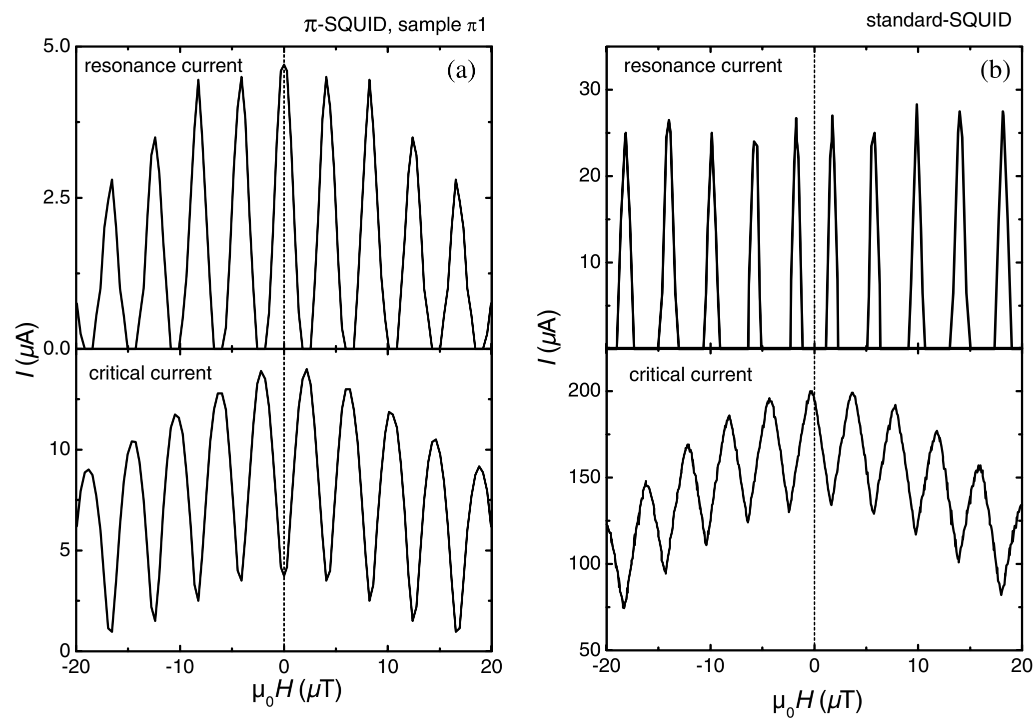

FIG. 3. Dependencies of the maximum resonance current I_{lr} and of the critical current I_c at 4 K of (a) a π SQUID and (b) the standard SQUID as a function of applied magnetic field.

$\beta_{c,\pi 2} = 2.4$ are obtained, which yield the slightly smaller values $C_{st} \cong 0.15$ pF, $C_{\pi,1} < 0.12$ pF, and $C_{\pi,2} \cong 0.1$ pF.

Equation (1) predicts that the envelope of the $I_{lr}(\Phi)$ dependence follows the envelope of the $I_c(\Phi)$ pattern. Qualitatively, this is shown by both types of SQUIDs (see Fig. 3). A reasonable agreement of the measurements with the theory is found in the range of applicability: $\beta_L \leq 1$ $[\beta_{L,\pi 1}(4.2 \text{ K})] = 0.49$ and $\beta_{L,\pi 2}(67 \text{ K}) = 0.127$. The corresponding fit yields a value for l of 0.045, which is a realistic number for the used SQUID configuration. In Fig. 4, the amplitude of the resonance current is depicted as a function of voltage for the two π SQUIDs at $T = 4.2$ and 67 K, respectively, together with the calculated values obtained from Eq. (2) by eliminating the parameter δ. No fitting parameter has been used. It is noted that for the π SQUIDs only a single resonance is observed, in accordance with the theory [15], which predicts that for $\Gamma < 2$ only the resonance $n = 1$ has to be visible; $\Gamma_{\pi 1}(4.2 \text{ K}) = 1.1$, $\Gamma_{\pi 2}(67 \text{ K}) = 0.7$. The resonance voltage increases as a function of temperature from 100 μV at 4.2 K to 180 μV at 67 K. This shift is attributed to the temperature dependence of L, and that of the dielectric constant of the $SrTiO_3$ substrate [23]. The temperature dependence provides further confirmation that the self-induced resonances are of the LC type and are not Fiske resonances; as for the latter the resonance voltage decreases with increasing temperature [24].

If the order parameter symmetry of the high-T_c cuprates was to comprise an imaginary s-wave admixture, the maximum of the resonance current would be a function of the s- to d-wave ratio and occur for an applied magnetic flux deviating from $n\Phi_0$. Since for the π SQUID the dc-current resonance is maximal for values very close to Φ_0, it is concluded that any imaginary admixture of an s-wave symmetry has to be very small.

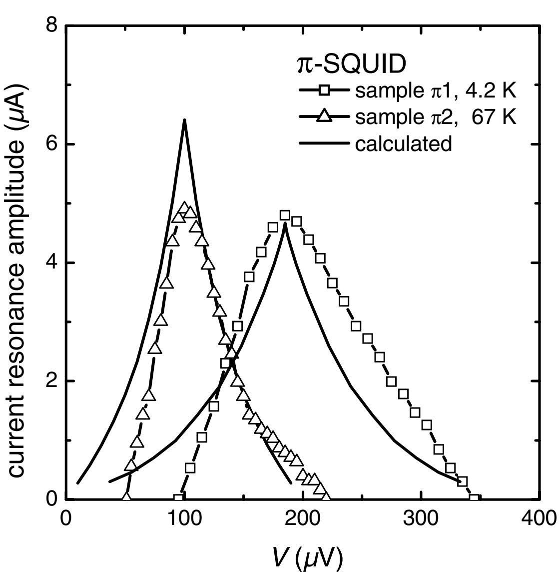

FIG. 4. Zero-field resonance current I_{lr} as a function of voltage for the two π SQUIDs at different temperatures.

In summary, self-induced resonances occurring in dc π SQUIDs have been observed at temperatures of 4.2 to 77 K. These resonances reveal that the $d_{x^2-y^2}$ wave symmetry induces in zero applied magnetic field circulating ac currents, which oscillate with the Josephson frequency. The high frequency behavior of the π SQUIDs provides evidence that in the voltage state the π SQUIDs behave complementary to standard SQUIDs, and that the π shift observed before in the zero-voltage state is present for Josephson frequencies up to several tens of GHz.

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