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QUANTUM INTERFERENCE EFFECTS IN JOSEPHSON TUNNELING

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Current flow through a Josephson junction has been shown[1] to depend periodically upon the magnetic flux contained within the junction—the period in contained flux being $(h/2e)$. This concept has been extended to include multiple junctions in parallel connected by superconducting links. Such a parallel configuration of two junctions leads to the expectation of <u>two</u> periodicities of the current with flux. One period is again associated with the flux contained in a single junction, but now another period arises associated with the flux enclosed in the area between junctions. This second period involves a quantum mechanical interference between the currents flowing through separate junctions in direct analogy with double-slit electron beam interference effects. The purpose of this Letter is to report experimental observation of such interference effects.

Current flow through a Josephson junction is given by[2]

$$j_{\mathrm{J}} = j_0 \sin\left(\gamma_a - \gamma_b - \frac{2e}{\hbar}\int_a^b A dx\right), \qquad (1)$$

where γ_a and γ_b are the phases of the wave function at superconductors a and b separated by the Josephson junction. Integrating (1) over the current-carrying area of the junction gives a total current having a functional form typical of "diffraction" effects:

$$I = I_0 \frac{|\sin(\Phi_j e/\hbar)|}{(\Phi_j e/\hbar)} |\sin(\Delta\gamma)|,$$

where Φ_j is the flux contained in the current-carrying area of the junction and $\Delta\gamma = \gamma_1 - \gamma_2$. If (1) is applied to two identical junctions connected in parallel by superconducting links, a double periodicity results. The integration of (1) over both junctions, keeping account of the relative phase between the separate junctions, leads to additional interference effects:

$$I \simeq I_0 \frac{|\sin(\Phi_j e/\hbar)|}{(\Phi_j e/\hbar)} |\sin(\Delta\gamma - \Phi_T e/\hbar)|,$$

where Φ_T is the total flux enclosed between junctions.

Double junctions were fabricated as shown in Fig. 1. The normal resistance of the junctions used was about $\frac{1}{2}$ ohm. Junctions were spaced ap-

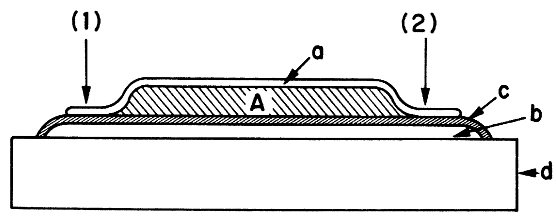

FIG. 1. Cross section of a Josephson junction pair vacuum-deposited on a quartz substrate (d). A thin oxide layer (c) separates thin (~1000Å) tin films (a) and (b). The junctions (1) and (2) are connected in parallel by superconducting thin film links forming an enclosed area (A) between junctions. Current flow is measured between films (a) and (b).

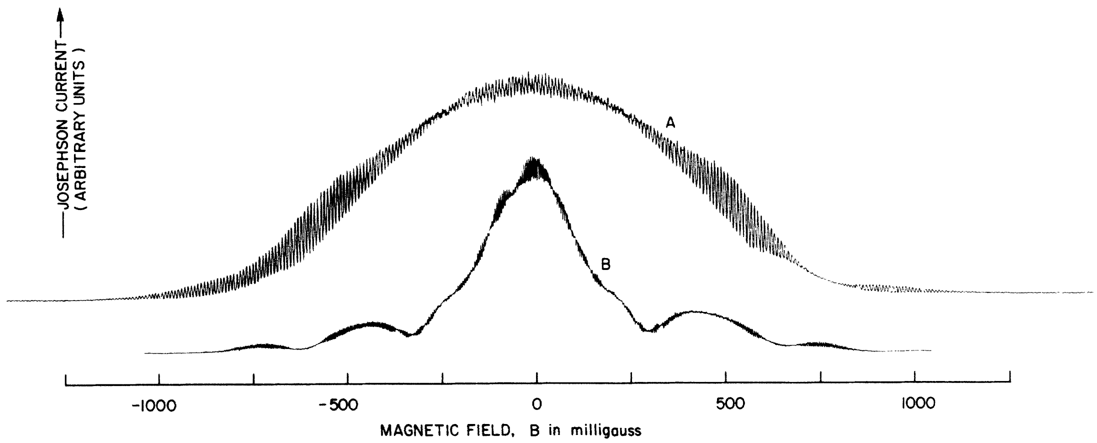

FIG. 2. Josephson current vs magnetic field for two junctions in parallel showing interference effects. Magnetic field applied normal to the area between junctions. Curve (A) shows interference maxima spaced at $\Delta B = 8.7 \times 10^{-3}$ G, curve (B) spacing $\Delta B = 4.8 \times 10^{-3}$ G. Maximum Josephson current indicated here is approximately 10^{-3} A.

proximately 3.5 mm apart forming an area between junctions ranging from 10^{-4} to 10^{-5} cm^2 for the data given herein. The junctions were tin-(tin oxide)-tin separated by a Formvar spacer.

Typical experimental results for two different junction pairs are given in Fig. 2. In the upper trace (A) the individual junctions are narrow showing only the central maximum of the single-slit diffraction in this field span but also clearly showing the interference effects between junctions. The lower trace (B) with somewhat wider junctions shows both the single-slit diffraction with side peaks[1] and the expected interference effects. As the magnetic field is rotated in the plane of the junction away from normal to the area between junctions, the field spacing between interference maxima increases as expected corresponding to the geometric change in enclosed flux.

This area between junctions was estimated from measurements of the capacity of this section, assuming a dielectric constant of 3.2 for the Formvar. From the field spacing between interference peaks and this estimated area, the flux period for the junction pair (A) is 2.7×10^{-7} G cm^2, while for junction pair (B) the period is 2.4×10^{-7} G cm^2. The flux period associated with the diffraction minima in junction pair (B) was found to be 2.5×10^{-7} G cm^2, using as area the width (0.8 mm) multiplied by twice the penetration depth (510 Å). This width (0.8 mm) is somewhat larger than the expected effective width for this junction assuming a "Josephson-length" effect. The effective width[1] for this junction is about 0.7 mm, yielding a flux period of 2.2×10^{-7} G cm^2.

This flux period from the diffraction minima is in reasonable agreement with previous work[1] and the theoretical value ($h/2e$). The somewhat larger period determined from the interference effects in these two junction pairs probably reflects the inadequacy of the area determination technique.

Similar interference effects have been observed in all Josephson pairs we have examined. We believe these data demonstrate interference effects (and thus phase coherence) in the quantum wave function in solids at distances, in these junctions, of up to 3.5 mm. The obvious experiment to measure the effects of vector potential alone is in progress.

[1] J. M. Rowell, Phys. Rev. Letters 11, 200 (1963).

[2] P. W. Anderson and J. M. Rowell, Phys. Rev. Letters 10, 230 (1963).