# PROBABLE OBSERVATION OF THE JOSEPHSON SUPERCONDUCTING TUNNELING EFFECT

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Josephson[1] has recently predicted theoretically a new kind of tunneling current through an insulating barrier between two superconducting metals. This anomalous current behaves like a direct tunneling of condensed electron pairs between the Fermi surfaces of the two metals. When the voltage difference across the barrier is zero, the current should be dc but may range between limits of the order of magnitude of the usual tunnel current above the gap, depending on the relative value of the phase of the energy gap function or "second Green's function $F$" on the two sides, while at a nonzero voltage difference $\Delta V$ it is alternating at a frequency $2e\Delta V/h$.

We have observed an anomalous dc tunneling current at or near zero voltage in very thin tin oxide barriers between superconducting Sn and Pb, which we cannot ascribe to superconducting leakage paths across the barrier, and which behaves in several respects as the Josephson current might be expected to.

Figure 1 shows an $X$ - $Y$ recorder plot of the tunneling current vs voltage for one of these structures at ~1.5°K. The lead and tin films are both approximately 2000Å thick, and the junction has dimensions $0.025 \times 0.065$ cm$^2$ and a resistance (both metals normal) of 0.4 Ω. Voltage is applied to two arms of the junction from a 1-kΩ potentiometer and the resulting current flow is measured as voltage across a series resistor of 10 Ω. The voltage appearing across the barrier is taken directly from the other two arms of the junction. Figure 2 shows the plot with current scale expanded to show the anomalous region near the origin. The current

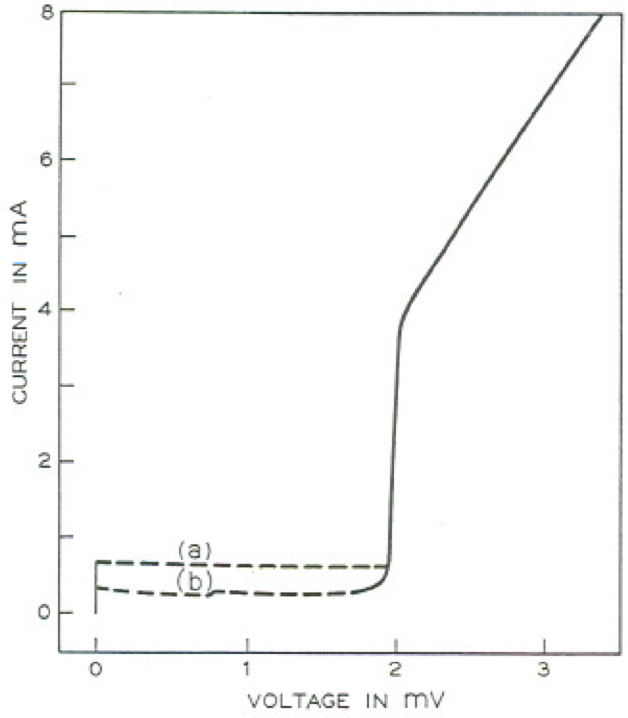


FIG. 1. Current-voltage characteristic for a tin-tin oxide-lead tunnel structure at ~1.5°K, (a) for a field of $6 \times 10^{-3}$ gauss and (b) for a field 0.4 gauss.

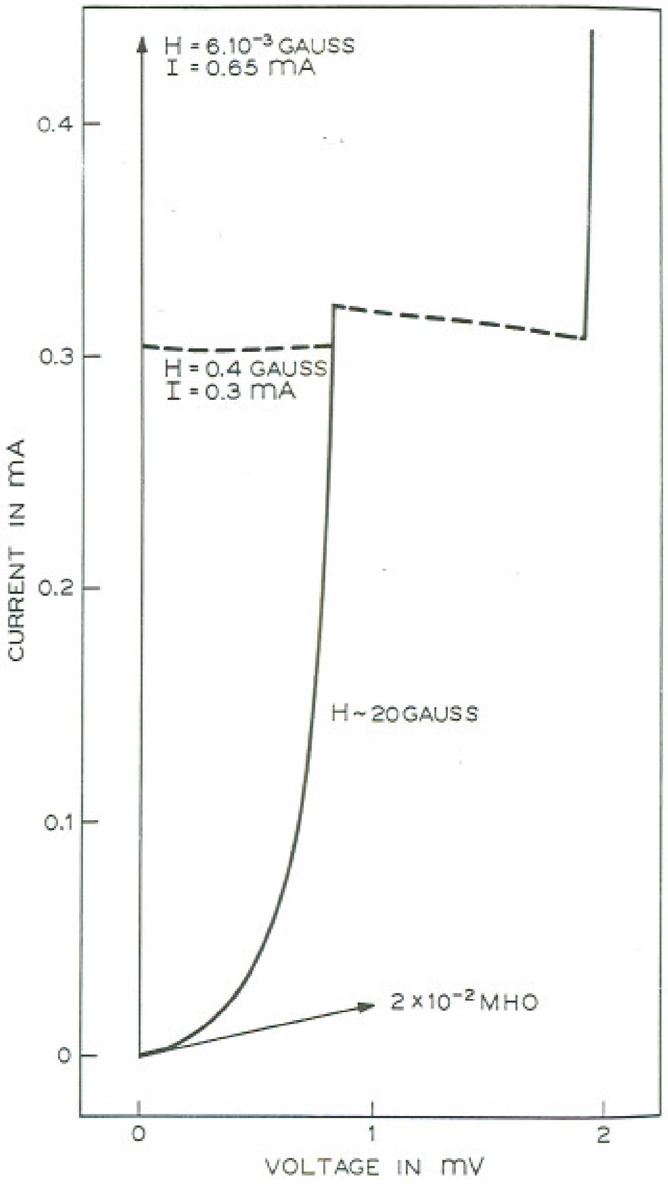


FIG. 2. Current-voltage characteristic for structure of Fig. 1 with expanded current scale. Note the conductance at low voltages in a field ~20 gauss.

at first increases up to a value of 0.3 mA with no voltage appearing across the barrier. At this point the junction becomes unstable and may fluctuate back and forth between the vertical characteristic and the expected "two-superconductor" characteristic. With a small increase in current, the junction settles stably on the latter. Expansion of the voltage scale showed some fluctuations even at lower currents in many cases.

One possible explanation that will be suggested is, of course, that in such thin junctions we have not avoided small superconducting shorts across the barrier. There are, however, four experimental points suggesting that this is indeed the Josephson effect.

(1) As pointed out in Josephson's Letter,[1] the effect should be quite sensitive to magnetic fields. Since the proposed proportionality to $\mathrm{Im}(\Delta_{\mathrm{Sn}}{}^*\Delta_{\mathrm{Pb}})$ is not gauge invariant, we expect an additional dependence on $\sin\int_1^2(2e/\hbar c)\vec{A}\cdot d\vec{l}$, where $\vec{A}$ is the vector potential, which will lead to cancellation of currents in various parts of the barrier if the magnetic flux flowing between the superconductors reaches one or two quanta. With an area of $\sim10^{-7}$ cm$^2$, this corresponds to about 1 gauss. We have found (see Fig. 2) that when the junction was carefully shielded by a mu-metal can with a measured interior field of $6\times10^{-3}$ gauss, the vertical characteristic reached 0.65 mA, with no shielding (0.4 gauss), 0.30 mA, and when less than 20 gauss was applied the anomalous behavior was not observed. Fine superconducting filaments should show anomalously high, not low, critical fields.

(2) The effect can only occur if both metals are superconducting and should be proportional to $\sim|\Delta_{\mathrm{Sn}}\Delta_{\mathrm{Pb}}|$. On cooling the junction we find that the vertical characteristic appears at the tin transition (as measured by the negative resistance region of width $\Delta_{\mathrm{Sn}}$ first appearing at $\Delta_{\mathrm{Pb}}$) within experimental error. It seems unlikely that the "superleaks" would have precisely the same $T_c$ as the tin film.

(3) Critical currents of finely divided specimens never exceed $10^7$ A/cm$^2$. Our observed maximum current of 0.65 mA corresponds, then, to an area $A$ of superleaks of not less than $6\times10^{-11}$ cm$^2$. Assuming a rather poor conductivity of $10^4$ ohm$^{-1}$ cm$^{-1}$ for the filaments, this leads to a conductance, which should be observed even when the filaments are normal, of

$$Y \geqslant \frac{10^4\times6\times10^{-11}}{10^{-7}} = 6\ \text{mho},$$

whereas (Fig. 2) we observe with an applied field at most $2\times10^{-2}$ mho, most of which is probably thermally excited quasi-particle tunneling.

(4) We attempt to "burn out" the leaks by passing increasing currents through the junction, checking the anomalous current between each step. We observed no change in the vertical characteristic for a number of junctions ($\frac{1}{10}$ to 1 $\Omega$) until (at a voltage usually between 0.3 and 0.6 volt) destruction of the junction resulted. Metallic leaks should burn out before the junction as a whole does.

These last arguments seem to us nearly to exclude the conducting leak hypothesis.

The maximum current we observe is still, even in the best units, about an order of magnitude less than predicted. Other questions concern the fluctuation effects and the fact that thin junctions are necessary to see the effect.

We believe that these questions are probably all best elucidated by looking at the effect as related to a coupling energy between the phases of the gap functions on the two sides. Calculations which will be reported elsewhere show that this energy is proportional to the negative cosine of the phase difference, and in magnitude is

$$\Delta E = (\hbar/e)J_1,$$

where $J_1$ is the maximum amplitude of Josephson's predicted current. This energy coupling is reduced both by the presence of magnetic fields and by driving current through the unit. In order to observe the dc Josephson effect, this energy must be large enough to keep the phases on the two sides coupled against thermal or other fluctuations.

The total magnitude of $\Delta E$ for the entire unit is rather small—of order 1 or a few eV in the thin barriers, $10^{-2}$ eV in the more normal units. Obviously the thicker units are completely unstable against thermal fluctuations (remember that most of the circuit is at room temperature or higher). The thin barriers are more stable, but as we drive larger currents through them, or apply stray magnetic fields, we lower the coupling energy, and random fluctuations will eventually destroy the dc current and replace it with noise.

A perfectly rigorous way to think of this process is that the energy $\Delta E$ serves as a barrier against the passage of quantized flux lines through the unit. It will act as a superconductor only if fluctuations over the applied magnetic stresses cannot drive lines through the barrier region at an appreciable rate.

We wish to acknowledge the assistance of L. Kopf in the preparation of the tunnel units, and discussions with V. Ambegaokar. B. D. Josephson informs us that he has independently reached some of the theoretical conclusions of the last few paragraphs.

[1] B. D. Josephson, Phys. Letters 1, 251 (1962).

# NUCLEAR MOMENT OF $Ni^{61}$ FROM NUCLEAR RESONANCE STUDIES IN STEADY EXTERNAL MAGNETIC FIELDS

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Recently the determination of the nuclear moment of $Ni^{61}$ has become of particular interest. Orton, Auzins, and Wertz[1] from an electron spin resonance study of the hyperfine splitting of $Ni^{+2}$ in MgO and a comparison of the hyperfine splitting of $Ni^{+2}$ with $Co^{+1}$ estimated a nuclear moment of $Ni^{61}$ of 0.3 nm. Bennett and Streever[2] re-examined the electron spin resonance spectra of nickel in MgO and nickel in germanium, and proposed that the previously estimated value of 0.3 nm for the nuclear moment of $Ni^{61}$ was in error by a factor of three, and that a value 0.9 nm was more consistent with the published spectra. Of course, associated with both values, the 0.3 nm and 0.9 nm, one expects possibly an error of about 20 % associated with a comparison of isoelectronic atoms. A knowledge of the nuclear moment of $Ni^{61}$ is important for an understanding of hyperfine fields in ferromagnetic metals and alloys. In order to clear up this ambiguity in the nuclear moment, we have studied the nuclear magnetic resonance of $Ni^{61}$, using free precession equipment, in applied external magnetic fields of up to 10 000 gauss. At 77°K we find above about 2500 gauss that the resonance frequency $\nu$ varies linearly with applied external field at a rate of $0.354 \pm 0.020$ Mc/kG-sec, corresponding to an uncorrected nuclear moment of $0.70 \pm 0.04$ nm. Corrections on this value are discussed below.

The $Ni^{61}$ nuclear resonance was observed using standard free precession equipment consisting of a pulsed rf oscillator operating at about 300 volts rf and suitable receiving equipment. Separate sending and receiving coils were used, the coil geometry being such that the coils were coaxial along an axis at right angles to the direction of the externally applied dc field $H_0$.

The sample consisted of about 2 grams of nickel powder with a particle diameter of about 10 $\mu$ which was isotopically enriched to about 100 % in the isotope 61. The free precession echo signal was observed directly on the oscilloscope and heterodyned with a known frequency. In Fig. 1 we plot resonance frequency against externally applied dc magnetic field at 77°K, where the frequency was measured up to 10 000 gauss. Above approximately 2500 gauss, the resonance frequency $\nu$ varies linearly with applied field at a rate of $0.354 \pm 0.02$ Mc/G-sec. The indi-

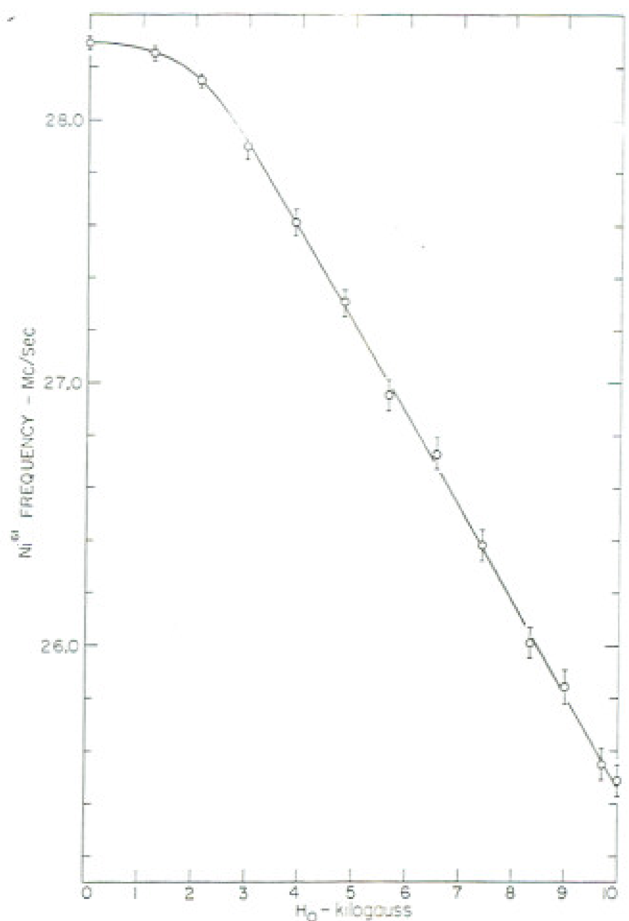


FIG. 1. Resonance frequency $\nu$ plotted against external dc field $H_0$ at 77°K.