QUANTUM INTERFERENCE FROM A STATIC VECTOR POTENTIAL IN A FIELD-FREE REGION

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Recent experimental confirmation[1] of the superconducting state as a truly long-range single quantum state has prompted several additional experiments utilizing the superconductor as an arena in which to test consequences of the quantum theory. The possibility that superconductivity represented such a state was suggested long ago[2] by London and has received strong support from the many experiments[3] on flux quantization. The experiments described here report a physical observation caused by a static vector potential ($\vec{A}$) in a situation where the magnetic field effects are negligible.[4]

The technique utilized in these experiments involves a measurement of the maximum supercurrent flowing through two Josephson junctions connected in parallel by superconducting links. It has been shown[1] that the supercurrent flow through such a configuration is modulated by the flux enclosed within the superconducting circuit. This modulation is periodic in the enclosed flux with a flux period of $h/2e$. In these previous experiments the flux was produced by a uniform magnetic field (B) applied to the superconducting system. By contrast, in the present experiment the flux is produced by a closely wound solenoid arranged to have no net axial current flow.

The configuration used is shown schematically in Fig. 1. Junctions 1 and 2 are formed of tin, tin oxide, tin, and are connected in parallel by tin superconducting links a, b. Current flow is measured between a and b. In this experiment a solenoid (A) was placed within the superconducting circuit. This solenoid (closely wound of 10^{-3}-inch copper wire to an outside diameter of 6×10^{-3} inch, 0.4 inch long) can provide a field within the solenoid while maintaining the field external to this solenoid at the superconductor vanishingly small. The measured ratio of these fields is at least 10^2. Thus a flux can link the superconducting circuit with no significant magnetic field at the superconducting elements. Since flux (Φ) is defined as $\Phi=\oint\vec{A}\cdot d\vec{l}$, such a configuration allows the determination of the response of the system to a static vector potential in the absence of a magnetic field at the superconductor.

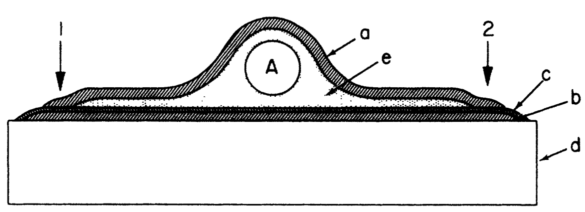

FIG. 1. Cross section of a Josephson junction pair vacuum-deposited on a quartz substrate (d). A thin oxide layer (c) separates thin (~1000Å) tin films (a and b). The junctions (1) and (2) are connected in parallel by superconducting thin film links enclosing the solenoid (A) embedded in Formvar (e).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

Measurements of the maximum supercurrent flow through such a circuit showed the expected periodicity of current with flux—both when the flux was applied by an external field ($\Phi=\int\vec{B}\cdot d\vec{s}$) and when produced by the enclosed solenoid ($\Phi=\oint\vec{A}\cdot d\vec{l}$). The flux period ($\Delta\Phi$) when modulated by vector potential ($\vec{A}$) alone is $\Delta\Phi=(2.1\pm0.1)\times10^{-7}$ G cm^2. This represents an average of 50 periods taken at several different temperatures. The field period (ΔB) when modulated by an external uniform field is $\Delta B=0.308\times10^{-3}$ G. From our best estimate of the area, this represents a flux period of $(2.1\pm0.2)\times10^{-7}$ G cm^2. Our inadequate knowledge of the area prevents a closer comparison of these two periods but within our accuracy they may be taken identical.

We believe this experiment demonstrates a physically observable effect produced by a static vector potential field under conditions where the magnetic field effects are negligible. This effect, of supercurrent modulation, is periodic with a period of 2.1×10^{-7} G cm^2, very nearly the flux quantum ($h/2e$), and is identical with the same modulation period produced by a uniform magnetic field. This observation seems to promote the vector potential ($\vec{A}$) to a position of experimental reality long enjoyed by its derivatives, the electric and magnetic fields. It now becomes significant to speculate on the philosophical implications of the role of potential in quantum mechanics.[5]

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BIQUADRATIC SUPEREXCHANGE*

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Recently, Harris and Owen[1,2] found it necessary to invoke a biquadratic exchange interaction in order to explain the energy level spectrum of Mn pairs in MgO. They used the expression

$$\mathcal{H}=J(\vec{S}^a\cdot\vec{S}^b)-j(\vec{S}^a\cdot\vec{S}^b)^2 \tag{1}$$

to fit the nearest-neighbor pair spectrum with $J/k=14.6°\mathrm{K}$, $j/k=0.73°\mathrm{K}$, and $j/J=0.05\pm0.03$. We have investigated the origin of the biquadratic exchange integral (j) and we have derived an explicit expression for j using a technique first employed by Keffer and Oguchi[3] to find the ordinary bilinear exchange integral (J). Anderson[4] first pointed out the possibility of a biquadratic superexchange interaction and roughly estimated its magnitude. Until now, however, there existed no quantitative treatment which could show that, in fact, a superexchange interaction was large enough to be responsible for the magnitude of j. This is necessary because an effective biquadratic exchange term can also arise via a mechanism[5] in which a balance is set up between elastic and exchange forces. Such a contribution to j is difficult to estimate, but Harris and Owen[1] state that it is too small to explain the observed value.

We have utilized the method of Keffer and Oguchi[3] to investigate terms in the superexchange problem quadratic in $\vec{S}^a\cdot\vec{S}^b$. Their procedure follows the treatment of permutation degeneracy due to Serber[6] (see also Anderson[7]) and treats the following three configurations:

Configuration A,
$\mathrm{Mn}^{++}(3)-\mathrm{O}^{--}(1,2)-\mathrm{Mn}^{++}(4)$;

Configuration B,
$\mathrm{Mn}^{++}(3)-\mathrm{O}^{-}(4)-\mathrm{Mn}^{+}(1,2)$;

Configuration C,
$\mathrm{Mn}^{+}(1,2)-\mathrm{O}^{-}(3)-\mathrm{Mn}^{++}(4)$;

where the numbers in parentheses label the electron orbitals. Configuration A is referred to as ionic. If the overlap integral between the Mn^{++} $3d$ electrons and the O^{--} $2p$ electrons[8] is designated by S, Keffer and Oguchi show that J is of order S^4, a result first pointed out by Yamashita and Kondo.[9] In particular, they find

$$J=-2S^4\{q_{13,24}{}^{AA}+2[(q_{14}{}^{BA})^2(q_{34}{}^{BB}+q_{13,24}{}^{CB})/(q_1{}^{BB})^2]-4(q_{14}{}^{BA}q_{134}{}^{BA}/q_1{}^{BB})\}, \tag{2}$$

where $q_1{}^{BB}$ is a measure of the transfer energy; that is, the energy difference between the ground (ionic) configuration A and the excited configuration B. The other terms represent the matrix elements of the Hamiltonian between different orbitals (i.e., $q_{13,24}{}^{CB}$ is related to the matrix element of the Hamiltonian between configurations C and B with orbitals 1 and 3 in configuration C, and 2 and 4 in configuration B, permuted respectively).

We have extended the treatment of Keffer and Oguchi to powers of S higher than fourth. We find the ionic contribution alone does give rise to a biquadratic exchange term, but one proportional to S^8. Using the approximate value $S\simeq0.05$, this implies $j/J=S^4=10^{-5}$, a result much too small. Upon consideration of the excited configurations B and C, however, we find that a biquadratic term appears first in terms of order S^6. This is in striking contrast to the result for the ordinary exchange integral in which the ionic and excited configurations contribute about equally to J, both being proportional to S^4. In detail, we find

$$j=\frac{8S^6}{q_1{}^{BB}}\left[q_{134}{}^{BA}-\frac{q_{14}{}^{BA}}{q_1{}^{BB}}(q_{34}{}^{BB}+q_{13,24}{}^{CB})\right]^2. \tag{3}$$

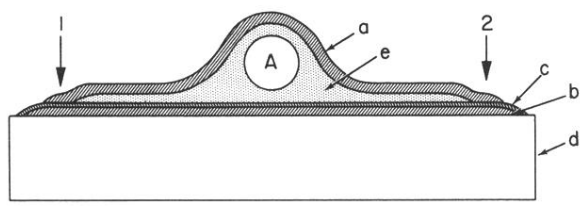

FIG. 1. Cross section of a Josephson junction pair vacuum-deposited on a quartz substrate (*d*). A thin oxide layer (*c*) separates thin (~1000Å) tin films (*a* and *b*). The junctions (1) and (2) are connected in parallel by superconducting thin film links enclosing the solenoid (*A*) embedded in Formvar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