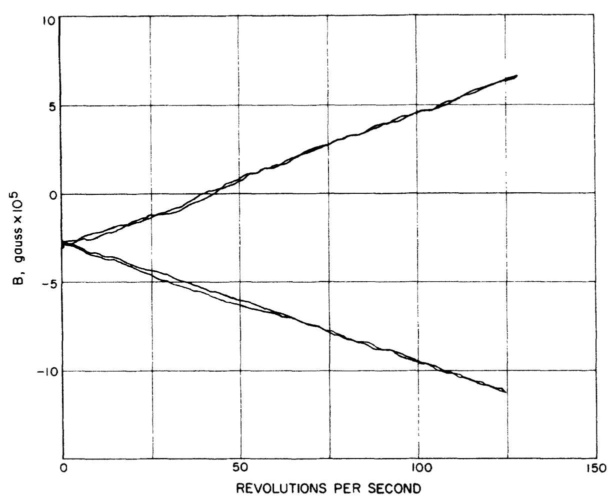

FIG. 1. Recording of magnetic field strength vs rotation rate in revolutions per second. The upper curve is for counterclockwise rotation and the lower curve for clockwise rotation. The material is a bulk lead foil.

by fitting curves such as those in Fig. 1. The agreement with Eq. (2) is good, especially if run 1 is omitted. This was the first experiment in which the effect was observed. The dependence of the effect on initial conditions for the shells considered here and for the simply connected case (where the original theories[1,2] gave different results) are being investigated.

I wish to acknowledge the assistance of the magnetometer group of the Laboratory's Applied Science Section in calibrating the magnetometer. I am grateful to Dr. Melvin Saffren for a helpful discussion and to Mr. Edwin Olli for his assistance in the construction and operation of the apparatus.

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CONSERVATION OF THE FLUXOID

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As originally noted by London,[1] a superconductor is expected to conserve and quantize a quantity which he called the fluxoid. This principle applied to a thin superconducting cylinder leads to the expectation that a sum of the trapped magnetic flux and the mechanical angular momentum of the persistent current (in appropriate units) will be conserved and quantized[2] in units of $h/2e$. Although the contribution of the mechanical momentum to the conservation law has been too small to be particularly significant in most experiments,[3] its presence leads to a temperature dependence of the trapped flux. The mechanical momentum is a function of penetration depth λ and therefore varies with temperature. Consequently the amount of trapped flux would also be expected to show an oppositional temperature variation if it is presumed that the quantum number is an adiabatic invariant. The purpose of this Letter is to report experimental confirmation of such a temperature variation of the trapped flux consistent with adiabatic invariance for small temperature oscillations.

The presence of the mechanical angular momentum in the fluxoid leads to a modification[2] of the flux quantum $h/2e$ to

$$\Phi_0=(h/2e)(1+2\lambda^2/r\delta)^{-1}$$

for the modified flux unit (Φ_0) trapped by a long thin (δ) cylinder of radius r and penetration depth λ. Total flux trapped by such a cylinder must be an integral number n of these units, $n\Phi_0$. This trapped flux is then temperature dependent through the known temperature variation of the penetration depth. A temperature variation ΔT will be expected to cause a change $\Delta\Phi$ in trapped flux $n\Phi_0$ of

$$\Delta\Phi\simeq -n(h/2e)(2/r\delta)[d(\lambda^2)/dT]\Delta T.$$

This anticipated temperature variation of trapped flux depends only on the adiabatic invariance of the fluxoid and not on its quantization. Such an effect should occur whatever the constant magnitude of the quantity represented by $nh/2e$.

The flux variation implies a voltage V:

$$V \simeq -n(h/2e)(2/r\delta)[d(\lambda^2)/dT](dT/dt). \quad (1)$$

In these experiments the temperature oscillation (dT/dt) was produced by second sound waves in superfluid liquid helium, the resulting voltage being detected in a loosely coupled pickup coil. A superconducting cylinder formed one wall of a cylindrical second sound cavity. The second sound resonances of this cavity produced the temperature oscillations generating the voltage expected from Eq. (1). Measurements were made of the amplitude of the thermal wave and the induced voltage as the cavity was tuned through resonance at a constant second sound frequency. Since the second sound wave velocity is a function of temperature, tuning was accomplished thermally by a slow drift in temperature through the resonance velocity.

Typical data are shown in Fig. 1. The upper trace shows the amplitude of the thermal wave as the cavity passes through resonance. Below, in the lower trace, is the voltage induced by this thermal wave from a superconducting cylinder carrying a persistent current. This persistent current is related to the trapped flux geometrically by the inductance of the cylinder. Voltage in the pickup coil as a function of average persistent current is shown in Fig. 2 at a particular temperature ($T = 1.89$°K) and thermal-wave amplitude. The dashed line is Eq. (1) using measured values[4] for all of the parameters. Amplitude of the thermal wave was obtained from a bolometer adjacent to the superconducting cylinder in the second sound cavity. Voltage in the pickup coil is related to voltage in Eq. (1) through the measured mutual and self inductance of the various circuit elements.

The expected temperature dependence of this voltage was also investigated. The voltage associated with a particular trapped flux was measured at various temperatures. This voltage was found to be temperature dependent, as expected, following the measured values of $d(\lambda^2)/dT$ to within about 5%.

Stability of this voltage with time is a measure of the persistence of the supercurrent (or adiabatic invariance of the fluxoid) under these perturbations. The maximum measured voltage in Fig. 2 corresponds to a flux change at the superconducting cylinder of about one quantum, $h/2e$. No change in voltage was detected in experiments up to two hours at this current level. However,

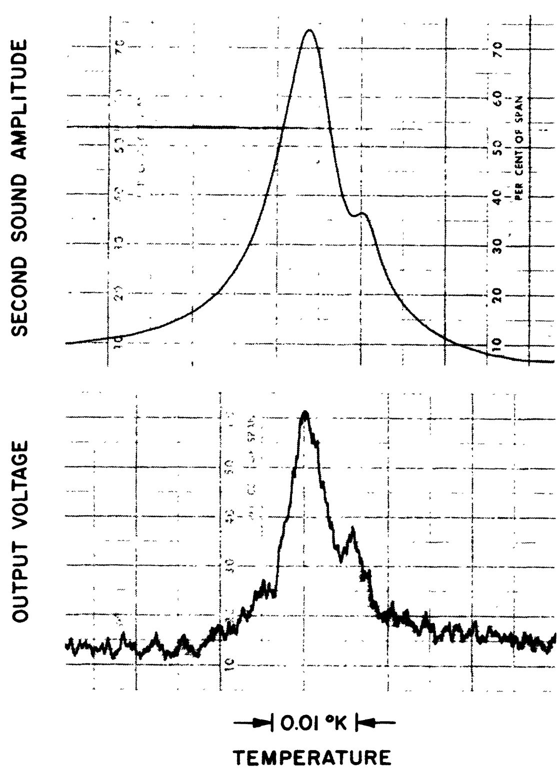

FIG. 1. Cavity response as a function of temperature at fixed frequency (1.28 kc sec^{-1}). Upper trace is second sound amplitude, lower trace is voltage induced from a persistent current; both plotted to the same temperature scale. Resonance peak at 1.89°K.

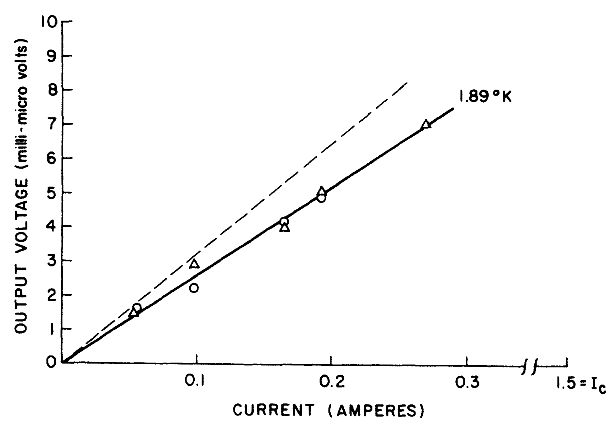

FIG. 2. Induced voltage in the pickup coil as a function of persistent current amplitude. Dashed line is the voltage anticipated from Eq. (1). Circles and triangles indicate opposite sense of persistent current flow.

this is the largest voltage that could be generated despite attempts to induce larger persistent currents in this cylinder. In this particular cylinder the maximum measured persistent current[4] is nearly six times larger (1.5 amperes). These data were taken on a tin cylinder 1 cm diameter, 1 mm long, and 1200Å thick. Similar results have also been obtained from a 1-cm cylinder 5 mm long and 450Å thick.

These experiments tend to confirm the adiabatic invariance of the fluxoid under small thermal perturbations. On a two-fluid model such a behavior indicates that the electrons condense only into a particular current-carrying state—the flux changing in such a way as to keep the fluxoid constant. The implication that adiabatic invariance under these perturbations applies only to flux changes less than one quantum is being investigated.

*Now with the National Science Foundation.

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ELECTRON SPIN RESONANCE OF THE *R* CENTER*

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van Doorn[1,2] has proposed a model for the *R* center in the alkali halides, Fig. 1, which is a cluster of three *F* centers forming an equilateral triangle lying in a (111) plane. Although this model predicts that the *R* center should be magnetic, extensive investigations by electron spin resonance of systems containing *R* centers[3-4] have not revealed the resonance nor given any conclusive evidence that the center is paramagnetic. Under conditions of low temperature (~2°K) and large applied uniaxial stress (~3kG/mm^2) the resonance can be observed as described below, lending considerable support to the van Doorn model.

Results of optical studies of the zero-phonon line of the R_2 band[6] with applied uniaxial stress[7] are consistent with the model of van Doorn. These studies further suggest that in a static lattice the lowest electronic state of the center would be orbitally doubly degenerate. If one includes the ion motion, a dynamic Jahn-Teller effect results[8] which still leaves a degenerate electronic-vibronic state lowest.

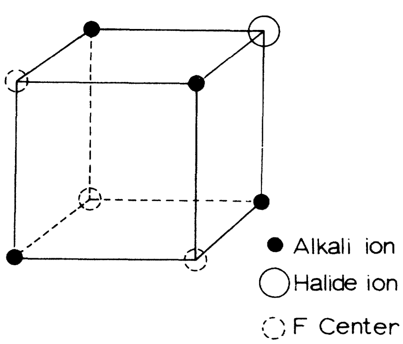

FIG. 1. The van Doorn model of the *R* center.

This degeneracy is probably lifted by residual strains in the crystal to give finally two Kramers' doublets with *g* tensors of almost axial symmetry along the [111] direction. The $\delta g_\perp$ should be of the order of the *F*-center *g* shift while the $\delta g_\parallel$ contains two terms, one inversely proportional to the Jahn-Teller splitting, the other inversely proportional to the strain splitting if that splitting is sufficiently large. The two Kramers' doublets are strongly coupled by the phonon field, and it is postulated that the electron spin resonance is normally broadened beyond observability because of T_1 processes involving the direct relaxation among these levels in a Finn-Orbach type process.[9] This postulate suggests an experiment under conditions of large applied stress, which gives a large energy separation, Δ, between the two Kramer's doublets, and low temperature, in order to suppress the relaxation process which varies as $\exp(-\Delta/kT)$.

Figure 2 shows the change in resonance signal produced by a [110] stress with the static magnetic field parallel to the [1$\bar{1}$1] direction. The strong line is the saturated *F*-center resonance while the weaker line, which develops with application of the stress, is the *R*-center reso-

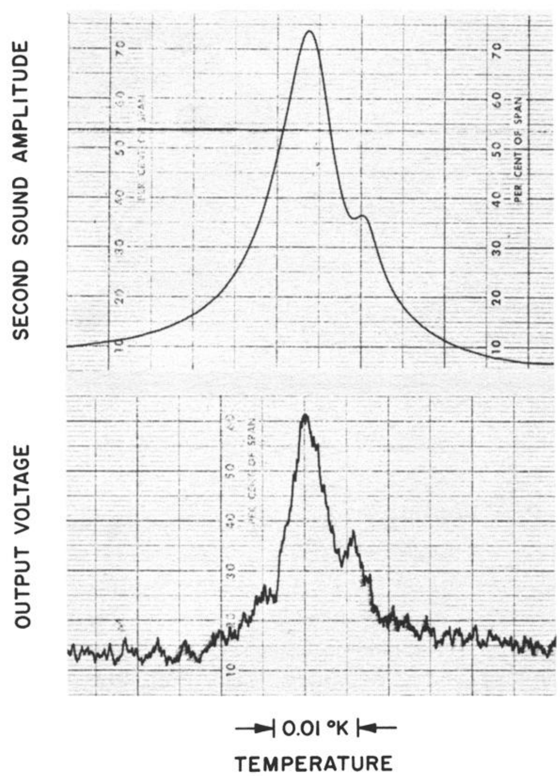

FIG. 1. Cavity response as a function of temperature at fixed frequency (1.28 kc sec^{-1}). Upper trace is second sound amplitude, lower trace is voltage induced from a persistent current; both plotted to the same temperature scale. Resonance peak at 1.89°K.