ing short-range order). For the ferromagnetic ground state with $S=\frac{7}{2}$, $\langle H_m \rangle = -3.5J$. The choice of $J=540\ \text{cm}^{-1}$ then yields the shift of $1900\ \text{cm}^{-1}$ observed[7] in EuO. For the antiferromagnetic phase of EuSe, one obtains $\langle H_m \rangle = \frac{1}{4}(-3.5J)$. The expected shift at 0°K upon transformation to the ferromagnetic phase is then $\frac{3}{4}(-3.5J)$, that is, $1420\ \text{cm}^{-1}$. At 4.2°K and 15 kOe, however, the magnetization of EuSe is about 0.8 of its saturation value at 0°K.[1] Since $\langle H_m \rangle$ is approximately proportional to M^2, we would therefore expect a shift in the band edge at 4.2°K of about $900\ \text{cm}^{-1}$, in reasonable agreement with the $1000\ \text{cm}^{-1}$ reported above. The value of $J=540\ \text{cm}^{-1}$ for the f-d exchange in Eu^+ is plausible in view of the results of Callahan[12] in the isoelectronic Gd^{++} which yield a value of $J=1013\ \text{cm}^{-1}$. The contraction of the orbitals in the more highly charged Gd^{++} ion would account for this larger exchange.

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MAGNETIC COUPLING BETWEEN TWO ADJACENT TYPE-II SUPERCONDUCTORS

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It is possible for a type-II superconductor to be in a resistive, yet superconductive, state. According to Anderson's[1] flux-creep model, the resistive behavior is associated with the motion of quantized flux vortices (fluxons) present in Abrikosov's[2] theory. This Letter deals with an experiment which shows that it is indeed permissible to interpret literally the voltage drop along a type-II superconductor as arising from the motion of flux.

The experimental arrangement is shown in Fig. 1. First, an Sn film a few thousand angstroms thick is evaporated onto a microscope glass slide. I shall refer to this film as the primary. The center section of the primary is reduced in width by outlining it with a razor blade. Next, a thin film of SiO_2 approximately 100-200 Å thick is evaporated over the primary film. Finally, a second Sn film is evaporated over the SiO_2 layer. I shall refer to this film as the secondary. The secondary film is made as thin as possible, i.e., of the order of 500-1000 Å, and it must be narrower than the primary film. The two metal films are electrically separated by the SiO_2 film, i.e., the measured resistance between them approaches infinity.

The experiment consists of passing a dc current I_P along the primary film and measuring the dc voltage developed both in the primary film V_P and in the secondary film V_S. Because of the narrow section in the center of the primary, the voltage drop in the primary is limited to a short length that is completely paralleled by the secondary. The current and voltage connections are shown in Fig. 1. When both the films are normal, or when the secondary film is in the normal state and the primary film is in the superconducting state, no voltage can be detected in the secondary loop as shown in Fig. 2. However, as soon as both films are superconducting, a dc voltage is seen in the secondary loop as well as in the primary circuit. This behavior is displayed for three different temperatures in Fig. 2. If the primary current is increased such that the film enters the normal state, the primary voltage jumps to a high value (of the order of 0.5 V) while the secondary voltage abruptly drops to zero.

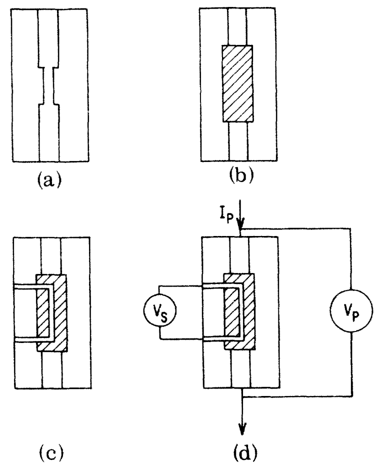

FIG. 1. Sample preparation. (a) An Sn film has been deposited onto a microscope glass slide. (b) A thin insulating layer of SiO_2 is deposited over the primary Sn film. (c) A second layer of Sn has been evaporated over the first two layers. (d) Current and voltage connections to the primary film, and voltage connections to the secondary film.

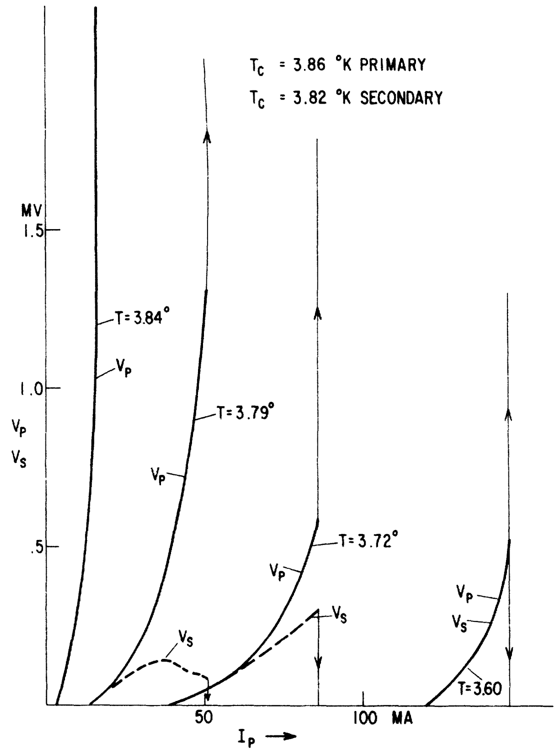

FIG. 2. The voltage measured across the primary V_P and the secondary V_S as a function of the primary current I_P at various temperatures T.

The secondary film is then also in the normal state, i.e., it is heated by the primary. Thus, the curves in Fig. 2 are not strictly isothermal and the indicated temperatures refer to the He bath.

As may be expected, the effect can be varied by an externally applied magnetic field, because the properties of the superconductors themselves depend upon magnetic fields. The experiment is independent of an applied electric field corresponding to an applied voltage of 100 mV between the two Sn films, which eliminates the possibility of any significant direct connection between the circuits. The experimental results are also essentially independent of the polarity of the primary current. By interchanging the role of the primary and the secondary film, the experiment does not work.

This experiment is, of course, consistent with Maxwell's equations, and the result can be explained on the basis of a simple model. Figure 3(a) schematically shows a voltmeter connected to a wire which has magnetoresistance. If a localized field ("flux spot") is made to enter the loop across the magnetoresistive wire, but to leave the loop across an ordinary wire, on the average the voltmeter would register a dc voltage. The time-integrated emf around the loop is equal in magnitude, but opposite in sign, for entry and exit of the "flux spot" and averages to zero, but because of the nonlinear behavior of the magnetoresistive wire, the voltage drop across the voltmeter does not average to zero. Figure 3(b) shows a more sophisticated model consisting of a superconducting film connected to a voltmeter. This is really a version of Volger's[3] unipolar generator. Because the "flux spot" makes the superconducting film normal, i.e., magnetoresistive, and because the voltmeter is always shunted by a superconducting path when flux enters the loop, practically no voltage would be registered on the voltmeter. When the flux leaves the loop, however, it crosses an ordinary wire and now the total emf appears across the voltmeter. Finally, Fig. 3(c) shows a type-II superconductor carrying a current. The simplest way of interpreting the voltage which may be seen on the voltmeter when the superconductor is in the resistive state is to consider "flux rings" to be created on one side of the film and annihilated on the other side. (In a zero applied magnetic field, the "flux rings" would be destroyed in the center of the film.) Both the voltmeter and the superconductor experience a flux-cutting action, the

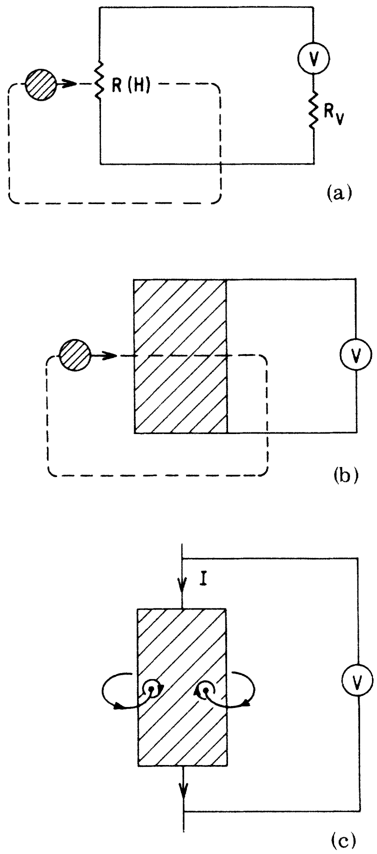

FIG. 3. (a) A loop consisting of a voltmeter with resistance R_V and a magnetoresistive wire with resistance $R(H)$. By moving the "flux spot" as indicated, the voltmeter would register a dc voltage. (b) A superconducting film connected to a voltmeter. Again, by moving the "flux spot" as indicated, the voltmeter would register a dc voltage. (c) It is possible for a type-II superconducting film to be in a superconducting, yet resistive, state. It can support a voltage because fluxons are created on one side of the film and annihilated on the other side.

superconductor by the fluxons and the voltmeter leads by the return paths of the flux. Since the magnetic field far from the superconductor is stationary, it is more common to speak of an electric field rather than the movement of flux, and Josephson[4] has shown that by properly averaging over the moving fluxons, we may adopt this point of view for the superconductor as well. It is interesting to note that we may look upon the voltage drop along an ordinary wire carrying current as being caused by moving flux; however, in that case the model may not be particularly relevant as the flux is not quantized.

By properly combining the two processes described in Figs. 3(b) and 3(c), we obtain the experimental configuration shown in Fig. 1. The secondary loop is equivalent to the unipolar generator of Fig. 3(b) while the primary film supplies the moving "flux spots." Thus, we understand that for the experiment to work, the secondary film must be spaced so close to the primary film that it experiences the moving fluxons rather than an electric field. In practice, this condition requires that the spacing between the films be smaller than the spacing between fluxons. Another necessary condition is that the secondary film is narrower than the primary film, otherwise the edge of the secondary film and the voltmeter leads experience exactly the same electric field, and nothing would happen in the loop containing the voltmeter.

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