# DIRECT EVIDENCE OF STEADY EMF INDUCED BY FLUX MOTION IN SUPERCONDUCTORS

Judea Pearl

Radio Corporation of America, RCA Laboratories, Princeton, New Jersey

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In recent years the phenomenological theory of superconductors in the mixed state has been totally dominated by the model of Abrikosov's[1] flux-line motion. This model implies that when transport currents pass through a superconductor in the mixed state, a force is exerted on Abrikosov's flux lines which causes a uniform motion of the lines at right angles to the current flow. A second implication of the model is that such a continuous motion of flux lines produces a steady potential difference across the superconductor in a direction perpendicular to the flux motion.[2-4]

In spite of its success in explaining a number of transport phenomena, the basic idea of flux motion was repeatedly subjected to severe criticism.[5,6] The origin of the driving force in a system where the magnetic energy is independent of the position of the flux lines is not at all apparent. Likewise, the induction of a steady potential difference in a stationary circuit which encloses a time-independent flux "appears" to be incompatible with the fundamental laws of electromagnetism. These difficulties called for an experiment enabling one to distinguish motion-induced emf's from ordinary Ohmic potential drops and, thus, prove or disprove the postulates underlying the flux-motion model.

In a recent communication[7] the author has proposed a simple scheme for performing such a test. It consists of forcing a continuous motion of flux lines in a currentless superconductor and searching for a steady voltage across it. The purpose of this Letter is to report a positive result obtained with a modified version of the arrangement proposed in Ref. 7, a result that furnishes a direct verification of the existence of steady emf's induced by flux-line motion.

Figure 1(a) shows a schematic view of the experimental arrangement. A permanently magnetized screw is coaxially inserted in a coil made of superconductive ribbon. A cylindrical iron shell provides an easy return path for the magnetic lines and forces the magnetic field at the ribbon to assume a radial direction. At regions of high field intensity, the magnetic field penetrates the ribbon and forms a mixed (or intermediate) state area in alignment with the spiral threads [see Fig. 1(b)]. As the screw rotates around its axis, the mixed-state area tends to stay in alignment with the threads, since this constitutes the lowest energy position for the flux lines. To produce this motion, a force is exerted on the flux lines in the direction of the energy gradient, as shown by the arrows in Fig. 1(b). This motion of flux lines has a component which is transverse to the length of the ribbon, and so a continuous motion of flux lines is established across the superconducting ribbon, and a dc voltage develops between its terminals.

A lead ribbon 12.5 $\mu$ thick and 2 mm wide was employed in the form of a coil with 150 electrically insulated turns. The reasons for using lead lie in its convenient critical temperature and its low pinning to flux-line motion. The voltage measured is independent of whether a mixed state or intermediate state is established, as long as there exists a pattern of current circulation which moves transverse to the ribbon. A copper coil (not shown) was wound on top of the lead and was used to cancel the ac component of the voltage due to irregulari-

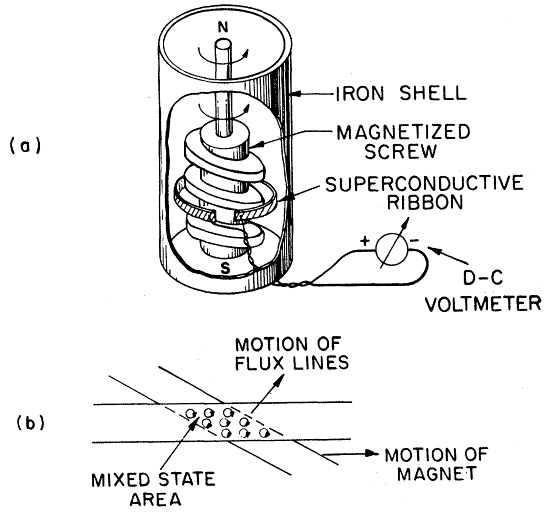

FIG. 1. (a) Schematic of experimental arrangement, showing rotation of magnetized screw inside a superconducting coil. (b) Magnified view of a portion of superconductive ribbon, showing motion of mixed state area and motion of individual flux lines.

ties in the motion. The magnetic field at the threads of the screw measured approximately 200 G.

Rotation speeds ranging from one to five cps were used, and dc voltages roughly proportional to the speed and as high as 100 $\mu$V were measured. A change in the direction of rotation resulted in a corresponding change of voltage polarity. The temperature dependence of the voltage is shown in Fig. 2. As the temperature rises, the voltage increases because the resistance to flux motion decreases and because a larger fraction of the flux is contained in a multiply connected structure. The voltage reaches a peak and then drops to zero at a critical temperature of 6.1°K. At this temperature the whole area facing the magnetized threads becomes uniformly normal and, so, the transverse motion of circulating currents ceases to exist.

In our experimental arrangement the total magnetic flux linking the measuring circuit remains constant in time; we conclude, therefore, that the origin of the observed voltage does not lie in the ordinary Faraday induction, but rather is associated with the hydrodynamics of the superfluid microstructure. When a rotating cylinder is moving in a fluid, a pressure difference develops in the fluid in a direction perpendicular to the cylinder motion. This phenomenon is known as the "Magnus force," and is also believed to be the mechanism underlying our observations. Here, the fluid circulation is provided by the persistent current loops flowing around the individual flux lines (or possibly normal regions), and the observed voltage results from hydraulic pressure difference in the electronic fluid. The hydrodynamical nature of flux line motion has been emphasized before,[8,9] and was also the basis for the calculations of Stephen and Bardeen.[10]

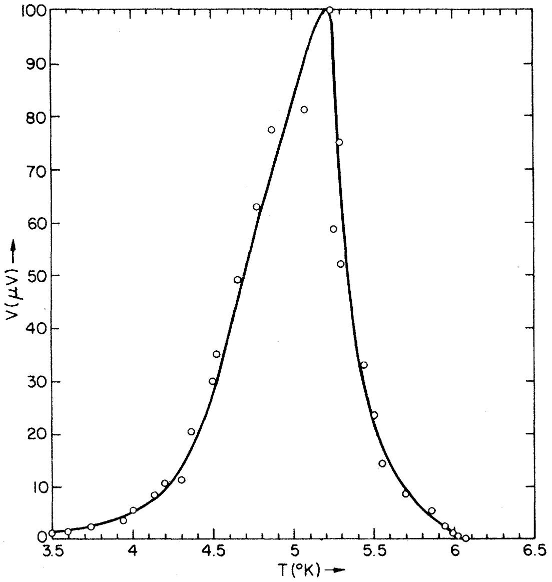

FIG. 2. Temperature dependence of observed voltage (rotation speed = 170 rpm).

Due to friction in the bearing, we were unable to cause rotation of the screw by applying transport current to the ribbon, as was suggested in Ref. 7. Our observation implies (by conservation of energy) the existence of current-induced motion of flux lines, and it seems that one should be able to observe the latter by a simpler experiment, involving no moving parts. If two superimposed superconducting strips, separated by an insulating layer, are placed in a perpendicular magnetic field, then a constant current flowing in one strip should induce a constant voltage in the other. This dc transformer action follows from the fact that current-induced motion of flux lines in one strip exerts a force on the flux lines located in the neighboring strip. If this dragging force is sufficient to overcome pinning due to defects, it will result in a continuous motion of flux lines in the currentless superconductor, which will induce a steady voltage across its length.

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