EXPERIMENTAL PROOF OF MAGNETIC FLUX QUANTIZATION IN A SUPERCONDUCTING RING*

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From theoretical considerations, based on wave mechanics, London[1] concluded that the magnetic flux frozen in in a twofold-connected superconducting body (ring or tube) should not have any arbitrary value, but only such values which are integer multiples of a basic unit ϕ_0,

$$\phi_0 = hc/e = 4.12 \times 10^{-7} \text{ gauss cm}^2. \qquad (1)$$

That means the magnetic flux should be quantized. Bardeen and Schrieffer[2] also agreed with this conclusion.

In order to verify a possible flux quantization, the mechanical torque exerted by a magnetic field H_x on a small superconducting lead tube with frozen-in magnetic flux has been measured.

From the following equation, one obtains the magnetic field H_{y0} necessary to freeze in just one flux unit ϕ_0:

$$H_{y0} = \phi_0 \times (4/\pi d^2), \qquad (2)$$

where d is the diameter of the tube. The diameter has to be chosen sufficiently small that the fluctuations of the earth's magnetic field can be neglected relative to the magnetic field adequate to freeze in one flux unit. This has been achieved with a tube of 10.3-micron diameter and 0.6-mm length (see Fig. 1), which gives a magnetic field of $H_{y0} = 0.5$ oe, according to Eq. (2).

The sample consists of a small lead cylinder, prepared by evaporating lead on a quartz fiber (of about 10-micron diameter and with a length of about 1 mm).
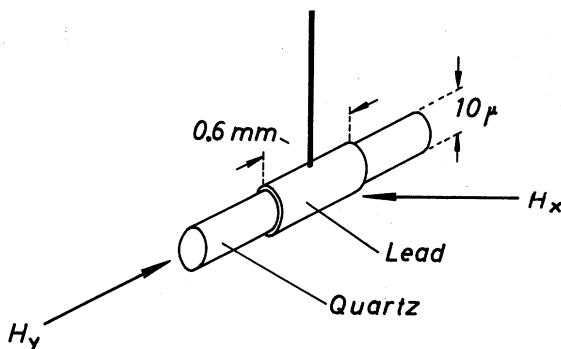

FIG. 1. Schematic diagram of the sample with the directions of the applied field H_y to be frozen in, and the measuring field H_x.

The very small torque, proportional to the frozen-in flux and to the measuring field H_x (normal to H_y), can be observed by an already known auto-resonance method.[3,4] The sample is suspended on a thin torsion fiber (normal to H_y and H_x) inside a coil. In connection with a mirror for recording the oscillation amplitude it represents a system of damped torsion oscillation. The oscillation of the system can be kept at a constant amplitude by the alternating torque, caused by periodically reversing the magnetic field H_x of the coil. The oscillating system itself controls the time of switching the field by means of a photoelectric device. The damping of the system being known, the constant resonance amplitude is a measure for the torque which acts on the sample.

Each experimental value was obtained in the following manner: 1. The sample was heated above the transition temperature; then a defined field to be frozen in, H_y, was applied. 2. After recooling below the transition temperature, H_y was switched off. 3. The resonance amplitude was measured as described above.

The resonance amplitude is proportional to the product (measuring field H_x) times (magnetic moment of the sample). The latter in turn is proportional to the frozen-in flux. Figure 2 shows the measured resonance amplitude divided by the driving field H_x as a function of the field H_y. (H_x has always been about 10 oe.)

As Fig. 2 shows, it is impossible to freeze in any flux between $H_y = -0.1$ and $+0.1$ oe. Near ± 0.1 oe there occur marked steps. Upon increasing the magnetic field H_y, the frozen-in fluxes remain nearly constant between 0.1 and 0.3 oe. At 0.3 oe another step occurs, again followed by a series of constant values.

This is exactly what is expected of a quantized magnetic flux in a twofold-connected superconducting body. If an arbitrary flux could be frozen in, the relation between magnetic flux and field H_y would be as shown in Fig. 2 by the dashed line. This has been obtained by measurements at comparatively high fields ($H_y = 10$ oe), in which case the value of one flux unit is already very small compared with the entire frozen-in flux.

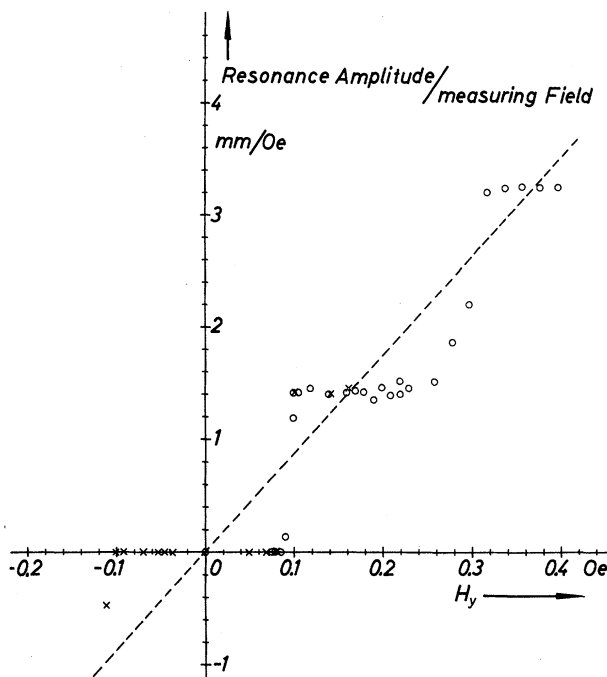With the microscopically measured diameter of

FIG. 2. Resonance amplitude divided by measuring field H_x as a function of the applied field H_y. The ordinate is proportional to the frozen-in flux. ×— First run; o— second run.

the lead tube, Eq. (2) predicts for the interval of the magnetic field strength corresponding to one flux unit a value of $H_y = 0.5$ oe. The experimentally observed interval, however, reaches only 0.2 oe, that is about 40% of the calculated value. So far the reason for this discrepancy is not clear. For example, an error of 60% in the determination of the lead tube's diameter would explain the difference, but such an error is improbable.

The experiments are being continued with higher fields H_y and other superconductors of various diameters.

Mercereau and Vant-Hull[5] also tried to verify London's postulate of the quantization of magnetic flux in a superconducting ring. The result of their experiments was negative.

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EXPERIMENTAL DETECTION OF TRANSITION RADIATION*†

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If an electron approaches the boundary between vacuum and metal, a changing dipole field due to the electron and its image charge is formed which, according to the theory of Ginsburg and Frank,[1] effects the emission of "transition radiation." In the experiment electrons bombarding a metal surface generate a visible radiation known as "Lilienfeld radiation." The results of the experiments done before this work are, however, contradictory.[2-4] Therefore we undertook to exclude by more careful experiments the influence of surface contaminations and to compare the experimental Lilienfeld radiation with the theoretical transition radiation by variation of different parameters.

Our investigations were carried out at pressures of about 10^{-9} mm Hg with massive heatable targets and with condensed films of more than 1 μ thickness. The electron beam was produced by field emission and pulsed with a frequency of 100 kc/sec. The energy of the electrons was in general 2-12 kev. The intensity of the Lilienfeld radiation was measured with a photomultiplier tube and a phase discriminator. The results of our investigations are as follows:

(1) The intensity of the Lilienfeld radiation is independent of the temperature of the target.