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COMPTON WAVELENGTH OF SUPERCONDUCTING ELECTRONS

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The purpose of this Letter is to report a <u>macroscopic</u> determination of the quantum of circulation, h/m, for superconducting electrons, and thus the Compton wavelength, h/mc. This determination was made utilizing a superconducting deBroglie wave interferometer,[1-3] such as previously discussed and used for magnetic flux detection.[4] Here, however, the interferometer is operated in constant applied flux, the interference modulation being introduced by mechanical rotation.

The essential property of the superconducting deBroglie wave interferometer is that the maximum supercurrent flow ($I_{\max}$) through it is a periodic function of the normalized action, $(1/2\hbar)\oint p dq$, where p is the canonical momentum of superelectron pairs, $\vec{p} = 2(m\vec{v} + e\vec{A})$, m and e being the mass and charge of the electron. This interference modulation of the maximum supercurrent can be expressed as[2]

$$I_{\max} = I_0 \left| \cos \frac{1}{2\hbar} \oint p dq \right|,$$

or, evaluating the line integral,

$$I_{\max} = I_0 \left| \cos 2\pi \left(\frac{l}{\hbar} + \frac{e}{h} \Phi \right) \right|,$$

where l is the mechanical "angular momentum" of the electron and Φ the magnetic flux. Experimental confirmation of both mechanical l and electromagnetic Φ modulation have previously been reported. Flux (Φ) modulation has been provided by both a magnetic field[1] and separately by a vector potential alone[4]; mechanical momentum modulation was provided indirectly by a current flow.[2]

In the experiment reported here the flux is held constant and the mechanical momentum provided directly by an actual rotation (Ω) of the circular interferometer ($l = mr^2\Omega$). In terms of this rotation the maximum supercurrent through the interferometer is

$$I_{\max} = I_0 | \cos 2\pi \{ (2m/h)(\pi r^2)\Omega + (e/h)(\pi r^2) B \} |. \quad (1)$$

Measuring the maximum supercurrent ($I_{\max}$) as a function of rotation rate thus yields a direct measure of h/m. This type of measurement was done with a vanadium interferometer[5] with an effective area (πr^2) of 0.074 cm^2 at rotation rates (Ω) ranging up to about 10 rad sec^{-1}. These measurements give a value for h/m of

$$h/m = (7.3 \pm 0.3) \times 10^{-4} \text{ J sec kg}^{-1},$$

and, consequently,

$$h/mc = (2.4 \pm 0.1) \times 10^{-12} \text{ m}.$$

By comparison, the accepted value of the Compton wavelength of the free electron is roughly

$$h/mc = 2.43\times 10^{-12} \text{ m}.$$

This type of experiment is somewhat similar to the Michelson-Sagnac experiments with light. The physical source of the phase shift differs, but the formal expressions are identical.[6] There is also, of course, a direct connection between these quantum effects and the classical London moment.[7,8] In a superconductor the action function [the argument of the cosine in (1)] must be zero, thus connecting a rotation (Ω) to a field (B) as

$$\vec{B} = -(2m/e)\vec{\Omega}.$$

Here B is the internal field generated by the rotation (Ω) of an infinitely long superconducting cylinder.

We believe these experiments serve as an additional demonstration of macroscopic quantum effects in superconductors and provide a direct measurement of the quantum of circulation, h/m, for superconducting electrons.

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RADIAL DEPENDENCE OF ENERGETIC ELECTRON FLUXES IN THE TAIL OF THE EARTH'S MAGNETIC FIELD*

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The NASA scientific satellite IMP-1 has made possible the detection of energetic electron fluxes of terrestrial origin out to a geocentric distance of 31.5 earth radii (about 200 000 kilometers). The major axis of the satellite's orbit changed orientation with respect to the sun-earth line by about one degree per day. The distribution of electron flux >45-keV kinetic energy thus could be determined also as a function of sun-earth-satellite angle. This angle should be extremely important for discussing terrestrial energetic particle fluxes, since the solar wind contains the distant geomagnetic field and aligns it in the sun-earth direction. This tail-like structure of the distant field was indicated by magnetometer measurements on Explorers X[1] and XIV[2] and in greater detail by IMP-1.[3] Beyond 10 earth radii geocentric distance and near the midnight meridian the field lines deviate markedly from dipole-like character. The field lines become aligned with the sun-earth line and show no sign of closing even at $31.5R_e$.[3] Trapping of charged particles, if it takes place at all, occurs on a scale entirely different from the Van Allen region. The purpose here is to describe the general character of energetic electron fluxes in the tail of the geomagnetic field and to show the radial dependence of their occurrence. The results come from thin-window Geiger-Mueller tubes arranged to discriminate against proton and bremsstrahlung counts. Details of this apparatus and some results obtained with it have already been published.[4]

Some observations of energetic particle fluxes near the midnight meridian beyond the Van Allen trapping region have already been reported.[5,4] It was shown that substantial fluxes of energetic electrons frequently occur in these regions at much larger radial distance than they do on the sunlit side of the earth. An example of the Geiger-tube rate near the midnight me-