

Evidence for Aharonov-Bohm Effect with Magnetic Field Completely Shielded from Electron Wave

Akira Tonomura, Nobuyuki Osakabe, Tsuyoshi Matsuda, Takeshi Kawasaki, and Junji Endo

Advanced Research Laboratory, Hitachi Ltd., Kokubunji, Tokyo 185, Japan

and

Shinichiro Yano and Hiroji Yamada

Central Research Laboratory, Hitachi, Ltd., Kokubunji, Tokyo 185, Japan

(Received 4 December 1985)

Evidence for the Aharonov-Bohm effect was obtained with magnetic fields shielded from the electron wave. A toroidal ferromagnet was covered with a superconductor layer to confine the field, and further with a copper layer for complete shielding from the electron wave. The expected relative phase shift was detected with electron holography between two electron beams, one passing through the hole of the toroid, and the other passing outside. The experiment gave direct evidence for flux quantization also.

PACS numbers: 03.65.Bz, 41.80.Dd

The Aharonov-Bohm (AB) effect¹ has recently received much attention as an unusual but important quantum effect.² The predicted effect is the production of a relative phase shift between two electron beams enclosing a magnetic flux even if they do not touch the magnetic flux. Such an effect is inconceivable in classical physics and directly demonstrates the gauge principle of electromagnetism.³

Although the affirmative experimental test was offered⁴ soon after its prediction, Bocchieri *et al.*⁵ and Roy⁶ questioned the validity of the test, attributing the phase shift to leakage fields. The authors' recent experiment⁷ using a toroidal magnet established the existence of the AB effect, under the condition of complete confinement of the magnetic field in the magnet; electron holography confirmed quantitatively the expected relative phase shift between the two beams. Bocchieri, Loinger, and Siragusa⁸ still argued that the phase shift could be due to the Lorentz-force effect on the portion of the electron beam going through the magnet.⁹

The present experiment¹⁰ is designed to provide a crucial test of the AB effect. A tiny toroidal magnet covered entirely with a superconductor layer and further with a copper layer is fabricated. The two layers prevent the incident electron wave from penetrating the magnet. In addition, the magnetic field is confined to the toroidal magnet by the Meissner effect of the covering superconductor. Then the relative phase shift between two electron beams, one passing through a region enclosed by the toroid and the other passing outside, is measured by means of electron holography. The experimental results detected the predicted relative phase shift, giving conclusive evidence for the AB effect. This experiment also demonstrated the flux quantization.¹¹

Tiny toroidal samples were fabricated by use of photolithography. A Permalloy (80% Ni and 20% Fe) thin film, 200 Å thick, was prepared by vacuum evaporation on a silicon wafer covered with Al (3000 Å thick), Nb (2500 Å thick), and SiO (500 Å thick); the SiO layer serves to reduce the coercive force of the Permalloy. After evaporation of a 2000-Å-thick layer of SiO on the Permalloy, the toroidal shape was cut out to the depth of the Nb surface. The NbO produced by the lithography processes at the Nb surface had to be removed to ensure a perfect contact with the Nb layer (2500 Å thick) that was subsequently sputtered on the whole structure (see Fig. 1). The superconducting contact was confirmed by another experiment. We note that the thickness of the upper SiO layer decreased to 500 Å after the ion sputtering.

A toroidal sample with a tiny support bridge (see the scanning electron micrograph in Fig. 2) was then cut so that the Permalloy toroid was completely covered

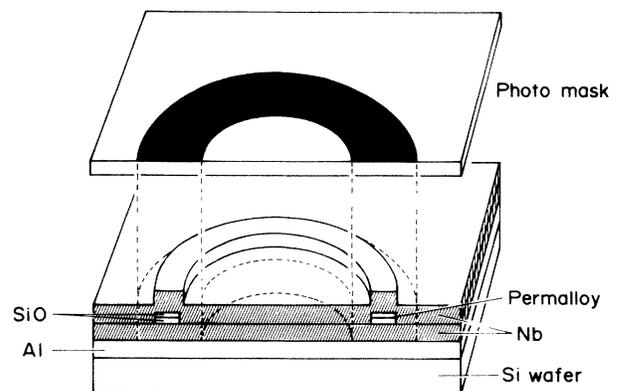


FIG. 1. Schematic diagram for fabrication of the toroidal magnet.

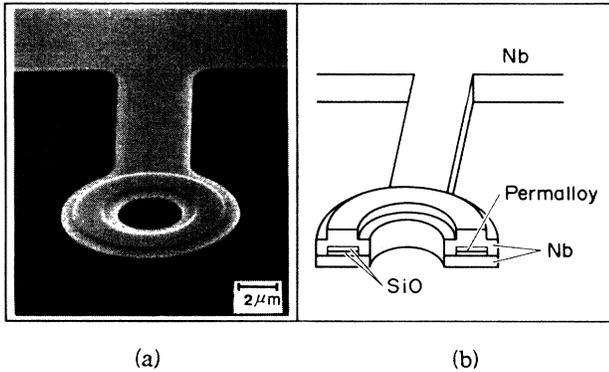


FIG. 2. Toroidal magnet. (a) Scanning electron micrograph; (b) diagram. The toroid is connected to a Nb plate by a tiny bridge for high thermal conductivity.

by the superconducting bulk Nb. The toroidal sample was peeled off the wafer by dissolving the Al in NaOH solution, and was placed on a Cu mesh. Finally, a copper film 500–2000 Å thick was evaporated on all of its surfaces; the film serves to prevent penetration of the electron wave, and to keep the sample from experiencing charge-up and contact-potential effects.

Electron holograms were formed in a 150-kV field-emission electron microscope (wavelength, 0.030 Å) that had a liquid-He-cooled specimen stage attached. The object wave, phase shifted by the sample, and the reference wave were brought together by the electron biprism to form an interference pattern, as shown in Fig. 3. The pattern was enlarged 1000 times by electron lenses and recorded on film as a hologram.

The phase shift due to the sample was reconstructed by means of He-Ne laser light (wavelength, 6328 Å) in the optical system shown in Fig. 4. Two waves, A and B, illuminated the hologram. Each wave produces two diffracted waves, one which reconstructs the phase shift due to the sample, and the other, its conjugate.

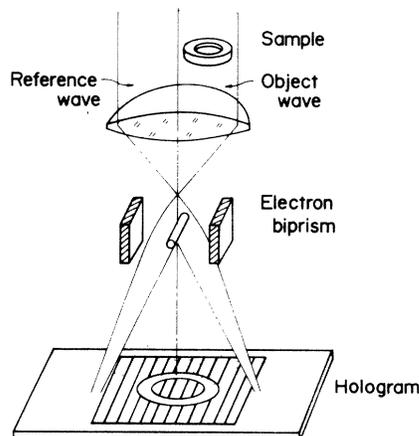


FIG. 3. Electron-optical system for hologram formation.

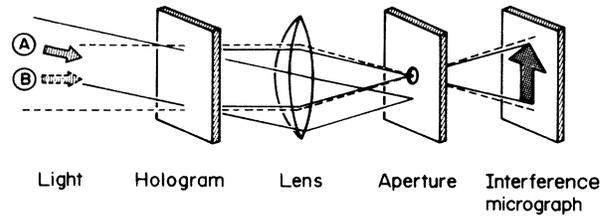


FIG. 4. Optical reconstruction system for interference microscopy.

An interference micrograph is obtained when the reconstructed image of beam A is superposed with beam B after passage through an aperture. Moreover, a twice-phase-amplified interference micrograph¹² is formed when the reconstructed image of beam A and the conjugate image of beam B are superposed by the tilting of beam B.

The leakage fluxes of fabricated samples at room temperature were quantitatively measured¹³ by interference electron microscopy, and only samples with flux less than $h/20e$ ¹⁴ were selected for this experiment. Figure 5 shows an example of a twice-phase-amplified interference micrograph, which indicates a very large leakage flux of $\sim 2h/e$.

Now, the AB effect is the production of a relative phase shift of $\pi\Phi/(h/2e)$ between two electron beams enclosing magnetic flux Φ . The interference micrograph in Fig. 6(a) is clear evidence for the AB effect. Each interference fringe inside the ring, i.e., the image of the toroidal sample, lies just in the middle of two fringes outside the ring. This shows that there is a relative phase shift $n\pi$ (n odd), as expected from the quantized magnetic flux $nh/2e$ enclosed within the superconducting Nb. That the relative phase shift here is an integral multiple of π can be seen precisely from the twice-phase-amplified micrograph obtained from the same hologram [Fig. 6(b)], in which there are no relative displacements between the fringes inside and outside the ring. We emphasize that the magnetic flux is confined within the superconductor and that the

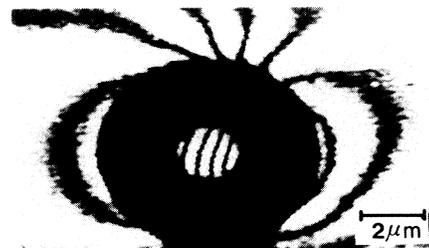


FIG. 5. Leakage fields from a toroidal magnet (phase amplification, 2×). Leakage flux can be quantitatively measured since a constant flux of $h/2e$ flows between two adjacent interference fringes.

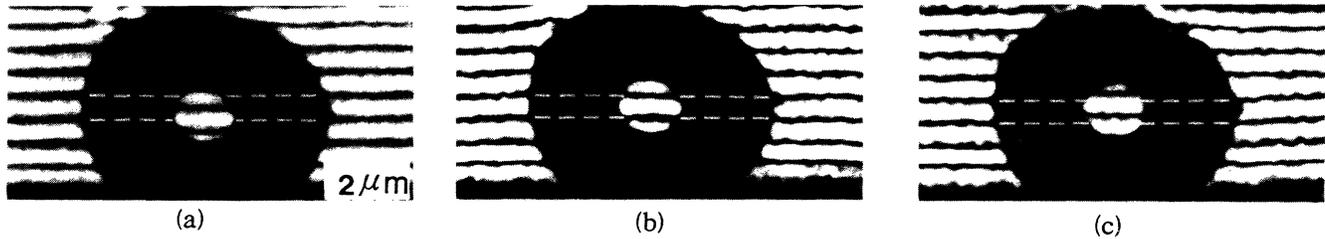


FIG. 6. Interference micrographs of a toroidal magnet at low temperatures. (a) $T = 4.5$ K (phase amplification, $1\times$); (b) $T = 4.5$ K (phase amplification, $2\times$); (c) $T = 15$ K (phase amplification, $2\times$). The enclosed flux is quantized in units of $h/2e$ when $T < T_c (= 9.2$ K). The number of fluxons is odd.

field is shielded from the electron wave by the Cu and Nb covering. It is estimated that the leakage flux is far less than $h/20e$, since the leakage flux at room temperature is less than $h/20e$ and the minimum thickness and penetration depth of Nb are 2500 and 1100 Å, respectively. Only a slight portion, approximately 10^{-6} , of the incoming electron wave is estimated to reach the magnetic field coherently, since a 150-kV electron beam has to penetrate through the Cu (~ 1000 Å) and Nb (2500 Å) layers for it. The sufficient shielding of electron penetration is also supported by the experimental result that the change in the Cu-layer thickness from 500 to 2000 Å had no effect on the interference fringes around the quantized magnetic flux.

If the temperature T of the sample is raised, the interference pattern changes abruptly when T crosses the superconducting critical temperature T_c ; the relative phase shift is no longer an integral multiple of π . In the case of Figs. 6(a) and 6(b), it in fact becomes $(0.32 + n)\pi$ as can be seen from Fig. 6(c). The transition was confirmed to be reversible. This behavior is evidence for the effect of the superconductor that confines the magnet flux quanta below T_c .

Of course, there are cases of even n , in which no relative displacements are observed, as shown in Figs. 7(a) and 7(b). With this sample, the relative displacement can be seen only when its temperature is raised above T_c ; the displacement in Fig. 7(c) represents a relative phase shift of $(0.25 + n)\pi$ (n even).

When the temperature T of the sample was further raised to room temperature, the relative displacement changed by half the fringe spacing in a twice-phase-amplified interference micrograph; this corresponds to the estimated decrease ($\sim 5\%$) in the magnetization of the Permalloy. This temperature dependence supports our view that the relative phase shift is controlled by the magnetic flux of the Permalloy.

The experimental results described above provide crucial evidence for the existence of the AB effect. Furthermore, the quantization of the flux trapped by a superconductor was directly observed with use of the AB effect of an electron beam.

The most controversial point in the dispute over experimental evidence for the AB effect has been whether or not the phase shift would be observed when both electron intensity and magnetic field were extremely small in the region of overlap. Since experimental realization of absolutely zero field is impossible, the continuity of physical phenomena in the transition from negligibly small field to zero field should be accepted instead of perpetual demands for the ideal; if a discontinuity there is asserted, only a futile agnosticism results.

The authors are grateful for the idea for this experiment, which was proposed by Professor Chen Ning Yang of the State University of New York.¹⁵ Also deserving of thanks are Dr. Ushio Kawabe of Hitachi, Ltd., for his advice and stimulation, Mr. Mikio Hirano of Hitachi, Ltd., for his help in preparing samples, and

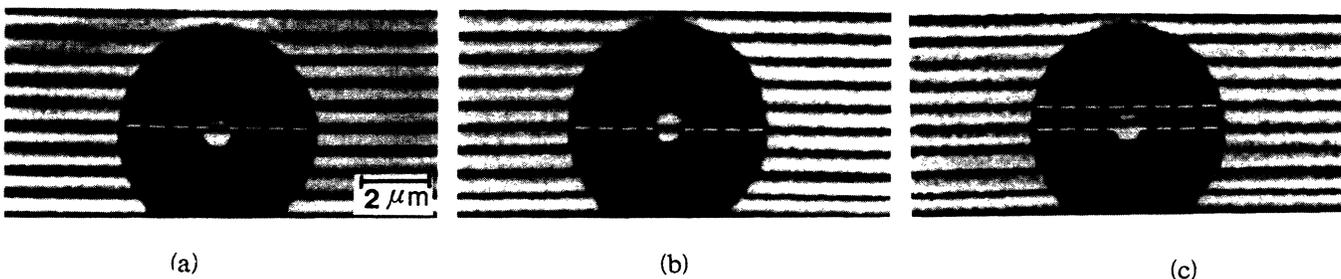


FIG. 7. Interference micrographs of a toroidal magnet at low temperatures. (a) $T = 4.5$ K (phase amplification, $1\times$); (b) $T = 4.5$ K (phase amplification, $2\times$); (c) $T = 15$ K (phase amplification, $2\times$). The number of fluxons is even.

Mr. Shuji Hasegawa of Hitachi, Ltd., for his assistance in the experiment. We also gratefully acknowledge the valuable discussions and advice in preparing this manuscript given by Professor Hiroshi Ezawa of Gakushuin University, and also by Dr. Akira Fukuhara of Hitachi, Ltd. Thanks are due to Professor Ryozo Aoki of Kyushu University for his cooperation in developing a liquid-He-cooled specimen stage.

¹Y. Aharonov and D. Bohm, *Phys. Rev.* **115**, 485 (1959).

²For example, S. Olariu and I. I. Popescu, *Rev. Mod. Phys.* **57**, 339 (1985).

³T. T. Wu and C. N. Yang, *Phys. Rev. D* **12**, 3845 (1975).

⁴R. G. Chambers, *Phys. Rev. Lett.* **5**, 3 (1960); H. A. Fowler, L. Marton, J. A. Simpson, and J. A. Suddeth, *J. Appl. Phys.* **32**, 1153 (1961); H. Boersch, H. Hamisch, K. Grohmann, and D. Wohlleben, *Z. Phys.* **165**, 79 (1961); G. Möllenstedt and W. Bayh, *Phys. Bl.* **18**, 299 (1962).

⁵P. Bocchieri and A. Loinger, *Nuovo Cimento Soc. Ital. Fis.* **47A**, 475 (1978); P. Bocchieri, A. Loinger, and G. Siragusa, *Nuovo Cimento Soc. Ital. Fis.* **51A**, 1 (1979); P. Bocchieri and A. Loinger, *Lett. Nuovo Cimento Soc. Ital. Fis.* **30**, 449 (1981).

⁶S. M. Roy, *Phys. Rev. Lett.* **44**, 111 (1980).

⁷A. Tonomura *et al.* *Phys. Rev. Lett.* **48**, 1443 (1982).

⁸P. Bocchieri, A. Loinger, and G. Siragusa, *Lett. Nuovo Cimento Soc. Ital. Fis.* **35**, 370 (1982).

⁹The phase shift was also detected when the top surface of a toroidal magnet was covered with gold film thick enough to prevent electron penetration. See A. Tonomura *et al.*, in *Proceedings of the International Symposium on Foundations of Quantum Mechanics, Tokyo, 1983*, edited by S. Kamefuchi *et al.* (Physical Society of Japan, Tokyo, 1984), p. 20.

¹⁰A similar experiment using a hollow toroidal superconductor was proposed by C. G. Kuper, *Phys. Lett.* **79A**, 413 (1980).

¹¹The quantization of the trapped flux in a hollow superconducting cylinder has been detected by electron interferometry. See H. Wahl, *Optik* **28**, 417 (1968/1969); B. Lischke, *Phys. Rev. Lett.* **22**, 1366 (1969).

¹²J. Endo, T. Matsuda, and A. Tonomura, *Jpn. J. Appl. Phys.* **18**, 2291 (1979).

¹³A. Tonomura *et al.*, *Phys. Rev. Lett.* **44**, 1430 (1980); T. Matsuda *et al.*, *J. Appl. Phys.* **53**, 5444 (1982); N. Osakabe *et al.*, *Appl. Phys. Lett.* **42**, 746 (1983).

¹⁴Holographic interference microscopy is estimated to be as precise as $\frac{1}{50}$ of a wavelength in an ideal case, which corresponds to a magnetic flux of $h/50e$. See A. Tonomura *et al.*, *Phys. Rev. Lett.* **54**, 60 (1985).

¹⁵C. N. Yang, in *Proceedings of the International Symposium on Foundations of Quantum Mechanics, Tokyo, 1983*, edited by S. Kamefuchi *et al.* (Physical Society of Japan, Tokyo, 1984), p. 27.

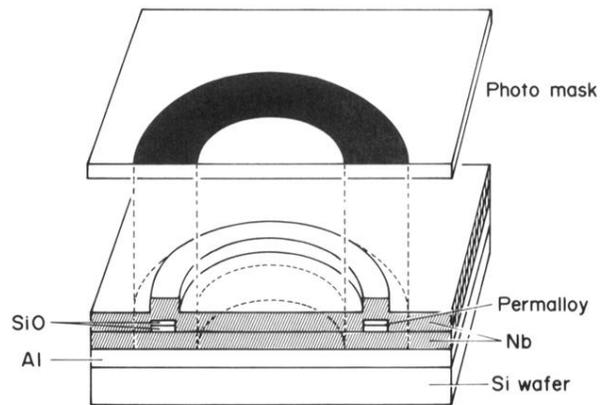


FIG. 1. Schematic diagram for fabrication of the toroidal magnet.

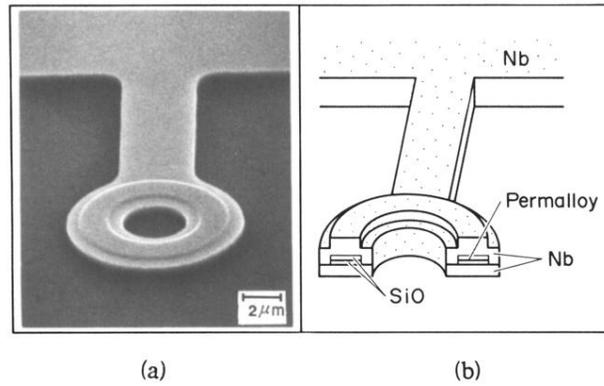


FIG. 2. Toroidal magnet. (a) Scanning electron micrograph; (b) diagram. The toroid is connected to a Nb plate by a tiny bridge for high thermal conductivity.

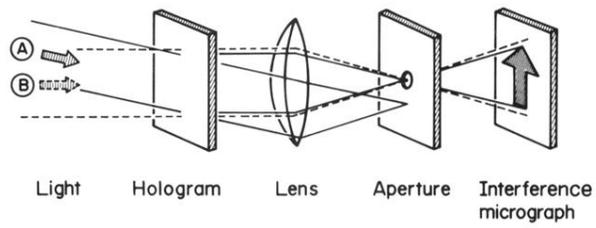


FIG. 4. Optical reconstruction system for interference microscopy.

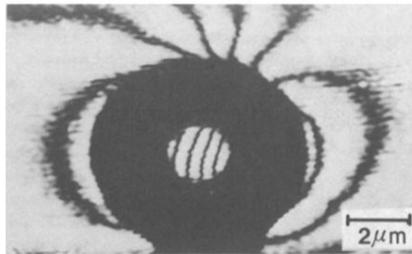


FIG. 5. Leakage fields from a toroidal magnet (phase amplification, $2\times$). Leakage flux can be quantitatively measured since a constant flux of $h/2e$ flows between two adjacent interference fringes.

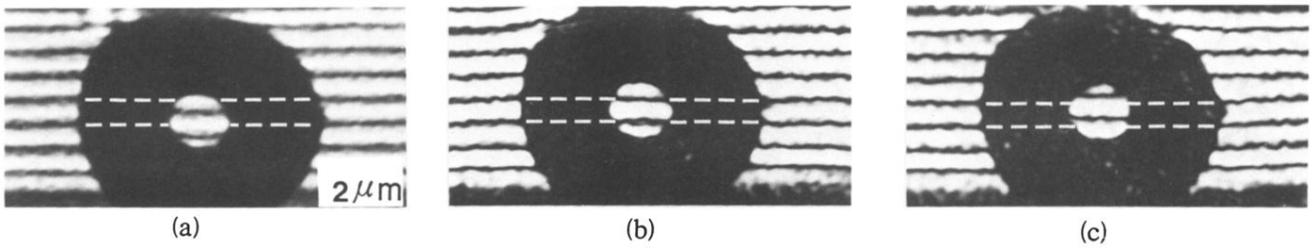


FIG. 6. Interference micrographs of a toroidal magnet at low temperatures. (a) $T = 4.5$ K (phase amplification, $1\times$); (b) $T = 4.5$ K (phase amplification, $2\times$); (c) $T = 15$ K (phase amplification, $2\times$). The enclosed flux is quantized in units of $h/2e$ when $T < T_c (= 9.2$ K). The number of fluxons is odd.

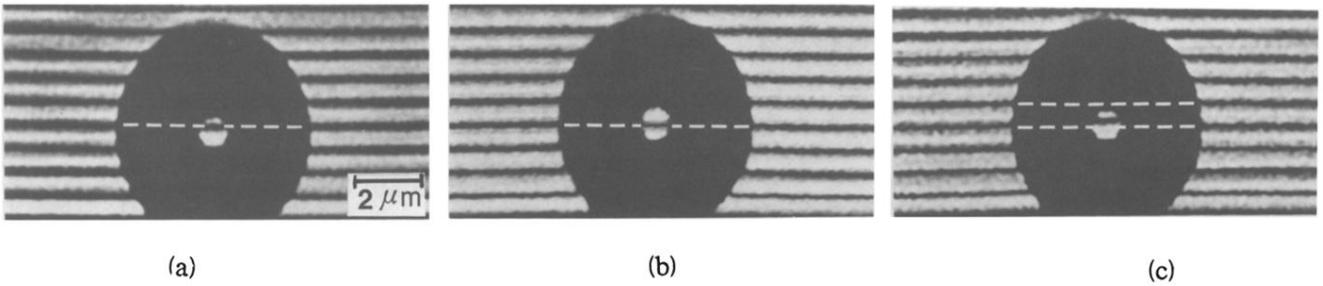


FIG. 7. Interference micrographs of a toroidal magnet at low temperatures. (a) $T = 4.5\ \text{K}$ (phase amplification, $1\times$); (b) $T = 4.5\ \text{K}$ (phase amplification, $2\times$); (c) $T = 15\ \text{K}$ (phase amplification, $2\times$). The number of fluxons is even.