New Diffraction Experiment on the Electrostatic Aharonov-Bohm Effect

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The electrostatic field distribution due to the contact potential difference in a bimetallic wire introduces a quantum phase difference which can be detected in Fresnel and Fraunhofer diffraction experiments by means of an electron microscope.

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In 1959, in an influential paper, Aharonov and Bohm[1] (hereafter referred to as AB) called attention to the significance that electromagnetic potentials have in quantum theory. The authors suggested two interference experiments in order to test their conclusions.

In one of these experiments, two coherent electron beams, coming from the same source, are made to interfere after having traveled through a field-free region. Enclosed between the two beams is a confined magnetic field, which can be generated either by a long thin solenoid or by a hollow superconducting cylinder. It has been shown that the electrons are influenced by the vector potential and suffer a phase difference, which has been detected by electron interference experiments (reviewed by Missiroli, Pozzi, and Valdrè[2]) and recently confirmed by holographic methods.[3]

In the other experiment a coherent electron beam is split into two parts and chopped. Subsequently, each part is allowed to enter a long cylindrical metal tube, the electric potential of which is varied only when the electron wave packets are well inside the tubes. The beams are then recombined to give an interference pattern. This experiment (which has never been carried out) should show a phase difference due to the time-dependent scalar potential even though no force is ever exerted on the electron wave packets.

Since in both proposed experiments electrons do not experience any field and hence any deflection, the two-beam interference experiment will show the displacement of the interference fringes (of an amount proportional to the phase diffference) with respect to the undeflected diffraction envelope.

In 1973 Boyer,[4] in his considerations on the AB effect, noticed that, if the experiment involving time-dependent electric fields is carried out by static potentials, its result will be very similar to that produced in the magnetic AB effect. When electrons enter and leave the tubes they experience classical electrostatic forces, which produce no net change of momentum or energy but only a classical time lag. This can be related to the phase difference $\Delta\phi$ calculated in the WKB approximation[4] through the de Broglie wavelength λ:

$$\Delta\phi = \pi \Delta V l / \lambda E, \tag{1}$$

where ΔV is the potential difference between the two tubes of length l, and E, in the nonrelativistic case, is the accelerating potential.

A different point of view in considering these experiments has recently been expressed by Aharonov,[5] who, in addition to the "true" AB effects (which are defined as type-1 nonlocal phenomena), introduced a new kind of quantum nonlocal phenomenon (referred to as type 2). In the type-2 phenomena the particles experience local interactions with fields (or other forces), which result in a change in their semiclassical action independent of the trajectory, and hence a change of phase for the quantum state of the particle. The electrostatic AB experiment proposed by Boyer can therefore be regarded as a nonlocal type-2 phenomenon.

This same conclusion holds for a new phase-shifting effect we have recently discovered and confirmed by means of electron interferometry experiments carried out with an electron microscope.[6] The aim of this paper is (a) to illustrate this effect and (b) to present new experimental evidence obtained by means of electron diffraction, performed in an electron microscope without having resorted to additional interferometry devices.

The use of the two tubes proposed by Boyer[4] requires a highly sophisticated experimental setup.[7] To overcome these difficulties we have conceived a different and simpler method in which the two tubes are replaced by a circular cylinder of radius a, made up of two parts of different metals C and D [Fig. 1(a)].[6] However, this geometry is not fully respected in the actual realization of the device, since it consists of a thin Wollaston platinum wire (< 1 μm in diameter), mounted on a platinum aperture (several hundred microns in diameter) and vacuum coated on one side with a layer of a different metal (aluminum in the present experiment). Nevertheless, one can expect an

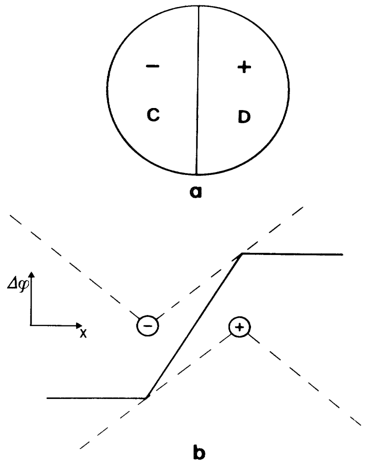


FIG. 1. (a) Schematic representation of the cross section of the bimetallic wire. (b) Phase shifts vs the x direction for a bimetallic wire modeled by two oppositely charged parallel wires.

effect by the following heuristic considerations. Roughly speaking, the contact potential difference causes a charge distribution between the two metals in such a way that the resulting field is equivalent to that produced by two parallel linear charge densities of opposite sign (no net charge on the bimetallic wire) which are laterally displaced one with respect to the other [Fig. 1(b)].

From the theory of the electron biprism[2] (the electric field of which is equivalent to that of a single linear charge density) it is known that the electrons passing on the same side of the biprism suffer a deflection proportional to the applied potential (or to the charge density), and independent of their distance x_0 from the biprism. The x axis is taken perpendicular to the electron beam and to the axis of the bimetallic wire. Moreover, from the wave point of view, the effect of the biprism on the electron wave front is to introduce a phase shift proportional to $|x_0|$.

From the above arguments the bimetallic wire can be modeled by a system of two biprisms of opposite power. Figure 1(b) depicts the influence that each biprism has separately on the phase of the impinging wave front (dashed lines). The resulting phase shift, plotted by a solid line in Fig. 1(b), is simply given by the sum of the contributions from each biprism. Therefore, the deflections produced on the electrons (on the right and the left sides of the system of the two biprisms) are exactly canceled out, whereas a constant phase difference arises because of their separation. In the region between the two biprisms the phase shift varies linearly and the deflections are added. However, this effect cannot be observed as the bimetallic wire can be considered as an impenetrable barrier for the electrons. By rotation of the bimetallic wire around its axis, the distance of the two linear charge distributions as viewed from the electron beam is varied, and hence the phase difference varies.

The above considerations explain the phase-difference effect due to the bimetallic wire, but do not give its magnitude. With the (ideal) geometry of Fig. 1(a), it is possible to calculate the electrostatic field due to the contact potential difference ΔV between the two metals, the electrostatic potential, and the phase difference in the WKB approximation. The result for the maximum phase difference is

$$\Delta\phi = \pi\Delta V 4a/\lambda E. \qquad (2)$$

Thus, the maximum effect of the bimetallic wire is equivalent to that of two tubes of length $4a$. The exact solution for the electrostatic field approaches the model of Fig. 1(b) in the limit $a \to 0$ when $a\Delta V$ is constant.

In order to confirm the predicted effect by means of diffraction methods and without resorting to additional interferometry devices, new experiments were carried out with a Philips model EM400T electron microscope equipped with a field-emission gun at an accelerating voltage of 40 kV. The bimetallic wire was inserted in the specimen position and could be rotated around its axis by $\pm 40°$ by means of the goniometer stage. The objective lens was switched off and the change from the in-focus image of the bimetallic wire to its Fresnel and Fraunhofer diffraction patterns was obtained by variation of the diffraction-lens excitation.

Observations made in the Fresnel mode with large defocus distance showed that the intensity of the interference-fringe system present in the region of the geometrical shadow of the wire, although weak, was high enough to be directly visible on the fluorescent screen.[8] Thus, by rotation of the bimetallic wire it was possible to observe directly the effect of the phase-difference variation as a shift of the interference fringes with respect to the unperturbed shadow edges. The images were recorded on a photographic plate with an exposure time of 10 s.

Some results obtained for three different angles ($-24°$, $0°$, and $24°$), together with the corresponding microdensitometer traces (magnified for the sake of clarity) are shown in Fig. 2.

It may be noticed that in Fig. 2(a) the fringes are symmetrical with a bright central maximum, corresponding to a phase difference of $2n\pi$. Figure 2(b) shows an intermediate case with a somewhat asymmetrical intensity distribution corresponding to a nonintegral fraction of the phase difference. In Fig. 2(c), the pattern is again symmetrical but with a central minimum, corresponding to a phase difference of $(2n+1)\pi$. This case represents the most relevant manifestation of the effect.

By the further lowering of the excitation of the dif-

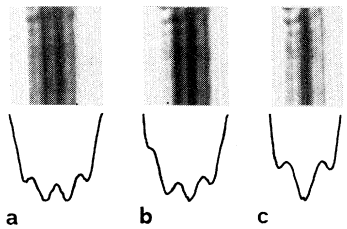


FIG. 2. Fresnel patterns showing the effect of the phase difference introduced by the bimetallic wire on the interference-fringe system present within the shadow image. Rotation angle (a) −24°; (b) 0°; (c) 24°. Microdensitometer traces below the photographs are drawn at higher magnification.

fraction lens, the Fraunhofer image was formed on the screen.[8] The direct observation carried out at a camera length of 100 m showed a bright central spot and two lateral streaks in the direction perpendicular to the wire. Very different exposure times were necessary in order to record the fine structure on the photographic plate. The diffraction images, taken with an exposure time of 10 s in order to record the large-angle contribution, show a series of spots. As it is known their spacing is inversely proportional to the wire diameter and their intensity is related to the constant phase difference. However, because of the high intensity of the direct beam, a large portion of the central area of the diffraction pattern was saturated, preventing the simultaneous recording of the first-order spots.

This is shown in the microdensitometer traces of Fig. 3, which correspond to the same rotation angles of the wire as Fig. 2. It can be ascertained that the patterns in Figs. 3(a) and 3(c) are nearly centrosymmetric, whereas Fig. 3(b) displays a more marked asymmetry according to the theoretical expectations. Unfortunately, we were unable to detect the phase difference between Figs. 3(a) and 3(c) because it was impossible to distinguish relative intensity within the transmitted beam. In addition, a direct comparison between the images was not possible because of the different spacings of the diffraction spots. In fact, the projected wire diameter varied with the angle of rotation because of the ellipsoidal instead of circular shape of the wire.

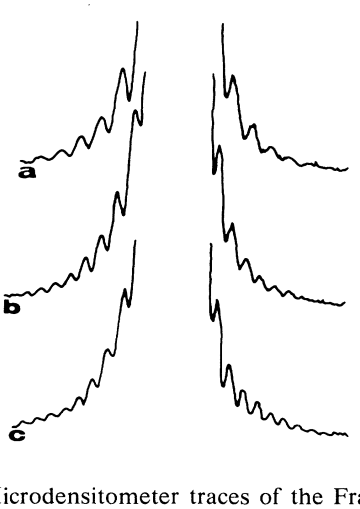


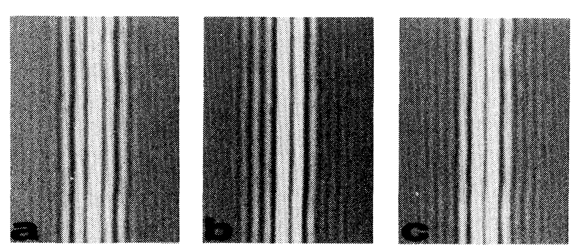
FIG. 3. Microdensitometer traces of the Fraunhofer diffraction patterns of the wire taken at different rotation angles: (a) −24°; (b) 0°; (c) 24°.

The diffraction patterns recorded at a lower exposure time (0.1 s) showed that the central spot was split into two parts and that the bimetallic wire had a net charge.[8] We took advantage of this additional biprism effect to give further evidence of the phase-difference effect. In fact, by a suitable excitation of the diffraction lens it was possible to image the Fresnel region, where the wave functions coming from either side of the wire overlap. The interference phenomena which result are much more striking than those recorded within the shadow image (Fig. 2).

The results from this experiment, reported in Fig. 4, were obtained with the same rotation angles as those of the foregoing figures. The difference of the effect between Figs. 4(a) and 4(c) is particularly evident. In the former, the intensity distribution is symmetrical with respect to a central maximum, whereas in the latter, it is symmetrical with respect to a central minimum.

The above-mentioned results are identical to those obtained by Lischke[9] on the magnetic AB effect, by using an electron biprism formed by a wire covered with a superconducting layer. The magnetic flux trapped within the cylinder caused the phase difference.

We have demonstrated that the electron diffraction patterns produced by a bimetallic wire are strongly affected by a constant phase difference, the amount of which can be varied by rotating the wire around its axis. Our experiments can be considered to be a sim-



(a) (b) (c)

FIG. 4. Fresnel images of the bimetallic wire taken with different angle of rotation (a) −24°; (b) 0°; (c) 24°. The biprism interference fringes are due to the net charge on the wire.

ple and convincing demonstration of the type-2 nonlocal phenomena predicted by Aharonov[5] and can be carried out with a commercial electron microscope and with standard specimen preparation techniques.

This work was stimulated by a remark made by Professor Y. Aharonov at the International Symposium on the Foundations of Quantum Mechanics, held in Tokyo in August 1984. He pointed out that the constant phase difference due to the bimetallic wire is a true quantum type-2 nonlocal phenomena. Useful discussions on the AB effect with Dr. J. Anadan, Dr. H. Lichte, and Dr. A. Tonomura at the symposium are also gratefully acknowledged. We are indebted to Professor U. Valdrè for the critical reading of the manuscript. Thanks are due to Philips Italia for technical assistance with the field-emission gun. This work has been supported by funds of Ministero della Pubblica Istruzione, Italia.

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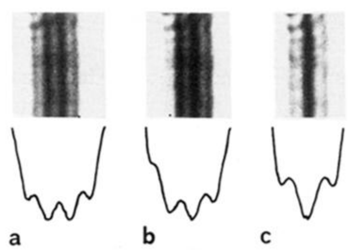

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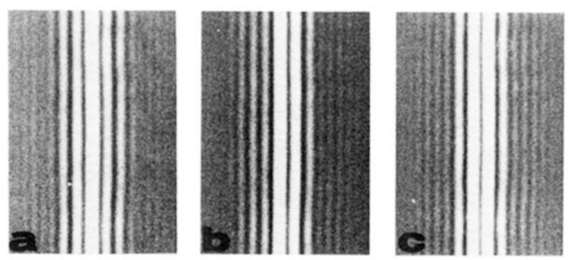

(a) (b) (c)

FIG. 4. Fresnel images of the bimetallic wire taken with different angle of rotation (a) $-24°$; (b) $0°$; (c) $24°$. The biprism interference fringes are due to the net charge on the wire.