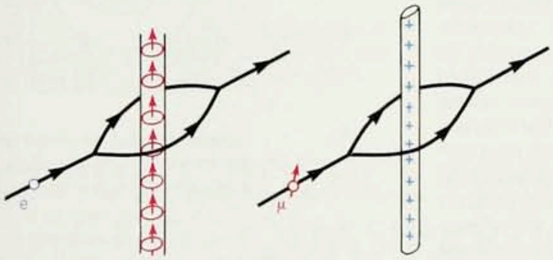
NEUTRONS CANNOT ENCIRCLE LINES OF ELECTRIC CHARGE UNPHASED

Glasses were raised at a conference at the University of South Carolina in December to toast the 30-year-old prediction that gave reality to the magnetic vector potential. According to that prediction, made by Yakir Aharonov (University of South Carolina and the University of Tel Aviv) and David Bohm (Birkbeck College of London University), an electron will experience a phase shift as it encircles an infinitely long solenoid, even though there is no magnetic field—only a vector potential—in the region where it travels. Almost all those who originally doubted this conclusion have long since been persuaded by several elegant experimental confirmations.

Now there may be a possible analog to the Aharonov–Bohm effect: At the recent anniversary conference on the fundamental aspects of quantum theory, researchers described their measurement of a phase shift for neutrons traveling around an extended charged electrode.[1] The experimental team consisted of Alberto Cimmino, Geoffrey I. Opat and Anthony Klein from the University of Melbourne, Australia, and Helmut Kaiser, Samuel Werner, Muhammad Arif and Russell Clothier from the University of Missouri at Columbia. Alfred Goldhaber (State University of New York at Stony Brook) described the experiment as a "*tour de force.*"

To visualize the analog, first note that the magnetic field configuration around a solenoid in the Aharonov–Bohm effect would not be changed if the solenoid were replaced by an infinite chain of magnetic dipoles, stacked end to end. (See the figure on this page.) An electron diffracting around this stack of dipoles will produce an interference pattern because of the different phase shifts induced along paths on either side of the dipole stack. Now interchange the electric charges and magnetic dipoles in that picture. The result is a magnetic dipole diffracting around an infinite line of charge, with the spin of the dipole being parallel to the line of charge.



Switch the charges (blue) and the dipoles (red) in the Aharonov–Bohm effect (left) and you have its "dual" (right). In the former, the different phases acquired along the two paths shift the electron interference pattern. A similar interference occurs for neutral particles with magnetic dipoles (such as neutrons), as shown by a recent experiment done by researchers from the University of Melbourne and the University of Missouri at Columbia. (Adapted from ref. 1.)

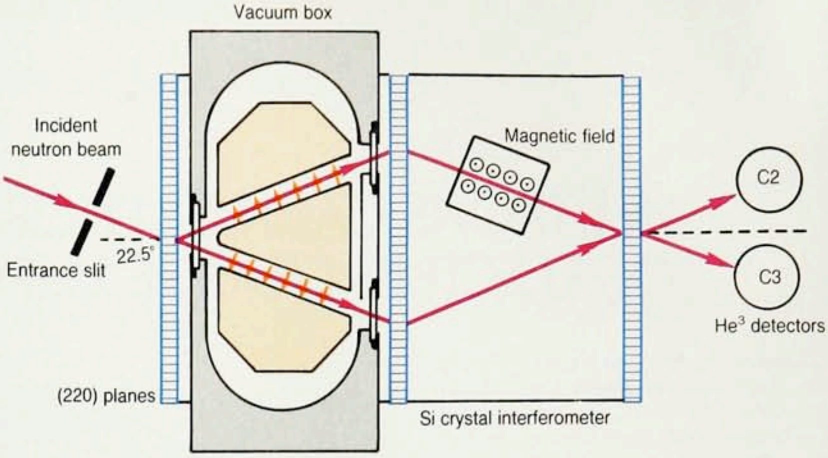
In a 1984 paper,[2] Aharonov and Aharon Casher (University of Tel Aviv) suggested that this interchange would produce an electromagnetic "dual" to the AB effect, and they predicted that polarized neutrons in this situation would manifest a shift in the interference pattern—an effect that has been named after the two theoreticians. In 1982, Jeeva Anandan (now at the University of South Carolina) had calculated[3] the phase shift experienced by neutrons in a more general configuration of electric and magnetic fields. In the AB effect, the phase shift depends on the magnetic flux enclosed by the electron path; in the dual effect, the phase shift should depend on the line charge density enclosed by the path of the magnetic dipole.

In the special case analyzed by Aharonov and Casher, with the neutron spins polarized parallel to the line of charge, the electric field cannot exert a force on the magnetic dipole, even through the magnetic field induced by the relative motion of the neutral particle and the electric field: The dipole, with a magnetic moment μ, is parallel to the induced magnetic field, and the torque on the dipole, which goes as $\boldsymbol{\mu} \times \mathbf{B}$, is zero. If the neutrons have no particular orientation, the force on them in general will be nonzero and the analysis is no longer as clean. Nevertheless a phase shift is still expected.

Detecting the phase shift

The effect was not easy to demonstrate: The Melbourne–Missouri experiment had to detect an extremely small phase shift. For reasonably achieved values of the charge density, the phase shift was predicted to be only 1.5 mrad for the neutron interferometer at Missouri. Even then the collaboration had to enclose as high a charge density as possible within the neutron's path. Because the phase shift depends only on the total charge enclosed and not on its geometry, the researchers substituted a charged central metallic electrode with an electric potential of 45 kV for the simple line of charge shown in the figure above. To accumulate the required number of about 10^7 neutron counts, the team collected data for many months.

The experiment was performed at the University of Missouri Research Reactor with a Bonse–Hart single-crystal silicon neutron interferometer. (See the figure on this page.) The incident neutron beam is diffracted by the first crystal slab and thus splits into two paths traveling around either side of the central electrode. The beams are diffracted again to recombine at the final crystal slab. The outgoing, interfering beams are measured by two He^3 proportional detectors.



Single-crystal neutron interferometer was used by the Melbourne–Missouri collaboration to measure the phase difference between neutrons that traveled two different paths (red) around a 45-kV central electrode (light orange) and recombined. The neutrons were diffracted along this path by slabs of silicon crystal (blue). He^3 proportional counters detected the resulting interference pattern. The top beam went through a magnetic field region, labeled B, whose strength was adjusted to give a value of the phase shift near $\pi/2$. The instrument was tilted so that the gravitationally induced phase shift would cancel any instrumental differences between the two paths. (Adapted from ref. 1.)

Although the AB dual involves polarized neutrons, the Melbourne–Missouri team was able to do the experiment with unpolarized neutrons. They introduced a spin-independent phase shift that could be adjusted to cancel the inevitable small differences in distance along the two paths. By tilting their interferometer so that one neutron traveled at a higher elevation than the other and hence felt a slightly smaller gravitational potential, they produced a gravitationally induced phase shift that compensated exactly for the experimental offset. This maneuver enabled the experimenters to use polarized neutrons.

The experimenters added one more phase shift—this one a spin-dependent phase shift introduced by a bias magnetic field parallel to the line charge. The field, which affected only one of the two neutrons, made the spin-dependent phase shift close to $\pi/2$ or $3\pi/2$, at which value the interferometer would have the greatest sensitivity because the count rate would be linearly proportional to the small additional phase shift from the electric field. Throughout the experiment, the polarity of the central electrode was periodically reversed. The phase shift measured in this experiment was 2.19 ± 0.52 mrad, about 50 percent higher than the value predicted theoretically.

Werner told us that the group's current agenda includes experiments to show that the phase shift is purely topological and does not depend on the particular orbit and to demonstrate that the phase shift is independent of the velocity of the neutrons. The experimenters would like to test the prediction that the phase shift depends on the line charge density, but that may be difficult, as they now are operating at the highest possible voltage to make the phase shift measurable.

Interpreting the results

While the AB effect is not predicted classically, it is a direct consequence of quantum mechanics, which expresses the phase of the wavefunction for a charged particle in terms of the line integral of the vector potential along the particle's trajectory.[4] Nevertheless, Aharonov and Bohm encountered considerable skepticism when they first pointed out this counterintuitive effect, because it challenged the prevailing view of the magnetic vector potential. Before the AB effect was predicted, many felt that the vector potential, though a useful concept, could not have a measurable effect because it is not uniquely determined. As long as the charged particle travels a closed path, however, the arbitrariness of the potential function cancels out of the calculated phase shift. Several experiments in the early 1960s measured the AB phase shift. But doubts lingered until 1986, when Akira Tonomura and his colleagues at Hitachi in Tokyo did an experiment[5] with a toroid that was shielded by a superconducting material to confine the field inside. That experiment removed all possible loopholes for alternative interpretations.

In the magnetic-dipole counterpart to the AB effect, the $\boldsymbol{\mu} \times \mathbf{B}$ term in the momentum gives rise to a phase shift that is analogous to that caused by the vector potential in the AB effect. But, if this counterpart had been uncovered first, it probably would not have caused as much stir as the AB effect did because it does not illustrate as clearly the role of electromagnetic potentials or, more generally, gauge potentials. In fact, some debate still continues over the interpretation of this more complex effect involving neutral particles with magnetic dipoles. One vocal critic is Timothy Boyer (City College of the City University of New York). He analyzes[6] the effect in terms of the purely classical force equal to $\nabla(\boldsymbol{\mu}\cdot\mathbf{B})$. This force can differentially affect the velocities of the neutron beams on either side of the line of charge, leading to a delay of one wave packet relative to another and thus giving rise to the observed phase shift, Boyer asserts. He feels that the AB effect stems from a similar shift in velocities and points out that energy is not conserved in the approach taken by Aharonov and Bohm.

In 1988, Aharonov and some colleagues showed that there is a hidden momentum term, due to which the net force on the neutron encircling a line of charge is zero.[7] Goldhaber has also argued that Boyer is not using the correct force law, and that in fact $\nabla(\boldsymbol{\mu}\cdot\mathbf{B})$ is not conservative.[8] He asserts that the force should be found as the time derivative of the kinetic momentum, which has, in addition to the canonical momentum, a second term equal to $\boldsymbol{\mu} \times \mathbf{E}/c$; this term represents the electromagnetically induced momentum localized on the magnetic dipole. When both terms are considered, the local force is zero and the second term plays the same role as the vector potential term in the AB effect.

Generalizing the effect

Goldhaber and Anandan independently have observed that the motion of a nonrelativistic neutral particle with spin through a classical Maxwell field is identical to that of a spinless particle carrying isospin in the presence of a particular classical Yang–Mills field. Goldhaber feels that this analogy is interesting both pedagogically, because it gives a way to visualize the influence of this new kind of field in more familiar terms, and computationally, as the non-Abelian gauge invariance permits transforming the equations of motion in ways that simplify their solution.

Anandan has covariantly generalized the effect to include magnetic as well as electric fields.[9] In his generalization not only does the $\mu \times \mathbf{B}$ term play the role of the vector potential, as in the counterpart to the AB effect, but the $\mu \cdot \mathbf{B}$ term takes the part of the phase shift from the electric scalar potential.

—BARBARA GOSS LEVI

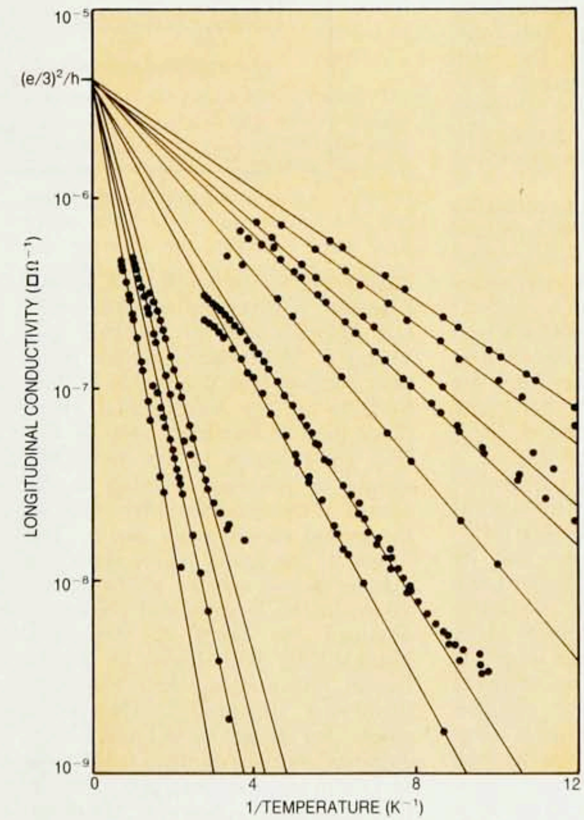
References

1. A. Cimmino, G. I. Opat, A. G. Klein, H. Kaiser, S. A. Werner, M. Arif, R. Clothier, Phys. Rev. Lett. **63**, 380 (1989).
2. Y. Aharonov, A. Casher, Phys. Rev. Lett. **53**, 319 (1984).
3. J. Anandan, Phys. Rev. Lett. **48**, 1660 (1982).
4. R. Feynman, R. B. Leighton, M. Sands, *The Feynman Lectures on Physics, Vol. II*, Addison-Wesley, Reading, Mass. (1964), p. 15.
5. A. Tonomura, N. Osakabe, T. Matsuda, T. Kawasaki, J. Endo, S. Yano, H. Yamada, Phys. Rev. Lett. **56**, 792 (1986).
6. T. H. Boyer, Phys. Rev. A **36**, 5083 (1987).
7. Y. Aharonov, P. Pearle, L. Vaidman, Phys. Rev. A **37**, 4052 (1988).
8. A. S. Goldhaber, Phys. Rev. Lett. **62**, 482 (1989).
9. J. Anandan, Phys. Lett. A **138**, 347 (1989).

EXPERIMENTS PROVIDE EVIDENCE FOR THE FRACTIONAL CHARGE OF QUASIPARTICLES

In the fractional quantum Hall effect, the Hall conductance is quantized. In the most common manifestation of the effect, which was first observed in the two-dimensional electron gas sandwiched between the semiconducting layers of a GaAs–AlGaAs heterostructure, the magnetic field dependence of the Hall resistance shows an ascending-staircase-type behavior with increasing field strength. The steps in the staircase correspond to Hall conductance values of the form $(p/q)e^2/h$, and they occur around the magnetic field values for which the number of electrons per magnetic field quantum is p/q, with p and q integers and q usually odd.

The Hall conductance of a two-dimensional electron gas in a strong magnetic field is quantized, according to the theory of the effect developed by Robert Laughlin (Stanford), because the ground-state energy of such a gas has minima at magnetic field values corresponding to q/p flux quanta per electron—that is, at field values at which the steps in the Hall conductance occur. For magnetic field values between the steps in the Hall conductance, however, the electron gas, according to the Laughlin theory, has the intriguing feature that it may be described in terms of excitations, or quasiparticles, with a charge that is a rational fraction of the electron charge $-e$. (The excitations are about the minimum-energy states, called the incompressible quantum liquid states—which occur, as already pointed out, at field values corresponding to q/p flux quanta per electron.) Specifically, as discussed by Duncan Haldane (University of California, San Diego), for magnetic field values near a p/q step, the electron gas may be described in terms of quasiparticles or quasiholes of charge $\pm e/q$.



Intercepts of the longitudinal conductivity at infinite temperature have the value $(\frac{1}{3}e)^2/h$ for magnetic fields near the Hall conductance steps $\frac{2}{3}$, $\frac{4}{3}$ and $\frac{5}{3}$ in several high-mobility samples. Similar data[1] for Hall steps p/q with $q = 5, 7$ and 9 give a value of $(e/q)^2/h$ for the intercept. At integer steps, where the transport is by electrons, the intercept is e^2/h. The q dependence provides striking evidence that the charge transport occurs through quasiparticles of charge $\pm e/q$. (Courtesy of Robert G. Clark, University of Oxford.)

Three experiments in the past two years have provided evidence for the fractional charge of quasiparticles. Two of those experiments probed the behavior of the longitudinal resistance (the resistance in the direction of the applied electric field) at magnetic field values in the vicinity of the steps, because the quasiparticles are expected to be responsible for the transport of charge at those field values. The third experiment probed electron transmission and reflection coefficients between two adjacent samples of the two-dimensional elec-