letters

Aptly named Aharonov–Bohm effect has classical analogue, long history

Writing about what is usually termed the Aharonov–Bohm (AB) effect, Peter Sturrock and Timothy Groves argue (PHYSICS TODAY, April 2010, page 8) that the same physics was discovered a decade earlier[1] and should rightly be called the Ehrenberg–Siday effect. I agree that Werner Ehrenberg and Raymond Siday deserve recognition for their anticipation of AB. Indeed, in recent talks celebrating the 50th anniversary of AB, I began by describing the unfairly neglected paper by Ehrenberg and Siday. Nevertheless, I have come to a different conclusion from Sturrock and Groves: The expression "Aharonov–Bohm effect" is justified, for two reasons.

First, although there is no doubt that the work by Ehrenberg and Siday anticipated how inaccessible magnetic flux can influence electron interference, that was as a curiosity, at the end of a paper whose main emphasis was the Hamiltonian analysis of electron optics. By contrast, Yakir Aharonov and David Bohm emphasized from the start, as an essential and general aspect of quantum mechanics, the physical influence of inaccessible fields that act nonlocally through the vector potential.

Second, Ehrenberg and Siday's semiclassical approximation—essentially applying the Dirac magnetic phase factor to electrons traveling on either side of the flux—implies a wavefunction that is multivalued and therefore not the correct solution of Schrödinger's equation. The lack of a single-valued wavefunction leaves their prediction open to doubt. By contrast, Aharonov and Bohm derived the exact single-valued solution for waves scattered by a flux line. Recently, it was shown that the Ehrenberg–Siday approximation corresponds to the first terms in a "many-whirls" representation that treats the exact AB wavefunction as a topological sum over paths circling the flux.[2]

Attribution of credit is a delicate matter. It tends to excite strong feelings, and I write about it reluctantly. But the Ehrenberg–Siday paper does seem to exemplify the unfortunate phenomenon identified by Alfred North Whitehead in a 1916 address to the British Association for the Advancement of Science: "Everything of importance has been said before, by someone who did not discover it."

In a companion letter in the April 2010 issue, Alexander Ershkovich correctly points out that the AB effect is present in classical Hamiltonian mechanics, even though remote magnetic fields cannot influence Newtonian trajectories. He advocates a "search for experiments that might prove . . . a classical analogue of the Aharonov–Bohm effect." Such an experiment exists already. In the classical physics of waves on a moving medium, the flow velocity acts like the vector potential in quantum mechanics, so the flow vorticity acts like the magnetic field; the analogy is precise. Fine details of the AB wavefunction were observed in ripples on the surface of water swirling irrotationally into a bathtub vortex,[3] whose core is the analogue of inaccessible magnetic flux.

References

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2. M. V. Berry, *J. Phys. A* (in press).
3. M. V. Berry, R. G. Chambers, M. D. Large, C. Upstill, J. C. Walmsley, *Eur. J. Phys.* **1**, 154 (1980).

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I am an author of the 1961 paper that first called the Aharonov–Bohm effect by that name.[1] The term has since appeared in more than 1000 published papers. However, it has been suggested a few times, most recently by Peter Sturrock and Timothy Groves, that the name does not do justice to Werner Ehrenberg and Raymond Siday, who found in 1949 that the motion of electrons can be influenced by magnetic fields confined to regions that the electrons do not enter.[2] I argue that the name Aharonov–Bohm effect is appropriate, although for a reason that I did not fully appreciate in 1961.

The 1959 Aharonov–Bohm paper profoundly changed the way we think about electromagnetic fields in quantum mechanics.[3] The gauge-invariant part of the vector potential was promoted to a real physical field, not just a convenient device for summarizing certain information about the electric and magnetic fields. In the words of C. N. Yang, "The electromagnetic field strength $f_{\mu\nu}$ in quantum mechanics underdescribes electromagnetism, as the Bohm–Aharonov effect demonstrates . . . information about the phase factor $\exp[ie\oint(\mathbf{A}\cdot dx)/\hbar_c]$ for all closed loops correctly describes electromagnetism."[4]

A century earlier, James Clerk Maxwell changed the way we think about action at a distance by identifying what we now call the Maxwell fields as real physical things that contain energy and momentum and that enable microscopic conservation laws; they are not just mathematical functions that summarize the necessary information about the past motions of charges.

Later those physical fields had to be quantized. Yakir Aharonov and David Bohm found that in quantum mechanics the Maxwell fields in a multiply connected region do not contain all the physics; the vector potential must also be endowed with reality to make sense of the subtler interactions in quantum mechanics.

Neither Aharonov and Bohm nor Ehrenberg and Siday were the first to observe that magnetic fields in places where a charged particle's wave function vanishes may influence the motion of that particle.[5] Paul Dirac, in his 1931 paper on magnetic monopoles, noted that the electron's wavefunction must vanish on singular flux lines but said nothing about that raising any question

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