letters

More variations on Aharonov–Bohm

Having read "The Aharonov–Bohm Effects: Variations on a Subtle Theme" by Herman Batelaan and Akira Tonomura (PHYSICS TODAY, September 2009, page 38), we note with some dismay that the principal effect, that related to magnetic flux, continues to be attributed to its re-discoverers rather than to the original discoverers. Batelaan and Tonomura write, "The AB effect was already implicit in the 1926 Schrödinger equation, but it would be another three decades before theorists Yakir Aharonov and David Bohm pointed it out."[1] That is incorrect: It took only two decades before the effect was pointed out, not by Aharonov and Bohm but by Werner Ehrenberg and Raymond "Rory" Siday.[2] Aharonov and Bohm cited that prior publication in their second article.[3]

According to Bohm's biographer F. David Peat, "After their first paper had been published, Bohm learned that the effect had already been postulated by a maverick physicist called Rory E. Siday."[4] It seems curious that the biographer should use the term "postulated" rather than "proposed" and that he should comment on Siday's personality but not on Ehrenberg's. One of us (Sturrock) knew them both: Raymond was very smart but somewhat brash; Werner was erudite and a model of propriety, who would never have subscribed his name to an article unless he was convinced it was correct.

It seems that the main scientific, rather than sociological, reason that the AB proposal was taken more seriously than the ES proposal is that the former was presented in the context of quantum mechanics, the latter in the context of electron optics. Aharonov and Bohm made a rapid transition from quantum mechanics to wave theory. Ehrenberg and Siday made a more detailed transition from geometrical optics to wave theory. For the case of magnetic flux, the two articles presented identical theoretical predictions. Our view is that the ES article was tedious but conceptually sound, whereas the AB article was lively but involved a questionable conceptual leap—namely, a relativistic generalization based on a noncovariant analysis.

Soon after Sturrock arrived at Stanford University in 1955, and before the Aharonov–Bohm publication, he asked Leonard Schiff, Stanford's quantum mechanics expert, whether Schiff found the Ehrenberg–Siday proposal convincing. He did.

In the interests of accuracy and of giving credit where credit is due, we think it would be appropriate to use "Ehrenberg–Siday effect" for the case of magnetic interference and to reserve "Aharonov–Bohm effect" for electrical interference.

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References

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3. Y. Aharonov, D. Bohm, *Phys. Rev.* **123**, 1511 (1961).
4. F. D. Peat, *Infinite Potential: The Life and Times of David Bohm*, Addison-Wesley, Reading, MA (1997), p. 192.

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The article about Aharonov–Bohm effects is interesting and comprehensive. The primary and best-known effect shows that the vector potential **A** of the electromagnetic field is a physical reality rather than a mathematical artifice. That reality was implicit in the Schrödinger equation, as the Hamiltonian H depends on **A** instead of the electric field **E** and magnetic field $\mathbf{B} = \nabla \times \mathbf{A}$. But the same statement also refers to the Hamilton–Jacobi equation in classical mechanics, so one may expect that a similar effect exists in classical physics as well.

Indeed, classical mechanics is governed by the fundamental Hamilton–Jacobi equation for the action S: $\partial S/\partial t + H = 0$, which naturally follows from William Hamilton's principle of least action. Both H and S depend on **A** (even with $\mathbf{E} = \mathbf{B} = 0$). Thus it is quite possible that the vector potential is also a physical reality in classical physics. Erwin Schrödinger arrived at his famous equation in 1926 by using a mechanics–optics analogy, the so-called eikonal equation. Hamilton in 1834 proved that eikonal and Hamilton–Jacobi equations are equivalent, so that the Schrödinger equation actually follows from Hamilton–Jacobi.

Had Hamilton known that classical mechanics does not always hold, quantum mechanics might have appeared a century earlier.[1] The analogy between the equations of classical and quantum mechanics provides a reason to search for experiments that might prove whether a classical analogue of the Aharonov–Bohm effect exists.

Reference

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The article by Herman Batelaan and Akira Tonomura on the Aharonov–Bohm effect brought back memories of a conference I attended at the University of South Carolina in 1989 commemorating both the 30th anniversary of the Aharonov–Bohm paper and the 5th anniversary of the 1984 paper by Michael Berry that introduced the geometric, now known as the Berry phase.

David Bohm, Yakir Aharonov, and Berry were all present. I particularly recall a plenary talk given by Bohm. In it, he expressed astonishment that certain physicists refused to accept the AB effect and even went to great lengths to try to disprove it. As he said, "It would be much more revolutionary for this effect to be wrong than for it to be right," since it was a clear consequence of fundamental quantum mechanics.

I considered his remark very Bohmian, in that (a) no one else would have said it that way, and (b) once uttered, it was obviously true. Bohm's habit, in his soft-spoken way, of making such blindingly original statements is one of the things I most remember about this unorthodox and profound thinker.

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Batelaan and Tonomura reply: Werner Ehrenberg and Raymond Siday did propose the magnetic version of what is now called the Aharonov–Bohm (AB) effect,[1] as Peter Sturrock and Timothy Groves point out. We had included this reference in the early versions of our manuscript. However, limited space directed the focus of the paper to the "effect without a force" discussion, rather than a historic perspective.

Alexander Ershkovich notes that in the Hamilton–Jacobi formulation of classical mechanics, both the action and the Hamiltonian depend on the vector potential; he ponders whether the AB effect might have a classical manifestation. Newton's formulation of classical mechanics is equivalent to the Hamilton–Jacobi formulation. Because the absence of a field means the absence of a force in Newton's formulation, classical trajectories are unaffected. That result is not expected to change in the equivalent Hamilton–Jacobi formulation. Thus the AB effect is usually considered to be a pure quantum effect. On the other hand, we may interpret "classical mechanics" in a broader sense, such as in general relativistic classical mechanics. In electrodynamics classical trajectories are not affected by a localized magnetic field through which they do not pass. However, considering that the energy content of a current-carrying solenoid is larger than that of one without current, the trajectory is clearly affected gravitationally, at least in principle. Though not due to the AB effect, that result elucidates that a generalized description may lead to other insights. The Hamilton–Jacobi equation may be an example of a theoretical vehicle by which to explore generalizations such as relativistic effects, separation of variables, multiple particle effects, or the classical limit of the de Broglie–Bohm theory.

C. Alden Mead recollects interesting statements made by Bohm. We agree fully with Bohm's statement that "it would be much more revolutionary for this effect to be wrong than for it to be right." Attempts to disprove the AB effect should be seen for what they are, outright attempts at finding limits to the validity of quantum mechanics itself. And although quantum mechanics is unfinished with respect to, say, decoherence theory and quantum gravity, the AB effect appears to be well within its validity range.

We do not share Bohm's astonishment that, as Mead relates, "certain physicists refused to accept the AB effect and even went to great lengths to try to disprove it." Rather, to risk overusing a platitude, extraordinary phenomena should be exposed to extraordinary scrutiny. Failed attempts to disprove an idea often provide insight into its fundamental character. In that context, we reiterate the main message of our article. Many facets of the AB effect—for example, the electric version, the dispersionless nature, relativistic momentum conservation, the relation to the Mott–Schwinger effect, and the AB effects for other than electromagnetic gauge-invariant theories—need exploration. We predict a bright future for the AB effect, with many surprises to come.

Reference

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Tools, trophies in interactive learning

The article by Edward Prather, Alexander Rudolph, and Gina Brissenden (PHYSICS TODAY, October 2009, page 41) makes several interesting points regarding the effectiveness of interactive learning environments in introductory astronomy courses. Yet two serious points regarding the instrumentation