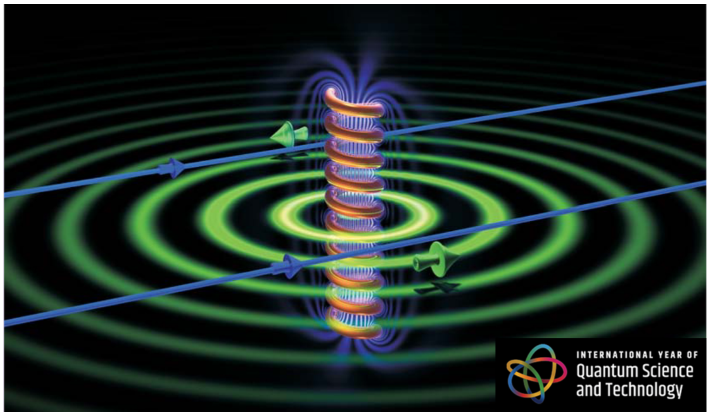
Quantum Milestones, 1959: Ghostly Influence of Magnetic Field

Aharonov and Bohm proposed a scenario in which quantum particles experience electromagnetic effects even though there is no field in their immediate vicinity.

By **David Lindley**

For the International Year of Quantum Science and Technology, we are republishing stories on the history of quantum physics from the archives of Physics Magazine and APS News. *The original version of this story was published in* Physics Magazine *on July 22, 2011.*

A 1959 *Physical Review* paper claimed that an electric or magnetic field could influence quantum particles even though the particles never experienced the field directly [1]. In classical electromagnetism there is no other way to influence a particle besides direct contact with the fields. Even though quantum mechanics was well established by then, the idea met with widespread skepticism. Arguments over the theoretical analysis and attempts at experimental verification continued for some years, but eventually the so-called Aharonov-Bohm effect took its place as a legitimate demonstration of unexpected physics in the quantum world.

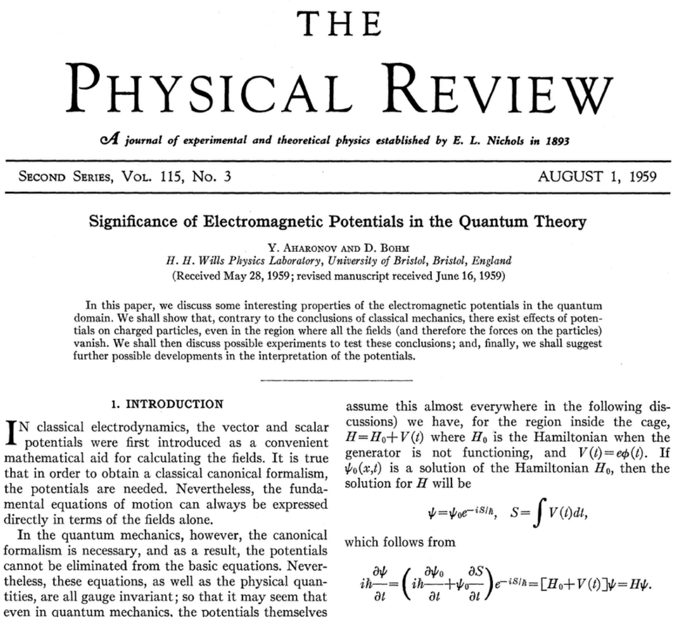


Electrons passing around opposite sides of an electromagnet feel negligible magnetic fields (purple), but the electromagnetic potential (green circles and arrows) affects them in opposite ways, leading to measurable consequences. Before the effect was proposed, physicists thought fields must interact directly with particles to cause measurable electromagnetic effects.
Credit: Physics Today 62, 38 (2009)/AIP

In classical electromagnetism, electric and magnetic fields are the fundamental entities responsible for all physical effects. There is a compact formulation of electromagnetism that expresses the fields in terms of another quantity known as the electromagnetic potential, which can have a value everywhere in space. The fields are easily derived theoretically from the potential, but the potential itself was taken to be purely a mathematical device, with no physical meaning.

In quantum mechanics, shifts in the electromagnetic potential alter the description of a charged particle only by shifting its phase—that is, by advancing or retarding the crests and troughs in its quantum wave function. In general, however, such a phase change does not lead to any difference in the measurable properties of a particle.

But in 1959 Yakir Aharonov and David Bohm of the University of Bristol, UK, devised a thought experiment that linked the potential to a measurable result. In their scenario, a beam of



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Significance of Electromagnetic Potentials in the Quantum Theory

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In this paper, we discuss some interesting properties of the electromagnetic potentials in the quantum domain. We shall show that, contrary to the conclusions of classical mechanics, there exist effects of potentials on charged particles, even in the region where all the fields (and therefore the forces on the particles) vanish. We shall then discuss possible experiments to test these conclusions; and, finally, we shall suggest further possible developments in the interpretation of the potentials.

1. INTRODUCTION

IN classical electrodynamics, the vector and scalar potentials were first introduced as a convenient mathematical aid for calculating the fields. It is true that in order to obtain a classical canonical formalism, the potentials are needed. Nevertheless, the fundamental equations of motion can always be expressed directly in terms of the fields alone.

In the quantum mechanics, however, the canonical formalism is necessary, and as a result, the potentials cannot be eliminated from the basic equations. Nevertheless, these equations, as well as the physical quantities, are all gauge invariant; so that it may seem that even in quantum mechanics, the potentials themselves

assume this almost everywhere in the following discussions) we have, for the region inside the cage, $H=H_0+V(t)$ where H_0 is the Hamiltonian when the generator is not functioning, and $V(t)=e\phi(t)$. If $\psi_0(x,t)$ is a solution of the Hamiltonian H_0, then the solution for H will be

$$\psi=\psi_0 e^{-iS/\hbar}, \quad S=\int V(t)dt,$$

which follows from

$$i\hbar\frac{\partial\psi}{\partial t}=\left(i\hbar\frac{\partial\psi_0}{\partial t}+\psi_0\frac{\partial S}{\partial t}\right)e^{-iS/\hbar}=[H_0+V(t)]\psi=H\psi.$$

Credit: Y. Aharonov and D. Bohm [**1**]

electrons is split, with the two halves made to travel around opposite sides of a cylindrical electromagnet, or solenoid. The magnetic field is concentrated inside the solenoid and can be made arbitrarily weak outside by making the cylinder extremely narrow. So Aharonov and Bohm argued that the two electron paths can travel through an essentially field-free region that surrounds the concentrated field within the electromagnet.

In this field-free region, however, the electromagnetic potential is not zero. Aharonov and Bohm showed theoretically that electrons on the two paths would experience different phase changes and that recombining the electron beams would produce detectable interference effects. That is, the intensity of the recombined beam would vary according to whether the phase-shifted wave functions reinforced or canceled each other—a measurable physical effect directly related to the potential, contrary to standard wisdom. However, the phase shift can also be calculated from the strength of the magnetic field, so that interference can be interpreted as an effect of a magnetic field that the electrons never actually pass through. Aharonov and Bohm argued that physicists must accept that in quantum mechanics the electromagnetic potential has genuine physical significance. They expanded on this point in a second paper in 1961 [**2**].

The Aharonov-Bohm paper "created a sensation," says Murray Peshkin, now at Argonne National Laboratory in Illinois. The troubling issue was that a quantum-mechanical measurement required what seemed to be an untenable interpretation of the electromagnetic potential. "There were lots of papers trying to make Aharonov-Bohm go away, or saying there was something wrong with the calculation," Peshkin says, but after about five years the criticism faded. It also emerged that a paper published ten years earlier [**3**] had hinted at the effect, but Peshkin, and also Michael Berry of the University of Bristol, have recently argued that Aharonov and Bohm nevertheless deserve credit for properly understanding the effect that bears their name [**4**].

Experimental papers demonstrating the effect began to appear soon after the first Aharonov-Bohm paper [**5**], but they too were criticized, often on the grounds that the paths on which the electrons traveled were not strictly devoid of a magnetic field. Such criticisms were empty, Peshkin says, because no one showed how tiny residual fields could cause the measured effect. Still, it wasn't until physicists performed an experiment in which the electromagnet was shielded by a superconducting screen, which rigorously blocked the magnetic field [**6**], that any remaining doubts about the Aharonov-Bohm effect were finally put to rest.

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