Nature **452**, 298-299 (20 March 2008) | doi:10.1038/452298a; Published online 19 March 2008

Quantum physics: Disturbance without the force

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Charged particles influenced by electromagnetic fields, even when the two never touch? Surely, it can only be quantum physics. But surprisingly, the quantum nature of this particular effect has been disputed.

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In the phenomenon known as the Aharonov–Bohm effect, magnetic forces seem to act on charged particles such as electrons — even though the particles do not cross any magnetic field lines. Is this evidence for electromagnetic forces that work in new and unsuspected ways? Or is it just that infamous source of Albert Einstein's discomfort — quantum-mechanical 'spooky action at a distance'? In the latest chapter in an involved history, detailed in *Physical Review Letters*, Caprez *et al.*[1] provide convincing evidence for the second of these options: that the Aharonov–Bohm effect is purely quantum mechanical in origin.

The history stretches back into the mid-nineteenth century, when Michael Faraday first proposed that lines of electric and magnetic force extend out into the empty space surrounding both magnets and electrical charges. The idea initially received a cool reception — ironically, in view of later developments, because Faraday's peers were wedded to the idea that these forces acted at a distance. But field lines, whose density gives the 'flux density', the magnitude of the field at a point, have proved both useful and exceptionally durable. A little later, Faraday's concept of electric and magnetic fields was fleshed out mathematically by two other titans of nineteenth-century physics, William Thomson (Lord Kelvin) and James Clerk Maxwell, who introduced and developed the unifying concept of the vector potential. In Maxwell's eponymous equations, in which he laid out his unified theory of electromagnetism, an electric field is produced when this vector potential changes with time; a magnetic field is produced when the vector potential changes spatially and has a vortex.

The vector potential, although initially regarded as a physical quantity in this formulation, became, in later standard treatments by Heinrich Hertz and Oliver Heaviside, a mere mathematical auxiliary: convenient for calculations, but possessing no direct physical meaning. Almost a century passed before, in 1959, Yakir Aharonov and David Bohm proposed[2] that in certain experimental contexts the vector potential itself would indeed have measurable effects, and thus its own physical reality. A paradigm had begun to shift: in modern physics, vector potentials, in the guise of 'gauge fields', are regarded as the most fundamental physical quantity in the quantum theories of the fundamental forces[3, 4, 5, 6].

In the quantum world, particles such as electrons can behave as waves. Electric and magnetic fields can shift electrons' wave fronts (or their phases) much as obstacles disturb ripples on a water surface. What Aharonov and Bohm concluded[2], however, was remarkable: that the phases of electrons passing through regions entirely free from electromagnetic fields could also be shifted. They envisaged an experiment in which two electron beams pass by on either side of an infinitely long, perfectly shielded magnetic coil, such that the electrons never directly experience magnetic fields or forces (Fig. 1). Aharonov and Bohm calculated that, when these two beams are subsequently guided to overlap and form interference fringes, the phases of the two beams would be shifted relative to one another. They attributed this effect to the vector potential, which does not vanish in the regions around the magnet through which the electrons had passed.

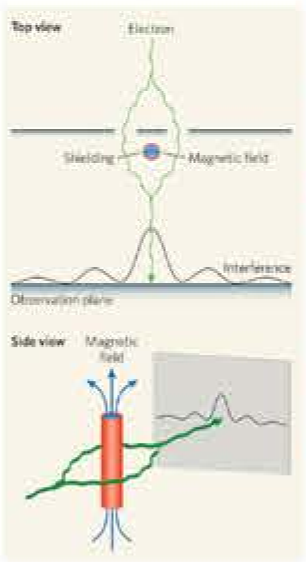

Figure 1: The Aharonov–Bohm effect.

In Aharonov and Bohm's original theoretical formulation of their effect, an electron beam is split into two, passing on either side of an (infinitely) long, perfectly shielded magnet. The result is a phase-shift evident in an interference pattern formed when the electron beams are recombined. It seems that the electrons 'feel' the non-local presence of the magnetic field through its associated vector potential, which permeates the space around the coil. An analogous effect, the Aharonov–Casher effect, which applies to 'quantum magnetic dipoles' (spins), can be demonstrated by replacing the magnet by an electrically charged cylinder. Caprez and colleagues' experiments[1] with a pulsed electron beam passed through a toroidal magnet seem to confirm that no unknown forces are involved in the Aharonov–Bohm effect — it is a purely quantum-mechanical phenomenon.

High resolution image and legend (41K)

The Aharonov–Bohm effect is pivotal: it is directly related to fundamental problems in quantum mechanics, such as whether a wavefunction has a single value at a point in space and the quantization of magnetic flux. But it is also controversial, in part because of the modern philosophical aversion, expressed by Einstein and others, to the concept of action at a distance. Conclusive evidence for its existence[7] was obtained only in 1986 by using, instead of the infinitely long magnets of the theoretical formulation, doughnut-shaped (toroidal) magnets covered with superconductors to shield any leakage of magnetic flux.

Even though the Aharonov–Bohm effect is regarded as a consequence of the Schrödinger equation — the general equation governing the evolution of a quantum system — questions have been raised as to whether it is a purely quantum-mechanical phenomenon or not[3, 4, 8, 9]. Several people have attempted to interpret the Aharonov–Bohm effect in the context of a classical interaction between the incident electrons and the coil[3]. For example, Timothy Boyer[9] has postulated a 'lag effect' ascribed to a force applied to the electrons. In standard classical theory, electric and magnetic fields are defined as forces exerted on charged particles, and so no forces would be exerted on electrons passing on either side of Aharonov and Bohm's perfectly shielded magnetic coil[3]. Where the necessary force, which would have to accelerate the electrons on one side of the coil and decelerate them on the other, would come from is unclear.

The contribution of Caprez *et al.*[1] is to rule out the possibility that the Aharonov–Bohm effect can be explained through the existence of such forces. They do this by timing how long the electrons of a pulsed beam, created by shaving electrons off a nanoscale tip using a femtosecond laser beam, take to pass through field-free regions in the hole of a toroidal magnet to a detector. Crucially, even when the electric current flowing through the magnet was changed — which would be expected to affect the magnitude of any possible unknown force — no additional time delay of electrons was detected. Thus, the Aharonov–Bohm effect would seem to be confirmed as a purely quantum-mechanical effect. Action at a distance is alive and well.

This use of a pulsed electron beam[10] is innovative and worthy of attention, as one can envisage its use in experiments to probe other, counterintuitive quantum effects. For example, it would be intriguing to test with this new technique the 'electrical' Aharonov–Bohm effect[3], in which two electron beams passing through two long, shielded metal cylinders, and experiencing no forces, can be phase-shifted when a potential is applied to one of the cylinders. To test this effect, both a pulsed electron beam and the synchronous application of the potential to the cylinder only when the beams are well inside are indispensable.

Faraday's magnetic field lines were essential to give us a mental picture of how the forces of classical electromagnetism worked, a picture that proved crucial to the development of the first electromechanical devices in the late nineteenth century. In much the same way, the outcome of these fundamental experiments might give us more of a handle on mysterious quantum effects such as action at a distance — and how we might use them to our advantage.

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