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Fringing fields and criticisms of the Aharonov-Bohm effect

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A recent paper attributes the Aharonov-Bohm effect to the fringing field leaking out of a finite solenoid rather than to the magnetic flux in the excluded region. This argument is seen to be absurd for a very long solenoid where the effect is attributed to the tail of the electron wave function very far from the point of measurement, and is completely refuted by toroidal geometry with no fringing field.

The Aharonov-Bohm effect demonstrates the influence on the motion of electrons of magnetic flux in a region from which the electron is excluded.[1] The theoretical predictions are a straightforward consequence of quantum mechanics with electromagnetic fields.[2] The validity of the calculations is not questioned; the results of the experiment do depend upon the value of the magnetic flux in the excluded region. However, for any finite solenoid, the lines of the flux must come out of the solenoid at the ends, and a measurement of the fringing field can always give the information about the flux in the interior. Thus this information is in principle available to the electron. This rather obvious and trivial remark is the basis of the recent questioning of the Aharonov-Bohm effect by Roy,[3] who claims that the whole effect is due to the fringing field and not to the flux in the interior.

Roy's elegant theorems are not needed to see that the flux inside a finite solenoid can be determined by a knowledge of the fringing field outside. The lines of force are continuous and must go somewhere where they can be measured. This is the essential content of Roy's paper. However, the parameter that enters into the Aharonov-Bohm effect is the flux within the solenoid. This is evident in the case of the infinite solenoid or the toroidal geometry, where there is no fringing field of lines of force leaking into the exterior region. To suggest that a finite solenoid one million kilometers long is qualitatively different from an infinite solenoid because the flux within can be determined by measurements on the fringing field outside seems absurd. This implies that the experimental result is not determined by the nearby flux but by the tiny tail of the electron wave function which extends out a million kilometers. The electron beam has negligible intensity in most of this "accessible" region. The flux in the region actually traversed by the bulk of the electrons does not determine the flux inside the solenoid.

In many experiments with idealized simple geometry, an infinitely long object is approximated by a physically realizable object of finite length. The electric field between two finite parallel plates and the magnetic field of a long but finite solenoid differ from the fields of the corresponding infinite systems by having weak "fringing fields" outside the space between the parallel plates or the interior of the solenoid. Because the solutions of Maxwell's equations are completely determined in a whole region when sufficient information is given regarding the fields at a boundary, a knowledge of the fringing fields outside a finite parallel-plate condenser or a finite long solenoid gives information about the fields in the interior.

Although the infinite geometry is never realized in practice, the finite system can be made sufficiently large for any given experiment so that the dependence of the experimental result upon the size of the system becomes negligible. The fringing fields change very markedly with the size of the system and go to zero in the infinite limit; yet for any finite size it is still possible to obtain information about the field in the interior by measuring the fringing field and using Maxwell's equations. However, it does not seem reasonable to attribute the experimentally observed effect to the fringing field rather than to the field in the interior.

The toroidal geometry is mentioned in Roy's paper but without any discussion. However, it is the clear counterexample to his basic argument. This is a finite system where the magnetic flux within a given region cannot be determined by a knowledge of the field strengths outside. Yet the Aharonov-Bohm effect has a dependence on the flux in the interior.

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