Comment on "Scalar Aharonov-Bohm Experiment with Neutrons"

Allman *et al.* [1], in an elegant experiment, have demonstrated something very like the electric Aharonov-Bohm effect (EAB). In EAB [2,3], an electron beam is split into two partial beams in a Mach-Zehnder interferometer. One partial beam experiences an electric potential V_1 for a time T, the other V_2. Neither ever experiences any electromagnetic field. However, the scalar potential energy term $-eV$ in the Hamiltonian causes a phase shift $\Delta\phi=(e/\hbar)(V_1-V_2)T$ which affects the observed interference when the two partial beams are recombined. EAB is a topological effect; the electron is confined to a multiply connected force-free region [3].

In [1], the idea is for the electron to be replaced by a neutron with spin in the $+z$ direction and the electric field to be replaced by a magnetic field B in the z direction. Then the eV term in the Hamiltonian is replaced by $\mu\sigma_z B$, where μ is the neutron's magnetic moment and σ_z is in practical effect equal to $+1$. In the neutron case, $\Delta\phi=(\mu/\hbar)(B_1-B_2)T$, and again an observable effect of a force-free field is exhibited by the interference when the two partial beams are recombined. Allman *et al.* call this the "scalar AB effect" (SAB) to emphasize its logical relation to EAB. In SAB, the spin factor in the wave function is constant and the spatial factor obeys the same differential equation as the EAB wave function, with μB substituted for eV.

In the actual experiment, unpolarized neutrons are used. Then the observed interference effect is an equal incoherent mixture of the effects to be observed with $\sigma_z=+1$ and $\sigma_z=-1$, which do not cancel each other.

Here I argue that SAB, unlike EAB, is not a topological effect. Although σ_z is a constant of the motion, the neutron's spin is still a quantum-mechanical variable whose operator equation of motion is the classical law $\hbar\dot{\boldsymbol{\sigma}}=2\boldsymbol{\mu}\times\mathbf{B}$. SAB is required for consistency with that equation of motion for a magnetic dipole in a local magnetic field which creates a torque on the dipole.

To see that, describe SAB in the σ_x representation instead of the σ_z representation of [1]. The initial unpolarized neutron beam is an equal incoherent mixture of two beams one with $\sigma_x=+1$ and one with $\sigma_x=-1$. In [1], the same statistical state was described as having two beams with $\sigma_z=1$ and -1, respectively. A neutron which initially had $\sigma_x=+1$ experiences a torque which causes its spin to precess around the z axis, differently in the two different magnetic fields. When the split beam is recombined, the interference is that of two beams with different spin directions in the x-y plane. A neutron which had $\sigma_x=-1$ has the same experience but with opposite torque. When the two initial σ_x states are mixed incoherently, the result is of course the same as that shown in Fig. 3 of [1]. Only the representation used in the calculation was different. However, the observed effect is now ascribed entirely to precession of the magnetic moment by the torque in a local magnetic field. That torque is an objective quantity since the experiment could have been done with a beam initially polarized in the $+x$ direction. The SAB experiment confirms the consistency of the quantum-mechanical equation of motion.

The SAB experiment could in principle have been done with a neutron beam polarized in the $+z$ or the $+x$ direction. In the $+x$ case, no topology or nonlocality would be involved. A neutron's polarization is rotated by a local magnetic field perpendicular to the spin. That rotation was detected by interferometry, but it could have been detected otherwise. Quantum mechanics entered the picture, apart from the choice of detection technique, only in the construction of the unpolarized beam. An equal incoherent mixture of $\sigma_x=+1$ and -1 is an unpolarized beam indistinguishable in principle from a like mixture of $\sigma_z=+1$ and -1. Only quantum-mechanical interference can describe the result for definite σ_z because there a magnetic field causes a phase shift instead of a rotation.

I thank Harry J. Lipkin for useful comments. These matters have also been remarked upon by J. Anandan and by A. Zeilinger [4]. This work was supported by U.S. DOE, Nuclear Physics Division, Contract No. W-31-109-ENG-38.

Murray Peshkin
Physics Division
Argonne National Laboratory
Argonne, Illinois 60439-4843

Received 26 May 1992
PACS numbers: 03.65.Bz, 42.50.−p

[1] B. E. Allman *et al.*, Phys. Rev. Lett. **68**, 2409 (1992).
[2] Y. Aharonov and D. Bohm, Phys. Rev. **115**, 485 (1959).
[3] M. Peshkin and A. Tonomura, *The Aharonov-Bohm Effect,* Lecture Notes in Physics Vol. 340 (Springer-Verlag, Berlin, 1989).
[4] J. Anandan, in *Proceedings of the Third International Symposium on the Foundations of Quantum Mechanics,* (Physical Society of Japan, Tokyo, 1989), p. 98; A. Zeilinger, in *Fundamental Aspects of Quantum Theory,* NATO ASI Ser. B, Vol. 144, edited by V. Gorini and A. Frigerio (Plenum, New York, 1985), p. 311.