Observation of the Phase Shift of a Neutron Due to Precession in a Magnetic Field*

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We have directly observed the sign reversal of the wave function of a fermion produced by its precession of 2π radians in a magnetic field using a neutron interferometer.

It is well known that the operator for rotation through 2π radians for a fermion causes a reversal of the sign of the wave function. We have directly observed this effect for neutrons precessing in a magnetic field using an interferometer of the type first developed for x rays by Bonse and Hart.[1] This experiment was first suggested by Bernstein[2] in 1967. At nearly the same time the possibility of observing this effect was noted by Aharonov and Susskind[3] and a tunneling experiment using electrons was proposed.

The interferometer, He[3] detectors, and peripheral apparatus employed in this experiment are the same as those used in the recent observation of gravitationally induced quantum interference.[4] A monoenergetic, unpolarized neutron beam (λ = 1.445 Å) is split at point A of the interferometer by Bragg reflection (Fig. 1). The one beam passes through a transverse dc magnetic field on the path AC. The relative phase of the two beams where they recombine and interfere at point D is varied by adjusting the magnetic field $\vec{B}$.

If we take the Hamiltonian for the neutron of momentum $\vec{p}$ and magnetic moment $\vec{\mu}$ to be

$$H \doteq p^2/2M - \vec{\mu} \cdot \vec{B},\tag{1}$$

it is easy to show that the phase shift to first order in $\vec{B}$ is

$$\beta = \pm 2\pi g_n \mu_N M \lambda B l / h^2 .\tag{2}$$

Here the $\pm$ signs are for spin-up and spin-down neutrons; g_n is the neutron magnetic moment in nuclear magnetons ($= -1.91$), μ_N is the nuclear magneton, h is Planck's constant, M is the neu-
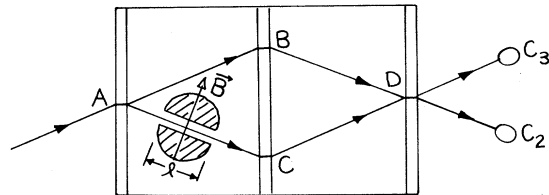

FIG. 1. A schematic diagram of the neutron interferometer. On the path AC the neutrons are in a magnetic field B (0 to 500 G) for a distance l (2 cm).

tron mass, and l is the distance over which the neutron is in the magnetic field.

We must add the contributions of spin-up and spin-down neutrons together since the experiment was done with unpolarized neutrons. There is always a residual phase shift δ in the interferometer due to various causes, including gravity. The counting rates at detectors C_2 and C_3 are expected to be

$$I_2 = I_2(\uparrow) + I_2(\downarrow)$$
$$= [\tfrac{1}{2}\gamma - \tfrac{1}{2}\alpha \cos(\delta + \beta)] + [\tfrac{1}{2}\gamma - \tfrac{1}{2}\alpha \cos(\delta - \beta)]$$
$$= \gamma - \alpha \cos\delta \cos\beta, \tag{3}$$

and

$$I_3 = I_3(\uparrow) + I_3(\downarrow)$$
$$= \tfrac{1}{2}\alpha[1 + \cos(\delta + \beta)] + \tfrac{1}{2}\alpha[1 + \cos(\delta - \beta)]$$
$$= \alpha[1 + \cos\delta \cos\beta]. \tag{4}$$

In these expressions we have taken β to be defined by Eq. (2) with the plus sign. The constants α and γ are the same instrumental parameters of Ref. 4. Thus, if the residual phase δ is fortuitously $\pi/2$, $3\pi/2$, ..., there will be no observable effect of the magnetic field on the intensities.[5] We circumvent this problem by first rotating the interferometer about the incident beam AB, thus using the effect of gravity to set the phase at a minimum of $I_2 - I_3$ which insures that $\delta = 0$, 2π, ... The major problem in this experiment was finding a method for producing a vari-

able magnetic field (~ 0 to 500 G) of uniform intensity over the beam dimensions (2 mm $\times$ 10 mm) in a limited space, which does not disturb the interferometer by heating, or in any other way. Our solution to this problem was to construct a small magnet using two cobalt-samarium permanent magnets, one of which has a variable position as shown in Fig. 2.

Equation (2) predicts that the field required for a precession of 4π (complete period) is

$$Bl = 272/\lambda, \tag{5}$$

where B is in gauss, l in centimeters, λ in angstroms. It is clear that the leakage field from the magnet must be included in a comparison of experiment with theory. We have experimentally determined $\vec{B}$ with a small magnetic field probe along the two beam paths ABD and ACD. The effective Bl for our magnet and interferometer is

$$\langle Bl \rangle = 2.7 B_{gap}(\text{G cm}), \tag{6}$$

where B_{gap} is the magnetic field in the magnet air gap.

Our first results are shown in Fig. 3. The oscillation period is 62 ± 2 G. Thus,

$$\langle Bl \rangle = 242/\lambda. \tag{7}$$

The agreement of this result is within the experimental errors which we are willing to assign to the measurement of the effective Bl.

It is clear that we have observed the complete rotation symmetry demanded by the spinor character of the neutron wave function. In classical physics $2n\pi$ rotations are unobservable. It should also be noted that in a superconducting quantum interference experiment this effect is not observ-
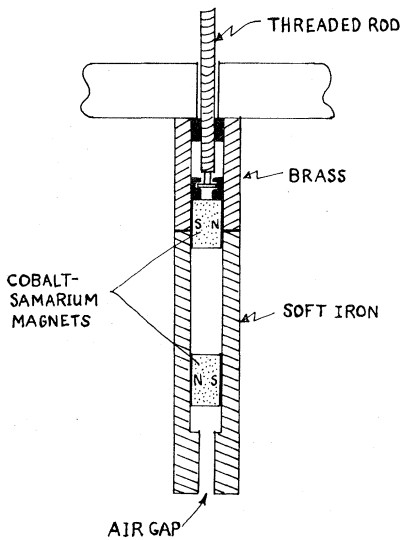

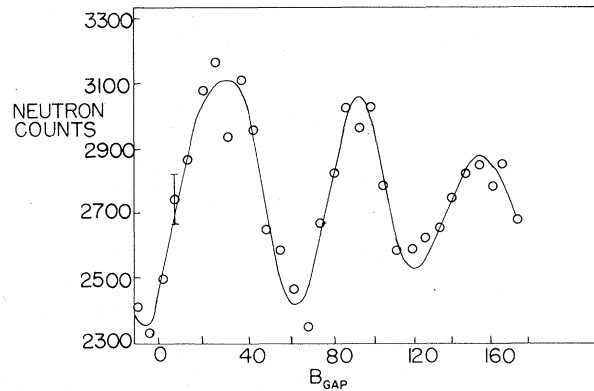FIG. 2. Diagram of the magnet used in this experiment.

FIG. 3. The difference count, $I_2 - I_3$, as a function of the magnetic field in the magnet air gap in gauss. Approximate counting time was 40 min per point.

able because the charge carriers are bosons.

This experiment was carried out at the Ford Nuclear Reactor, University of Michigan. The technical assistance of B. Poindexter is gratefully acknowledged.

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[1]U. Bonse and M. Hart, Appl. Phys. Lett. 6, 155 (1965). That this design would work as a neutron interferometer was shown by H. Rauch, W. Treimer, and U. Bonse, Phys. Lett. 47A, 369 (1974).

[2]H. J. Bernstein, Phys. Rev. Lett. 18, 1102 (1967).

[3]Y. Aharonov and L. Susskind, Phys. Rev. 158, 1237 (1967).

[4]R. Colella, A. W. Overhauser, and S. A. Werner, Phys. Rev. Lett. 34, 1472 (1975). This experiment was proposed by A. W. Overhauser and R. Colella, Phys. Rev. Lett. 33, 1237 (1974).

[5]The importance of the residual phase δ was pointed out recently by M. A. Horne and A. Shimony, to be published.

Spectrum of Strange-Quark–Antiquark Bound States*

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(Received 19 May 1975)

A calculation is made of the energy levels of the bound states of a strange quark and its antiquark with an interaction which includes an attractive Coulomb potential term, a confining linear potential, and spin-orbit, quadratic-orbit, spin-spin, and quadratic-spin interactions. Good agreement is obtained with observed mesons, and the existence of other mesons is predicted.

Within the framework of the quark model, we regard the φ meson as the lowest $^3S_1$ bound state of a strange quark s and its antiquark $\bar{s}$, and the η' meson as the lowest $^1S_0$ bound state of this system. Other mesons are known which can be interpreted, as we shall see, as excited $s\bar{s}$ states. We shall consider the spectrum of $s\bar{s}$ bound states using a rough analogy with the states of positronium. Specifically, we assume that the s and $\bar{s}$ quarks are subject to an attractive Coulomb-like potential, a short-range interaction effective in S states only, a spin-orbit interaction, and an interaction which goes like the square of the orbital angular momentum L. We depart from the positronium analogy by omitting still other terms present in the electron-positron interaction (like the tensor force) and by including a linear potential which confines the quarks.

Linear and/or Coulomb-like potentials have been used previously by a number of authors[1-5] to describe bound states of a charmed quark and its antiquark. Gunion and Willey[6] have considered the spectrum of mesons made of $s\bar{s}$ quarks (and the spectrum of other hadrons) using a linear confining potential with spin-spin and spin-

orbit interactions but without a Coulomb-like potential. De Rújula, Georgi, and Glashow[2] have considered the hadron spectrum in perturbation theory using Coulomb-like forces. The paper of De Rújula, Georgi, and Glashow contains a good discussion of the theoretical justification of Coulomb-like models.

Our treatment of the $s\bar{s}$ interaction differs from those given in previous works in two important ways. First, although we solve an ordinary Schrödinger equation, we partially include the effects of relativity by using relativistic kinematics. Second, we include terms present in the positronium interaction which have been omitted previously except as perturbations. It turns out that the $s\bar{s}$ coupling strength is sufficiently large that a perturbation treatment and the use of nonrelativistic kinematics are both inadequate approximations. In particular, although we obtain good agreement with experiment in our model, we cannot obtain this agreement if we evaluate the effect of the spin-orbit potential in perturbation theory.

The interaction H' responsible for the fine-structure splitting in positronium is given by[8]