Observation of 2π Rotations by Fresnel Diffraction of Neutrons

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We report on the first observation of Fresnel diffraction of a beam of unpolarized slow neutrons by individual ferromagnetic domain boundaries. The observed occurrence of destructive interference in the experiment demonstrates that the phase of a spinor wave function changes by a factor of -1 when the particle described by that wave function is rotated by an odd multiple of 2π radians.

Normal geometrical ideas lead to the conclusion that the rotation of a physical system through a complete revolution about a fixed axis should be equivalent to the identity operation and hence its effect would be unobservable. In 1967 it was suggested by Aharonov and Susskind,[1] and independently by Bernstein,[2] that for half-integral-spin systems such rotations could lead to observable effects in interference experiments.

In a previous paper[3] we outlined in detail how such an observation might be accomplished and proposed an experiment based on the Fresnel diffraction of unpolarized neutrons by a ferromagnetic domain boundary. In this paper we report the outcome of that experiment, which was carried out at the high-flux reactor of the Institut Laue-Langevin in Grenoble, France.

Figure 1 shows a schematic layout of the experiment: A high-flux beam of monochromatic cold neutrons, which has been given lateral coherence by its passage through a 5-μm slit, is transmitted through a carefully oriented and aligned ferromagnetic crystal. The crystal, which is in the shape of a thin foil, contains long, straight Bloch walls, i.e., boundaries separating domains of opposite magnetization. In traversing the foil on either side of a domain boundary the spin of the neutron precesses in opposite directions. The two parts of the wave function thereby acquire a relative phase shift which leads to the appearance of a Fresnel diffraction pattern in the plane of observation. This is due to the interference of the waves that have passed through the foil on opposite sides of the domain boundary.

In traversing a foil of thickness d, containing magnetic fields $+B$ and $-B$, on the left and right of the domain boundary, the relative angle of precession of the neutron spin is given by

$$\alpha = \alpha_L - \alpha_R = 2\alpha_L = 2\gamma B(dm\lambda/h), \tag{1}$$

where γ, m, and λ are the neutron gyromagnetic ratio, mass, and wavelength, respectively. The theoretical prediction is that destructive interference will occur for precession angles α which are an odd multiple of 2π. This should appear as a null in the center of the Fresnel pattern.

A classical Fresnel-diffraction situation was set up as follows: A beam of neutrons originating in the cold source of the high-flux reactor was monochromated to $\Delta\lambda/\lambda = 2.3\%$ at $\lambda = 4.33$ Å by Bragg reflection from a crystal of pyrolytic graphite followed by filtering in a block of poly-

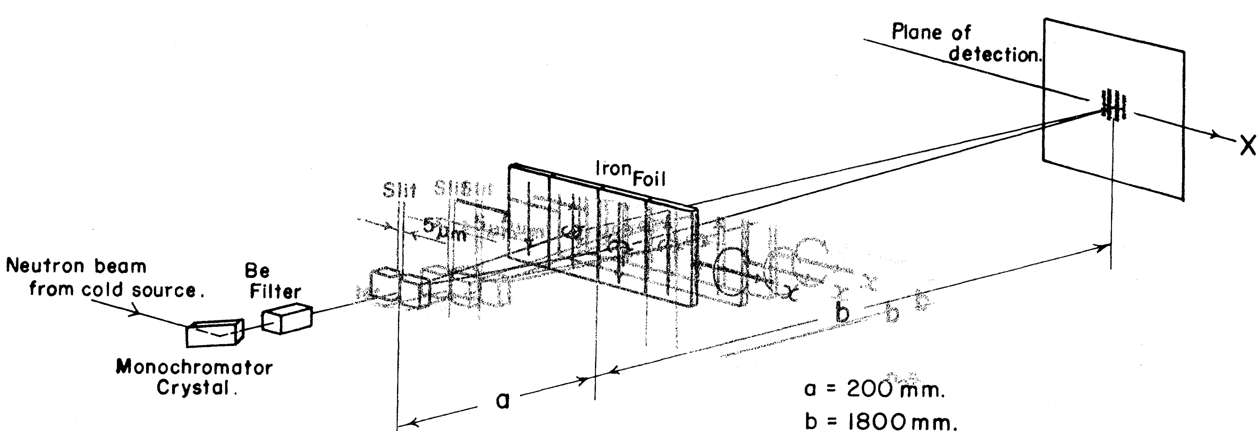

FIG. 1. Schematic layout of the apparatus.

crystalline beryllium. The lateral coherence of the beam was then defined by passing it through a slit 5 μm wide and 2 mm high, situated 200 mm in front of the ferromagnetic specimen. The slit system, made of gadolinium embedded in cadmium, was in the form of two parallel cylinders kept apart by 5-μm aluminum foil. The specimen, cut from a sheet of cubic-textured Fe-3%Si, was mechanically and chemically polished. The domain boundaries, shown in Fig. 2, which were made visible by the Bitter method, were carefully aligned to be parallel with the slit to better than ± 2 mrad.

The slit assembly and specimen holder were mounted on an optical bench inserted in one end of a rigid, antivibration-mounted steel tube which also served as magnetic shield. The detection screen was mounted at the other end of the steel tube, at a distance of 2 m from the slit. The detection system, based on the track-etch method,[4] consisted of a polished slab of boron carbide, fully enriched in ^{10}B. A sheet of cellulose nitrate was vacuum held against the target and recorded the tracks of α particles produced in the surface of the target by the reaction ^{10}B(n, α). These tracks, rendered visible by subsequent etching of the plastic film in a warm sodium hydroxide solution, recorded the spatial distribution of the neutrons arriving at the target. The spatial resolution is comparable with the range of the α particles in the target, viz., ~5 μm. The efficiency, however, is somewhat low, of the order of 5% for neutrons of 4.33 Å wavelength, necessitating exposures of 20 to 60 h duration. With track densities of $\sim 5\times10^5$ cm^{-2} the diffraction patterns recorded on the film are clearly visible to the naked eye using oblique illumination. For quantitative evaluation the patterns were photographed by dark-field microscopy, enlarged, and the track distribution counted by eye using a reference grid.

In a preliminary experiment, a gadolinium cylinder (similar in construction to one side of the first slit) was used in place of the iron foil. The resultant diffraction pattern was in excellent agreement with the well-known Fresnel pattern of a straightedge, convoluted with the resolution function due to the finite width of the source slit. This result, which is chiefly of pedagogic interest, will be published elsewhere. The iron-foil specimen was then carefully aligned and exposed. The thickness of the specimen was measured to be 72 ± 1 μm. The internal B field in iron diluted by 3% Si is 1.98 T. According to Eq. (1), this gives a relative angle of precession of $\alpha = 9.1 \times 2\pi$, near enough to an odd multiple of 2π to show substantial destructive interference if the proposition to be verified holds. The result is shown in Fig. 3(a) together with a theoretical curve, calculated from the geometry of the apparatus using standard Fresnel-diffraction theory.[3,5] Apart from a normalized vertical scale, and an origin shifted to the center of the measured pat-

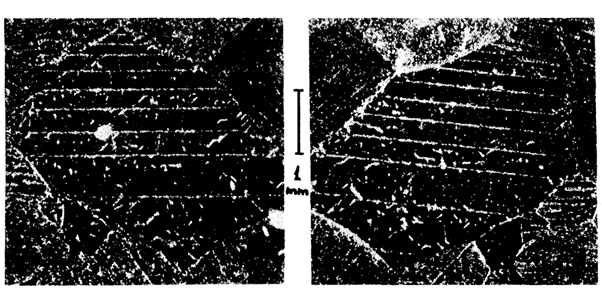

FIG. 2. Bitter patterns on front and back surfaces of cubic-textured Fe-3%Si foil. Straight domain walls several millimeters in length are seen to intersect both faces of the (100) crystal.

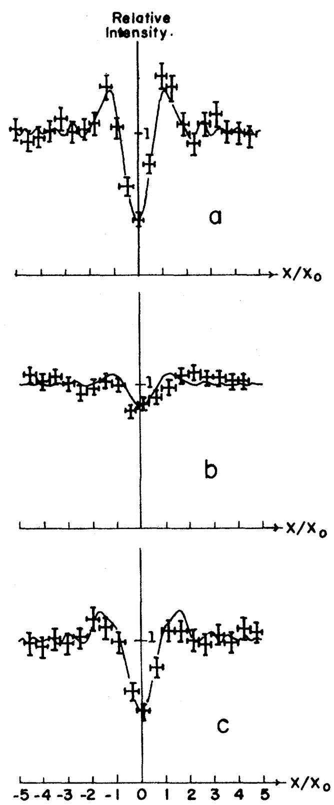

FIG. 3. Fresnel-diffraction patterns showing interference of neutrons whose spins were precessed by relative angles of (a) $9.2\times2\pi$ rad (b) $10.2\times2\pi$ rad, and (c) $11.2\times2\pi$ rad.

tern, the only free parameters in the fit are the relative angle of precession α and the width of the resolution function. The angle α for the theoretical curve is closer to $9.2\times 2\pi$ implying a measurement error of about 1 μm in the thickness of the foil. The width of the resolution function is somewhat greater than expected on the basis of coherence calculations; we believe this is due to kinks in the domain boundaries which give them an effective width of the order of 5 to 10 μm over a length of 2 mm, rather than the theoretically predicted few hundred angstroms.

Other exposures were carried out with the foil tilted backwards about the horizontal x axis so as to present a greater thickness to the neutrons that traverse it. The angles of tilt were calculated to give effective thicknesses corresponding to precession angles of $10\times 2\pi$ and $11\times 2\pi$, respectively. The results are shown in Figs. 3(b) and 3(c) in which the theoretically fitted curves actually correspond to $10.2\times 2\pi$ and $11.2\times 2\pi$, the discrepancy, once again, being due to possible errors in the foil thickness. Vertical error bars on the experimental points represent counting statistics while the horizontal bars are histogram bin widths. The horizontal scales on the graphs are in Fresnel units,[3,5] X_0, where

$$X_0 \equiv \left(\frac{a+b}{a}\right)\left(\frac{\lambda ab}{2(a+b)}\right)^{1/2} = 62\ \mu\text{m} \qquad (2)$$

using the values a and b given in Fig. 1.

The results clearly show that the predicted destructive interference, caused by the phase shift of the wave function due to rotation, occurs near odd multiples of 2π and tends to disappear near even multiples of 2π.

During the course of the present work, Rauch *et al.*[6] and Werner *et al.*[7] also observed the spinorial interference of neutrons using perfect-crystal interferometers. It is interesting to note that similar experiments were carried out as late as 1934, aimed at elucidating the vectorial nature of light.[8]

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