NEUTRON REFRACTION AT INDIVIDUAL DOMAIN BOUNDARIES IN A FERROMAGNET

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Double refraction of neutrons (λ = 1.45 Å) at the domain boundaries in a Fe + 3.5% single crystal is observed with a double-crystal spectrometer. The refracted ray intensities oscillate depending upon the angle of incidence at the boundary, and the angular separation of the rays diminishes as the incidence angle increases. The results show that in this crystal a simple model of laminar domain structure is realized, characterized basically by domains that are 0.13 cm wide with 180° boundaries oriented parallel to the [100] direction of easy magnetization.

THE study of neutron refraction at domain boundaries in ferromagnets yields information, unobtainable by the usual classical methods, about the internal domain structure. Magnetic refraction of neutrons was first observed experimentally in the passage of a well-collimated neutron beam through unmagnetized iron.[1] The observed effect consisted in small angular spreading (amount to a few minutes) of the beam as the result of multiple refraction at domain boundaries, and disappeared when a saturation field was applied to the sample.

Shull[2] observed refraction in magnetized prisms using a double-crystal neutron spectrometer. We have previously[3] demonstrated that the high angular resolution of this technique could be used to investigate magnetic refraction at domain boundaries. The study of multiple refraction processes yields information only about certain integral features of domain structure such as the average domain size for a given model of the structure. Very much more information can be obtained through experimental study of the refraction processes occurring separately at individual domain boundaries.

THEORY

The relative refractive index of an unpolarized neutron beam crossing a domain boundary (Fig. 1a) is given by the familiar formula (see[4], for example)

$$n_{1,2} = \mp n_2 / n_1 \cong 1 \pm \mu B / E, \quad (1)$$

where μ and E are the neutron magnetic moment and energy, and B is the saturation magnetic induction of the ferromagnet.

Equation (1) shows that double refraction corresponds to the two spin states of the neutron, i.e., two polarized beams are formed. It is easily shown that the angular deflection of each refracted ray from the initial direction is given by

$$\Delta\alpha = \pm \mu \frac{B}{E} \operatorname{ctg} \alpha \quad (2)$$

when the incidence angle obeys the condition $\alpha > \alpha_{cr} = (2\mu B/E)^{1/2}$. For E = 40 MeV (λ = 1.45 Å), B = 1.98 × 10^4 gauss, and α = 1° the angle between the refracted rays in the case of Fe + 3.5% Si is $\Delta = 2\Delta\alpha = 72''$. This shows that to observe an individual refraction of thermal neutrons angular resolution of the order of a few seconds is required, which can be achieved only by using a double-crystal spectrometer.

We shall consider neutrons traversing a system of parallel boundaries (Fig. 1b, c) corresponding to the simplest model of ferromagnetic domain structure. In this case the neutron beam intensity has two components: the intensity of refracted neutrons (I_r) and the intensity of neutrons that traverse the boundaries without being refracted (I_{unr}). When α is small, I_{unr} at first diminishes with increase of the angle while I_r increases, so that at tan α = d/L all neutrons are refracted. In the interval d/L ≤ tan α ≤ 2d/L a fraction of the neutrons cross a single boundary. The remaining neutrons cross two successive boundaries at which the changes of the magnetic induction have opposite signs; consequently, the angular deviations [given in (2)] of the neutrons at the two boundaries compensate each other, so that the twice-refracted beam is parallel to the initial beam. Therefore in this angular range I_{unr} increases again while I_r decreases etc.

In the general case, refracted rays should not be observed when an even number of boundaries are crossed, but the primary beam should be fully refracted after crossing an odd number of boundaries. Consequently I_{unr} and I_r vary periodically as functions of tan α (Fig. 1d):

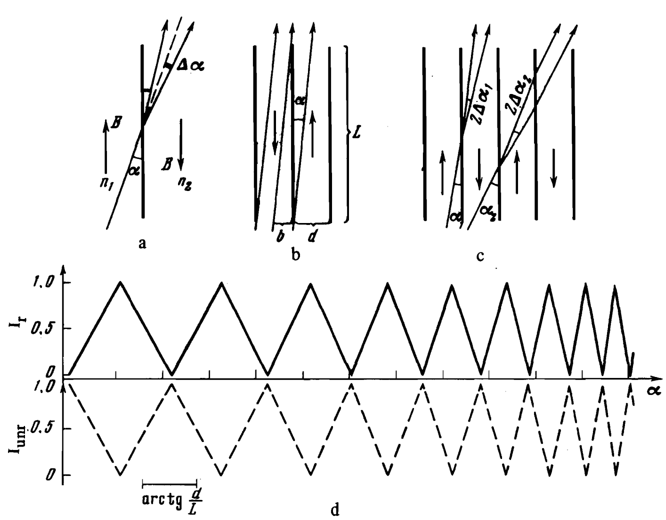

FIG. 1. Neutron refraction (a) at a domain boundary and (b, c) at a system of parallel boundaries. The calculated variations in the intensities of the unrefracted beam (I_{unr}) and refracted beam (I_r) are shown (d) as functions of the incidence angle α for a periodic system of parallel boundaries.

$$I_{\text{unr}} \sim |(2n-1) - Ld^{-1}\,\text{tg}\,\alpha|,$$
$$I_{\text{r}} \sim 1 - |(2n-1) - Ld^{-1}\,\text{tg}\,\alpha|, \qquad (3)$$

where n = 1, 2, 3, ... is the number of periods of oscillation and $2(n-1)d/L \le \tan\alpha \le 2nd/L$.

The foregoing remarks hold true within the framework of geometric neutron optics; this is equivalent to the assumption that the time of interaction between a neutron and a domain boundary is smaller than the Larmor precession period. In actuality, at small angles of incidence and large (of the order 1μ) thicknesses of the Bloch walls, which are characteristic of silicon iron, effects can appear which are associated with a finite probability of adiabatic neutron spin flip;[5] this is equivalent to crossing a partially transparent boundary without refraction.

EXPERIMENT

The measurements were performed with a double-crystal spectrometer[3] mounted on a universal diffractometer,[6] at λ = 1.45 Å. The sample was a 14 × 10 × 1-mm Fe + 3.5% Si plate cut along the (110) plane from a single crystal that was grown by zone melting without a crucible at the Physics Institute of the Czechoslovak Academy of Sciences.[7] The sample was placed between perfect germanium crystals (Fig. 2a). The neutron beam, formed by a collimator of borated polyethylene with cadmium-coated walls (60 mm long with a 6 × 0.5-mm aperture), traversed the plate at an angle α to the [001] direction. Two kinds of experiments were performed. First, we obtained integral measurements showing how the intensity of neutrons that traversed the sample and were reflected by the analyzing crystal in the parallel position (θ = 0) depended on the sample's angle of rotation (α). In this case the variation of intensity indicated the deflection of neutrons from their initial direction. Secondly, differential measurements were used to study the angular distribution of refracted neutrons: With the sample in a fixed position, the dependence of the intensity on the rotational angle θ of the analyzing crystal was measured. It should be noted that in both cases the angular resolution was determined by the width of the reflection curve of the double-crystal spectrometer (3.2″ at λ = 1.45 Å).

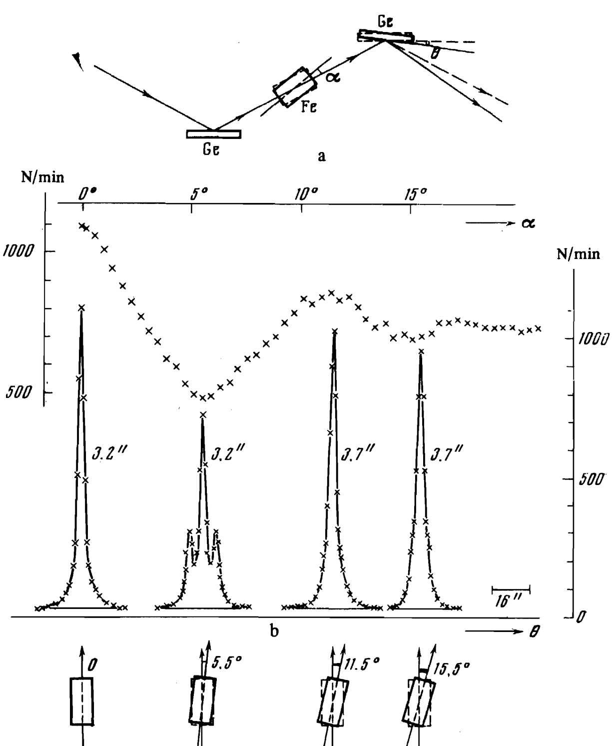

FIG. 2. a) Scheme of experiment. b) Maximum intensity of reflection from the second Ge crystal versus rotational angle of the sample (integral curve). The solid curves represent the dependence of the intensity at a given angle α on the rotational angle of the second Ge crystal (differential curves); each curve is labeled with the angular width of the central maximum. c) Positions of the sample that correspond to the differential curves in Fig. 2b.

The integral curve (at the top of Fig. 2b) is oscillatory; the transmission maxima and minima are observed at angle multiples. In the range α > 20° (not shown in Fig. 2) the oscillations are damped and the intensity increases monotonically until at α = 90° it reaches a maximum (corresponding to α = 0). Similar oscillations are observed when the sample is rotated 180° and when the sign of α is reversed. The differential curves (rocking curves) for characteristic values of α are shown at the bottom of Fig. 2b. At α = 0 only one peak is observed, having the width 3.2″ that equals the width of the reflection curve in the absence of the sample; as α is increased additional symmetrically located satellites appear. The separation of the satellites decreases monotonically as α increases (Fig. 3b) and the dependence of their intensity on α is oscillatory (Fig. 3a). The combined intensity of the central peak and the satellites remains unchanged.

DISCUSSION OF RESULTS

In the monocrystalline plates of silicon iron cut along the (110) plane the domain boundaries form an angle φ with the surface (Fig. 4); in perfect crystals this angle is 45°.[8] For an arbitrary angle φ the form

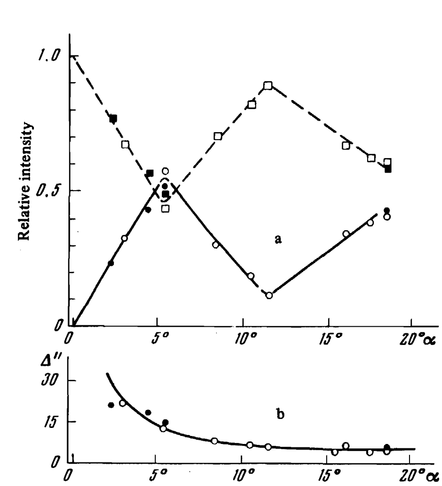

FIG. 3. (a) Intensities of refracted neutrons (○, ●) and unrefracted neutrons (□, ■) as functions of α. (b) Angular separation (in seconds) of satellites as a function of α; the dark and light circles correspond to the different signs of α.

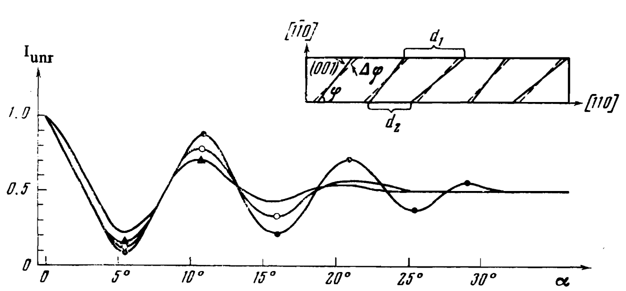

FIG. 4. Effect of variations in domain width and in transparency resulting from adiabatic neutron spin flip, on the calculated intensity of unrefracted neutrons; ●—$\overline{\Delta d/d}$ = 0.1, ○—$\overline{\Delta d/d}$ = 0.15, ▲—$\overline{\Delta d/d}$ = 0.20. The solid $\overline{\Delta d/d}$ = 0.20 curve was calculated taking adiabatic spin flip into account. The upper diagram represents the orientation of the sample and domain boundaries.

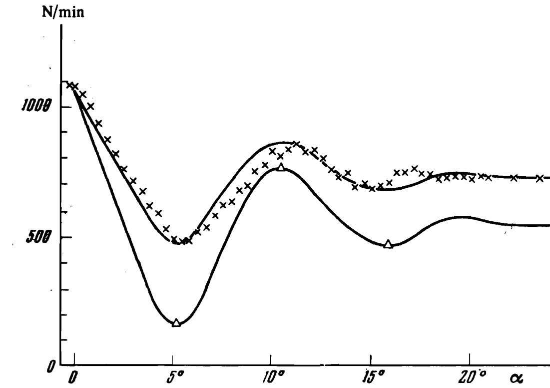

FIG. 5. Intensity of unrefracted neutrons as a function of α. Δ—calculated curve for $\overline{\Delta d/d}$ = 0.20 (see the preceding figure). X—experimental points. For the calculated solid curve, boundary transparency ≈ 15% was assumed, independently of the angle.

of Eq. (2) is preserved subject to the condition that $\Delta\alpha$ denotes the horizontal component of deflection and α is the angle between the neutron velocity and the line representing the intersection of the boundary and the horizontal plane.

The experimental separations of the satellites within the entire investigated range of α are in agreement with a curve calculated on the basis of Eq. (2) (Fig. 3b). Consequently, inside the crystal a domain structure is realized having 180° boundaries that lie in the [001] direction. The absence of satellite broadening shows that the boundaries are planar to within a few minutes. From the locations of the minima and maxima on the curves in Figs. 2b and 3a it was determined by using (3) that the domains have width d = 1.36 mm, which is close in order of magnitude to the values measured when using the techniques of powder patterns[9] and x-ray topography[10] for similar samples.

The experimental I(α) curves (Figs. 2b and 3a), unlike the theoretical curves (Fig. 1d), are characterized by rapid damping of the oscillations. This indicates the irregularity of the real domain structure, i.e., domain width variations in the crystal that can be associated with some variation of the angle φ for different boundaries (Fig. 4). The same figure shows calculated I(α) curves for the average spreads $\overline{\Delta d/d}$ = 0.1, 0.15, and 0.2. The experimentally observed damping is described best by $\overline{\Delta d/d}$ = 0.2, which corresponds to an average 9° angle of boundary disorientation.

Although the foregoing hypothesis completely describes the character of the damping of the oscillations (and, correspondingly, the presence of an unrefracted beam in each differential rocking curve), the average intensity on an experimental curve is considerably higher than on the theoretical curve. This indicates a certain degree of boundary transparency. One possible explanation is a finite probability of adiabatic neutron spin flip when traversing a "thick" Bloch wall at a small angle. It can be shown that this probability is given by

$$P=\frac{k^2}{k^2+1}\sin^2\frac{\pi}{2}(k^2+1)^{1/2}, \tag{4}$$

where $k = 4\pi B\delta/hv \sin\alpha \sin\varphi$, v is the neutron velocity, and δ is the Bloch wall thickness (~ 0.5 μ for silicon iron[11]). A calculation based on (4) yields a result of the order of 10%, decreasing rapidly as α increases (the upper curve in Fig. 4). Consequently, the observed discrepancy can have another cause: discontinuities of the boundaries, which may be associated with the presence of internal domains of closure.[12]

Only a small amount of refraction occurs at the boundaries of closure domains, because of the large incidence angles. Therefore the presence of these domains is equivalent to the formation of "apertures" in the main boundaries and to increased intensity of the unrefracted beam, having only slight dependence on the angle α. Figure 5 illustrates how this hypothesis agrees with experiment. Certain additional experimental facts (the appreciable, to 5″, broadening of the central peak at α = 45°, and some asymmetry of the integral and differential curves when the sign of α is changed) also indicate the presence of domains of closure. The foregoing results show that our present approach utilizing the described experimental technique yields information about both the "geometric" properties of the domain structure (the type of structure and the parameters of its irregularity, average domain size, boundary orientation etc.) and its "physical" properties (the type of domain boundaries, their transparency etc.). It also follows from this work that in experiments with colder neutrons in silicon iron it will be possible to determine the thickness of the Bloch walls, i.e., to perform the experiment proposed by Newton and Kittel.[5]

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