PHYSICAL REVIEW VOLUME 133, NUMBER 3B 10 FEBRUARY 1964

Studies of the Optics of Neutrons. III. Problems of Polarization of Slow Neutrons

OTTO HALPERN
Pacific Palisades, California
(Received 2 July 1963)

Various loosely connected problems dealing with the polarization of neutrons are discussed. We treat successively questions of polarization technique, the influence of absorption on polarizing mirrors, the connection between polarization and coherence, and finally the possible influence of the domain structure on the relative magnitude of nuclear- and magnetic-scattering amplitudes.

THERE are, at present, three known methods by which slow neutrons may become polarized. First, there is the original method of Bloch,[1] consisting of the transmission of neutrons through magnetized ferromagnets. In this method, the two polarization states of the neutrons are scattered with different intensities; the penetrating beam is, therefore, enriched in that component which is less scattered. Denoting for the moment the nuclear-scattering amplitude by a_n and that of the magnetic scattering by a_m, we find that the two different states are scattered with an intensity given by

$$(a_n \pm a_m)^2, \tag{1}$$

respectively. It is not permissible to assume that, even apart from the form factor, the amplitude a_m is independent of direction, as shown in detail in an old paper by Halpern and Johnson.[1] The relation (1) holds for every Laue spot (Debye ring) with a different value of a_m for each; the final intensity is then calculated by taking a suitable average over all a_m. The procedure makes it necessary to use rather large blocks of iron and, therefore, involves a considerable loss of intensity for the transmitted beam; one sees that the transmitted beam is so polarized that its direction of polarization leads to an a_m, the sign of which is opposite to that of a_n. The polarization achieved in this way is never very great and hardly ever reaches 50%.

The second method consists in total reflection from a magnetized mirror, which becomes birefringent and reflects totally at the critical angle for the first polarization state, while the second polarization state, which has a smaller critical angle, is reflected only to a small extent. Therefore, the reflected beam, if the conditions are otherwise ideal, is nearly totally polarized; the loss in intensity in the reflection process is not much larger than 50%. On the other hand, the collimation (and monochromization) leads to a large loss of neutron intensity. The choice of the magnetized substance to act as a mirror depends on other properties, to which we shall return. In both methods, the same procedure can be used for analyzation and polarization. The spin in the polarized reflected beam is so oriented that its magnetic amplitude a_m has the same sign as a_n, as opposed to the method of transmission.

While the two methods enumerated can serve in principle for all cases, the third method is based on a more accidental compensation.[1] In certain ferromagnetic crystals, it may happen for an individual Laue spot that the nuclear scattering amplitude is accidentally about as large as the magnetic amplitude for one of the polarization states. Then one state will hardly be reflected at all, and the reflected beam will consist almost totally of the other polarization state. The extent to which this will happen depends more or less on the accidental agreement of a_m and a_n for the individual Laue spot. In the hands of Shull and his collaborators,[1] this method has proven itself and has led to high degrees of polarization. Here also, the nuclear amplitude has the same sign as the magnetic amplitude of the beam scattered into an individual Laue spot. One sees that the use of one method for polarization and another for analyzation is possible only when these amplitude relations are carefully observed.

If the mirror method is used for analyzation of a polarized beam, an observation of a second reflection being made, care must be taken to ensure the absence of gravely distorting errors. If, for example, the second reflection of a polarized beam has a reflection coefficient of say $(100-\alpha)\%$, one should assume, under ideal conditions, the presence of a beam which is $(100-2\alpha)\%$ polarized. This may be quite misleading if the mirror is not a total reflector at the critical angle as, for example, in the presence of absorption. In the first paper of this series,[2] a formula is given for the reflection coefficient from a mirror.[1] This formula reads, in customary notation:

$$r = 1-2(A/Na\lambda)^{1/2}. \tag{2}$$

Here, λ denotes the wavelength of the incident-neutron beam, N the number of scattering centers per unit volume, a the scattering amplitude, and A the product $N\sigma_a$ wherein σ_a stands for the cross section of absorption. This first approximation, valid only for small absorption, may be simplified to read

$$r = 1-2(\sigma a/\lambda a)^{1/2}. \tag{3}$$

The result is wavelength-independent on account of

[1] We refer the reader to a comprehensive article by D. J. Hughes on Neutron Optics [Ann. Rev. Nucl. Sci. 3, 93 (1953)] giving a discussion of the background of the problems here treated and an extensive review of literature.

[2] W. C. Dickinson, L. Passell, and O. Halpern, Phys. Rev. 126, 632 (1962).

the $1/v$ law of absorption. For the case of a Co mirror, we obtain about 80% for r at the critical angle. If a second reflection is made with this arrangement, the reflection coefficient of only 80% does not signify polarization of only 60%, but incomplete reflection of an almost totally polarized beam. Ferromagnetic mirrors must therefore be studied very closely for their reflection properties before they are used for analyzation of polarized-neutron beams. Co mirrors recommended for other reasons may not be advantageous on account of the imperfect reflection properties.

As shown by Halpern and Holstein,[1] polarized beams are totally depolarized by very thin layers of unmagnetized ferromagnets, a fact which has been made use of almost routinely for the purpose of depolarization in double-transmission experiments, etc. The neutron interferometer described by Maier-Leibnitz[3] allows the separation of the neutron beam into two, and the subsequent observation of interference fringes from the superposition of the two separated beams. If now a very thin piece of ferromagnetic material is inserted into the path of one of these rays, the interference fringes may be expected to disappear. After passage through the thin ferromagnetic sheet, the state of polarization of one beam must be random with respect to that of the second, and therefore, no interference pattern should be observable any longer. This method of destroying coherence seems to us simpler than most optical procedures.

Lately, preliminary reports have been published (by Menzinger and Paoletti[4] on one hand, and Ferrier and Shull[5] and Shull[6] on the other) which deal with scattering problems of polarized-neutron beams. Although, due to the preliminary character of these publications, a really thorough analysis cannot be hoped for (the relative direction of polarization and propagation of the beam does not seem to be given), we want to make a few remarks on some problems hinted at. Menzinger and Paoletti[4] find a marked temperature dependence of the ratio between nuclear coherent scattering and magnetic scattering in the diffraction of a polarized beam by a single Co crystal at different temperatures, while Shull and his collaborators[5,6] measure the same ratio for a paramagnetic crystal which (in most cases) has partially oriented magnetic dipoles. Menzinger and Paoletti suggest two explanations, or a combination of both, for the effect that they observe. They consider the possibility that the temperature factor which, for the nucleus, is assumed to be the Debye-Waller factor valid in x rays, might be different for the (mostly outer) magnetically active electrons; they also discuss the possibility that the magnetic form factor itself may be temperature-dependent. Shull and Ferrier,[5] on the other hand, assume that the angular dependence of the magnetic-scattering amplitude is given by that of the magnetic form factor alone; this is allowed only if $\mathbf{q}\cdot\mathbf{s}=1$. For the exact definition of the vectors, reference may be made to the original paper of Halpern and Johnson.[1] It is explained there that, on account of the dependence on $\mathbf{q}$, the value of the amplitude depends even on the azimuth apart from the scattering angle. Whether Menzinger and Paoletti make the same assumption cannot be stated for lack of data.

In their two attempted explanations, the last-named authors seem to have paid no attention to the fact that the original Debye-Waller factor refers to electrons alone, although it was calculated for the motion of the nucleus. Confirmation of the applicability of this factor to the case of x rays therefore shows that, at least as an average over all electrons, it is a very good approximation, though separate statements about individual shells cannot be made. It must, on the other hand, be noted that it is highly unlikely that the outer shells should not move rigidly connected with the nucleus.

The assumption that the form factor of the outer shells should be temperature-dependent seems unlikely. The electronic and crystal dimensions are hardly changed by temperature expansion. On the other hand, in the paper of Halpern-Holstein,[1] it was shown that the depolarization of polarized-neutron beams depends very sensitively on the state of saturation and on the domain structure. That these might change a little cannot be excluded, particularly since the change of the nuclear to magnetic-amplitude ratio is only small for temperature changes of 600° and since no data about the real extent of saturation are given. It must be pointed out that one needs to know the saturation up to fractions of 1% so as to avoid depolarizing effects.

[3] H. Maier-Leibnitz (private communication).

[4] F. Menzinger and A. Paoletti, Phys. Rev. Letters **10**, 290 (1963).

[5] C. G. Shull and R. P. Ferrier, Phys. Rev. Letters **10**, 295 (1963).

[6] C. G. Shull, Phys. Rev. Letters **10**, 293 (1963).