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OBSERVATION OF SPATIAL SPLITTING OF A POLARIZED NEUTRON BEAM AS IT IS REFRACTED ON THE INTERFACE OF TWO MAGNETICALLY NON-COLLINEAR MEDIA

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Investigating the magnetic properties of matter by polarized neutron reflection or refraction, as a rule samples are used whose magnetization vector is collinear with the direction of an external magnetic field (collinear magnetic media). If the magnetization vector of the sample is non-collinear with the magnetic field vector due to the internal or shape anisotropy of the sample (the case of magnetically non-collinear media), in the magnetic field neutrons experience a transition from one spin state (denote "+" or "-") to the other ("-" or "+") as they go through the interface. The total energy of neutrons does not change, which results in a change in the kinetic energy of neutron motion in the direction perpendicular to the interface. As a result, the neutron beam spatially splits into a beam of neutrons which have experienced a transition to a new spin state (the beams are then denoted as "+-" or "-+") and a beam of neutrons which have not experienced such transition ("++" or "--" beams).

This effect was predicted by Ignatovich in 1978 [1]. In [2,3], expressions for the coefficients of transmission and reflection from an interface of two magnetically non-collinear media are obtained and can be used in experimental data processing. To determine the direction of refracted neutron beams, we use the energy conservation law. For squared glancing angles of refracted neutron beams, we obtain:

$$(\theta^{++})^2=\theta_i^2-\alpha[U+\mu\cdot(B-H)]\cdot\lambda^2 \qquad (1)$$

$$(\theta^{--})^2=\theta_i^2-\alpha[U-\mu\cdot(B-H)]\cdot\lambda^2 \qquad (2)$$

$$(\theta^{+-})^2=\theta_i^2-\alpha[U-\mu\cdot(B+H)]\cdot\lambda^2 \qquad (3)$$

$$(\theta^{-+})^2=\theta_i^2-\alpha[U+\mu\cdot(B+H)]\cdot\lambda^2 \qquad (4)$$

where $\alpha=2m/h^2$, θ_i is the glancing angle of the incident neutron beam; U is the potential energy of the nuclear interaction of neutrons and matter; B is the induction in the sample; H is the external magnetic field strength; μ is the magnetic moment of the neutron; m is the mass of the neutron; h is Planck's constant; λ is the neutron wavelength.

A magnetically non-collinear medium can be most simply realized with the help of shape anisotropy in the sample when the strength vector of an external magnetic field is directed at an angle to the surface of the magnetic film.

In [4,5], spatial splitting of a polarized neutron beam reflected from a magnetic film is observed.

In [6,7], spatial splitting of a polarized neutron beam on transmission through a magnetic layer on a nonmagnetic substrate (two interfaces) is investigated. In this case, the neutron beam goes through the magnetic layer and leaves the sample through the edge of the substrate. Because the beams "++" and "--" coincide in direction (in (1) - (2) it is necessary to take B = H), spatial splitting of the polarized neutron beam into two beams and of the nonpolarized neutron beam into three beams is observed.

In the refraction of neutrons as they go through a magnetic layer (two interfaces), the interference between neutron beams takes place due to multiple reflection from the layer boundaries. This leads to a very complicated picture of the dependence of the neutron flux on the wavelength. A simpler picture may possibly be observed in the case of neutron refraction on one interface.

In this article the refraction of a polarized neutron beam on the interface of two magnetically non-collinear media is investigated. The sample is the magnetic film Fe(86%)Al(9,6%)Si(4,4%) with the thickness 20 μm and a Cr 500 Å intermediate nonmagnetic layer. The size of the sample is 5 (along the beam) × 20 (in the vertical direction) mm^2, the thickness of the nonmagnetic substrate $CaTiO_3$ is 1 mm. The glancing angle of the neutron beam θ_i=4.8 mrad, the mean square divergence of the incident neutron beam is ±0.05 mrad, the mean square angular resolution of the spectrometer is ±0.2 mrad, the neutron wavelength varies in the interval λ=1.6 ÷ 4 Å. The external magnetic field strength is H=4.5 kOe, the angle between the sample plane and the magnetic field strength vector is $\beta=70^0$. The neutron beam falls on the surface of the film and leaves the film through the edge.

In the measurements we use a position-sensitive detector and a scheme for complete polarization analysis (a polarizer, two spin-flippers and an analyzer), which makes it possible to register four neutron intensities in different measuring modes: I(off,off) – two spin-flippers off; I(on,off) – the first spin-flipper on, the second off; I(off,on) – the first spin-flipper off, the second on; I(on,on) – two spin-flippers on.

With flippers 1 and 2 "on" ("off"), the polarizer - flipper 1 and the flipper 2– polarization analyzer sections predominantly transmit neutrons in the state "-" ("+"). The measurements are conducted with the SPN-1 spectrometer at the IBR-2 pulsed reactor in Dubna.

In Figs. 1a-d the neutron intensity for four measuring modes over the specified wavelength interval λ=2.02÷2.57 Å (the average wavelength $<\lambda>$=2.25 Å) is shown as a function of the angle θ between the sample plane and the direction of the refracted neutron beam. The measuring time in each "off,on" or "on,off" mode is about 6 times larger than in the "off,off" ("on,on") mode and is approximately 15 hours.

The peak at θ=4.8 mrad on the right corresponds to the direct beam (neutrons that missed the magnetic layer). The indices "+-", "--", "++" and "-+" mark the neutron beams refracted on the vacuum-magnetic film interface. The experimental values for the angular positions of these beams are given in Table 1. One can see that the smallest deviation from the direct beam has the beam "+-" (Fig. 1a) and the largest deviation has the beam "-+" (Fig. 1d). It should be noted that the beams "--" (Fig. 1b) and "++" (Fig. 1c) do not coincide in direction in contrast to the case of the refraction on two interfaces. So, one can see that the beam with one initial spin state "+" spatially splits into beams with different final spin states, "-" or "+".

The beam of neutrons with the initial spin state "-" also splits into two beams (Figs. 1b and 1d). In this case, in the measuring mode "on,off" in addition to the beam "-+" at 2.8 mrad there appear the beams "++" at 3.3 mrad and "--" at 4.1 mrad. The two latter beams are observed because the probability of their going through the sample is comparatively high while the polarization efficiency of the polarizer and the analyzer is not hundred percent.

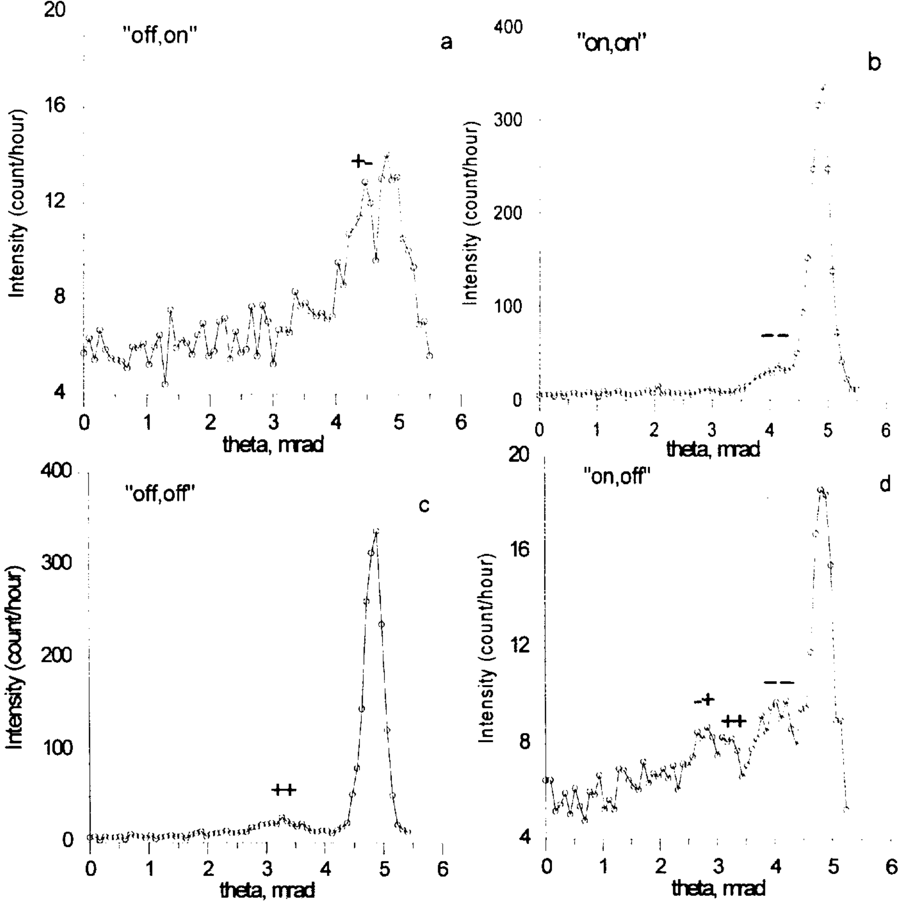

Fig.1. The dependence of the neutron intensity on the angle between the sample plane and the direction of the refracted neutron beam (the neutron wavelength interval $\lambda=2.02\div2.57$ Å, the average wavelength $\langle\lambda\rangle=2.25$ Å) for different measuring modes:
a) "off,on" ; b) "on,on" ; c) "off,off" ; d) "on,off" .

To analyze the experimental data, Eqs.(1)-(4) are used. To determine the energy of nuclear interaction between the neutron and the magnetic layer of the sample, measurements are conducted in an external magnetic field H=4.5 kOe parallel to the film plane ($\beta=0^0$). In this case, no splitting of the polarized neutron beam takes place (the beams "+-" and "-+" are absent). From the positions of the beams "++" and "--" the energy of nuclear interaction of the neutron with the magnetic layer is obtained, U=160 neV. The magnetic field induction is determined by measuring spin precession in the sample, B=12.2 kG. The obtained parameters are used to determine the direction of refracted neutron beams. The experimental and theoretical values of the angels θ between the plane of the sample and the direction of refracted beams are summarized in Table 1. One can see that the experimental and theoretical values coincide within the angular resolution of the spectrometer ±0.2 mrad.

Table 1

U=160 neV; B=12.2 kG; λ=2.25 Å; θ_i=4.8 mrad		
θ, mrad	experiment	theory
+-	4.4	4.4
--	4.1	4.0
++	3.3	3.2
-+	2.8	2.6

So, in the conducted investigation of neutron refraction on the interface of two magnetically non-collinear media splitting of a polarized neutron beam was observed. The beam of neutrons initially in the spin state "+" or "-" splits into two beams in the states "+" and "-". All split beams have different spatial positions. The reported phenomenon has been observed for the first time.

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Наблюдение пространственного расщепления поляризованного пучка нейтронов при преломлении его на границе раздела двух магнитно-неколлинеарных сред

Экспериментально наблюдено пространственное расщепление поляризованного пучка нейтронов при преломлении его на границе раздела двух магнитно-неколлинеарных сред. Пучок нейтронов в начальном спиновом состоянии «+» или «–» расщепляется в пространстве на два пучка нейтронов в состояниях «+» и «–». Все четыре расщепившихся пучка находятся в разных пространственных позициях. Данное явление наблюдено впервые.

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Observation of Spatial Splitting of a Polarized Neutron Beam as It Is Refracted on the Interface of Two Magnetically Non-Collinear Media

In the conducted experimental investigation of neutron refraction on the interface of two magnetically non-collinear media spatial splitting of a polarized neutron beam was observed. The beam of neutrons initially in the spin state «+» or «–» splits into two beams of neutrons in the states «+» and «–». All four split beams have different spatial positions. The reported phenomenon has been observed for the first time.

The investigation has been performed at the Frank Laboratory of Neutron Physics, JINR.

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