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V.L.Aksenov, Yu.V.Nikitenko, S.V.Kozhevnikov, F.Radu,
R.Kruijs*, M.Th.Rekveldt*

GENERATION OF NEUTRON STANDING WAVES AT TOTAL REFLECTION OF POLARIZED NEUTRONS

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*Interfaculty Reactor Institute, Delft University of Technology,
Mekelweg 15, 2629JB, Delft, The Netherlands

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1. INTRODUCTION

The neutron standing wave is generated in the process of neutron propagation in a crystal or a layered structure. Being a periodic spatial distribution of the neutron density the neutron wave demonstrates itself as "anomalous" neutron wavelength dependence of the probability of some neutron absorption process. Standing waves were first observed in 1956 when the effect of anomalous neutron absorption was detected in the $CdSO_4$ monocrystal experiment [1]. Later, a number of experiments were carried out to investigate different characteristics of the neutron wave field of that type. In [2-6], careful investigations of the processes of "anomalous" absorption in InSb and CdS crystals were conducted. In particular, in [5-6], the conclusion about coherency conservation in neutron wave propagation if the neutron wavelength corresponds to the resonance of a strongly capturing Cd nucleus, is made. In [7], anomalous standing wave field-related incoherent scattering on the hydrogen nuclei spins is studied. Generation of neutron standing waves in crystals depends on the elastic strain field. In this connection, a number of works [8,9] were conducted to investigate the reflecting capability of vibrating or bent crystals.

Similarly to neutrons, X-ray radiation propagating in layered structures has standing waves [10]. In [11], it is suggested to use X-ray standing waves for structure determination. The method consists of the measurement of the angular dependence of the secondary radiation intensity caused by X-ray absorption (secondary fluorescence, photo, or Auger-electron emission). The secondary radiation contains information about its emitting atoms. Registering the characteristic radiation we can determine the type and number of atoms and thus obtain detail structural information [12]. X-rays are scattered on the electron density. Their application is, therefore, limited to materials with a small charge number of the element.

Neutrons have a high penetrability and possess the magnetic moment. They are, therefore, used to investigate media containing elements with a larger charge number or/and magnetoactive atoms. The characteristic radiation arising on neutron capture is primarily the characteristic gamma-radiation of a majority of nuclei (note that namely in [1] the wave field of neutron standing waves was discovered by registering gamma-radiation emitted by Cd nuclei). In [13], neutron standing waves in a layered structure with a characteristic layer thickness of the order of several hundred angstroms were observed. The gamma-radiation intensity of a 84Å gadolinium layer was measured as a function of the neutron glancing angle. The observed dependence has a number of maximums corresponding to different orders of neutron wave absorption. The authors [14] make the conclusion about the observation of resonance enhanced standing waves. In fact, the enhancement is realized only if the node of the standing wave is on the gadolinium layer. For glancing angles at which on the gadolinium layer there is the antinode of the standing wave the enhancement regime is not realized due to high neutron absorption.

This article suggests the new measuring method based on the use of standing waves with a particular, "+(-)", spin state (neutron spin projection is in/opposite the direction of the magnetic field). The standing wave with a particular spin state can be used to determine the spatial position of the layer that causes changes in the population of neutron spin states in the magnetic field. Such population changes may be due to neutron-nucleus spin-dependent interaction and the interaction of the neutron with the electronic shell of the atom. The second interaction is responsible for the coherent spin transition of the neutron at transmission through the interface of magnetic noncollinear media (or a magnetic noncollinear layer). All neutrons that are reflected, refracted and undergone transition in a magnetic noncollinear medium form a secondary radiation which is the test of the magnetic atom. The flux of such neutrons is concentrated in a small solid angle. This ensures a high luminosity and a higher than background useful neutron count. As a result, we have the spatial sensitivity of measurements on the atomic scale.

Below are the results of the experimental verification of the possibility of generation of neutron standing waves with a particular spin state at total reflection as well as their application for the determination of the position of magnetic noncollinear layers.

2. MEASURING METHOD

Let us discuss the qualitative picture of the formation of neutron standing waves at total neutron reflection. The optical potential (Fig.1a.) of the coherent neutron interaction consists of a transforming (transformer), phase shifting (phase shifter) and a wave reflecting (reflector) region. In the phase shifter, at the distance L from the reflector there is a magnetic layer (neutron spin-flipper) with the magnetization vector noncollinear to the external magnetic field direction. Let the incident neutron wave in vacuum be $\psi_0^{\leftarrow}$. Having travelled through the transformer the $\psi_0^{\leftarrow}$ function transforms into $\psi^{\leftarrow}(x)$. In the shifter, there propagates the resulting wave $\psi^{\leftarrow}(x)$ being the sum of waves with different reflection multiplicities from the "shifter-reflector" or "shifter-vacuum" interfaces. The reflecting wave is reflected from the reflector with the amplitude r. This leads to the appearance of the opposite running wave $\psi^{\rightarrow}(x)=\exp(ikx)r\exp(ikx)\psi^{\leftarrow}(x)$. The waves $\psi^{\rightarrow}(x)$ and $\psi^{\leftarrow}(x)$ interfere. As a result, in the shifter at the distance x, there is formed the standing wave $\psi(x)=(1+e^{ikx}re^{ikx})\psi^{\leftarrow}(x)$ with the spatial period T_x:

$$T_x=(\lambda/2\sin(\theta))/(1-\beta U_{sh}(\lambda/\sin(\theta)^2))^{1/2}, \qquad (1)$$

where $\beta= 2m/h^2$, h is the Planck constant, m is the neutron mass, λ is the neutron wavelength in vacuum, θ is the glancing angle of the neutron beam, U_{sh} is the potential of the coherent interaction of the neutron and the phase shifter.

For the reflected neutron beam with the "- (+)" spin state we have

$$J_{R,-(+)} \sim \quad |\alpha_{+,sf(nsf)}\psi^{+}(x_m) + \alpha_{-,nsf(sf)}\psi^{-}(x_m)|^2 =$$

$$|\alpha_{+,sf(nsf)}\,(\psi^{+\rightarrow}(x_m)+\psi^{+\leftarrow}(x_m))+\alpha_{-,sf(nsf)}(\psi^{-\rightarrow}(x_m)+\psi^{-\leftarrow}(x_m))|^2 \qquad (2)$$

where the coefficient α is expressed in terms of the transmission and reflection amplitudes of the phase shifting region from the spin-flipper to the "shifter-vacuum" interface, x_m is the position of the spin-flipper. Equation (2) shows that the reflected neutron beam J_R is determined not only by the interference of opposite running waves with particular spin states but also by the interference of waves with the neutron spin states "+" or "-" in the shifter. The interference of opposite running waves results in that the neutron intensity is a periodic function of the neutron wavelength and the spin-flipper coordinate. At the same time, the interference of waves with different spin states leads to washing or even twinning of intensity peaks. The washing is the stronger the larger is the magnetic field strength in the shifter. It is clear that the neutron flux from one spin state to the other is maximum when the antinode of the standing wave $|\psi^{\rightarrow}+\psi^{\leftarrow}|^2$ coincides with the position of the spin-flipper. In this case, the following condition must be met

$$L+\Delta(\lambda)=nT_x(\lambda)\ , \qquad (3)$$

where L is the distance from the spin-flipper to the neutron reflector, $\Delta(\lambda)$ is the spatial shift caused by a change in the reflection amplitude phase from the reflector. Condition (3) is equivalent to the Bragg condition satisfied in neutron reflection from a structure with the period L. At the same time, the term $\Delta(\lambda)$ appears due to the fact that the neutron energy in the direction perpendicular to the interface has a value comparative to the interaction potential. In fig. 1b, there are exemplified the standing wave harmonics that realize the first, second and the third absorption orders of the neutron wave for the wavelengths λ_1, λ_2 and λ_3, respectively

Figures 2a,b illustrate the dependence of the coefficient of neutron reflection without and with a change in the initial neutron state "+", R_{++} and R_{+-}, from the structure glass/Cu(2000Å)/Ti(x)/Co(50Å,17.9 kOe) in the magnetic field H=10 kOe directed at the angle $\gamma=80^0$ to the plane of the sample (to the magnetization vector of the cobalt layer). It is seen that in the total reflection region (λ >2.1Å), the coefficients R_{++} and R_{+-} are in antiphase and there holds the condition $R_{++}+R_{+-}=1$. This is the evidence of the fact that the incident neutron beam is distributed between the reflected fluxes of neutrons that did not experience and experienced the transition. Figure 2 shows that the period of the standing wave tends to a finite value of the order 500Å as the wavelength increases in accordance with Eq. (1) for the phase shifting titanium layer with a negative

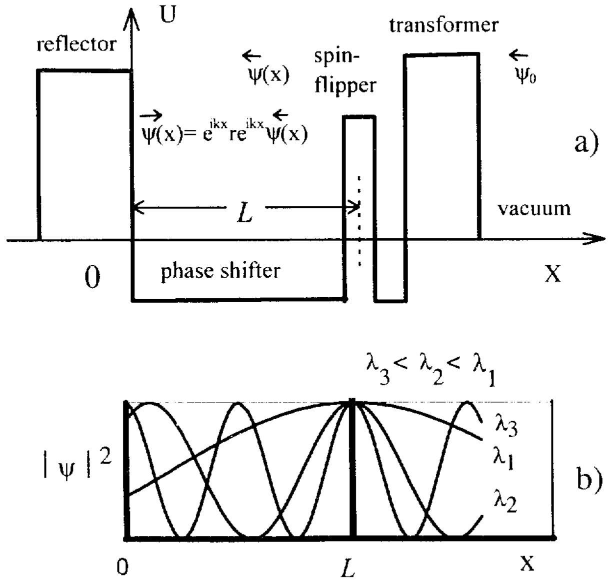

Fig. 1. The scheme of the optical potential in the generation of neutron standing waves at total reflection.

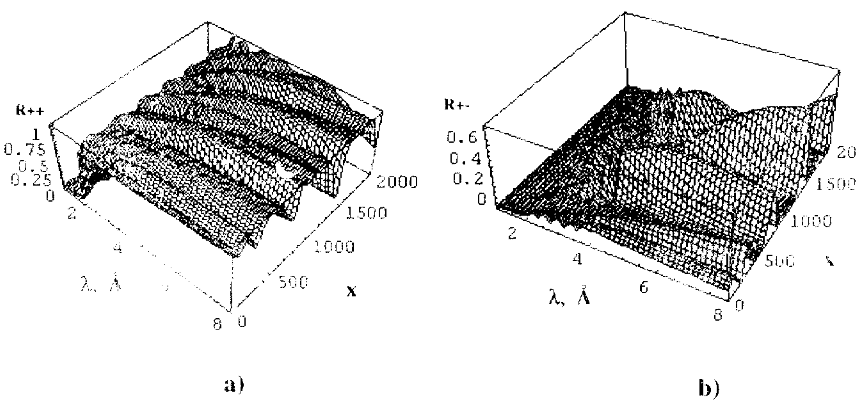

Fig. 2. The dependence of the neutron reflection coefficient on the wavelength λ and the thickness of the phase shifting titanium layer X for the structure glass/Cu(2000Å)/
Ti(X)/Co(50Å, 17.9 kOe).

nuclear potential. Let us estimate the luminosity of the measurement of changes in the shifter thickness (changes in the position of the magnetic noncollinear cobalt layer). The calculation shows that for the neutron flux 10^5n/cm^2/sec on the sample measuring 50mm×100 (along the beam direction) a change in the shifter thickness by 0.1Å results in a count change equivalent to a measuring error over a measuring period of several hours. Thus, the sensitivity of measurements in the standing wave regime allows the observation of changes in the spatial position on the level of 10^{-4} of the standing wave period.

3. INSTRUMENTATION

The reported measurements were conducted on the SPN spectrometer of polarized neutrons (Fig. 3) at the IBR-2 pulsed reactor in Dubna. The neutron beam from the polarizer is collimated using Cd diaphragms on the 3 m flight path to the sample. The mean square devitation of a θ =2.5÷4 mrad glancing angle of the incident beam in the direction of a normal to the reflecting surface of the sample is ±0.25 mrad. The neutron beam reflected from the sample is registered with a ^{3}He gas position sensitive detector. The detector is at the distance 2.6÷8 m from the sample. The neutron beam spectrometry is accomplished by measuring the neutron time of flight from the moderator to the detector. The wavelength mean square deviation is within the range 0.017÷0.02Å. The reflected neutron beam from the sample is transmitted through a polarization analyzer. Between the polarizer and the sample and between the sample and the analyzer there are installed two spin flippers to change the polarization of the incident on the sample and the reflected from the sample neutron beams. The measurements consist of registering the reflected from the sample neutron counts J(on(off),on(off)) in turn in four measuring modes corresponding to four states "on(off), on(off)" of two spin-flippers.

The sample is a multilayer structure Cu(1000Å)/Ti(2000Å)/Co(60Å)/Ti(300Å) on a glass substrate measuring 100mm×60mm×5mm. The upper 300Å titanium layer is to protect cobalt from oxidation. For the sample to be magnetically noncollinear a magnetic field is applied at an angle γ to the sample plane. The magnetic field is varied from 10 Oe ÷ 7 kOe and the angle γ is varied within the limits 0 ÷ 90 degrees of arc.

4. RESULTS OF MEASUREMENTS

Figures 4a,b show the wavelength dependence of the parameters α(off,on) and α(off,on) for external magnetic fields H=6.75 kOe and H=4.6 kOe and angles $\gamma=80^0$ and $\gamma=0^0$. The parameters α are the ratios of neutron counts (with subtraction of the background count J_{fon}) and are related by $\alpha(off,on)=\Sigma_{\Delta\theta 1}(J(off,on)-J_{fon})/\Sigma_{\Delta\theta 3}(J(off,off)-$

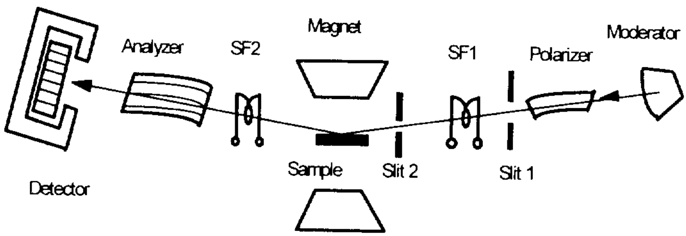

Fig. 3. The experimental layout.

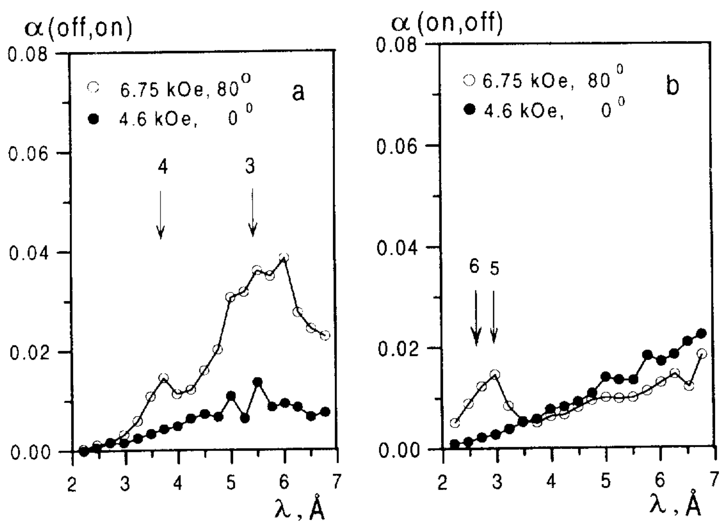

Fig. 4. The wavelength dependence of the ratios of counts α(off,on) and α(on,off) for glancing angle of the incident beam 3.2 mrad, the sample to detector distance 3m.

J_{fon}) and α(on,off)=$\Sigma_{\Delta\theta 2}$(J(on,off)-J_{fon})/$\Sigma_{\Delta\theta 3}$ (J(on,on)-J_{fon}). In the first approximation, the parameters α(off,on) and α(on,off) are proportional to the reflection coefficients R_{+-} and R_{-+}. Due to the fact that the energy of the potential interaction between the neutron and the magnetic field changes at neutron transition from one Zeeman sub-level to another, neutrons are reflected in the nonspecular direction [15]. In this connection, the summation in the expressions for the parameter α is over the intervals of the glancing reflection angle of nonspecular beams $\Delta\theta_1$= 4.34÷8.33 mrad and $\Delta\theta_2$=0÷1.99 mrad and of the specular beam $\Delta\theta_3$= 2÷4.34 mrad. It is seen that the curves corresponding to $\gamma=80^0$ have peaks at λ=3.7 and 5.6Å (Fig. 4a) and λ=2.8Å (Fig. 4b). The peaks are connected with the appearance of neutrons with a spin state opposite to the initial one. Let us emphasize that the increase in neutron counts after transition at certain neutron wavelengths is not connected with an increase of the neutron transition probability but is caused by an increase of the neutron density at the position of the magnetic noncollinear layer of cobalt atoms (see Eq. (2)). The observed peaks(λ=5.6 and 3.7Å) correspond to the third and the fourth absorpsion orders (n=3 and n=4) at the initial "+" spin-state(see Eq. (3)). The peak at 2.8Å is actually formed by two peaks of the fifth and the sixth absorbsion orders at the initial "-" spin-state. The absence of lower multiplicity orders for the spin-state "-" is due to the existence of the forbidding condition that is realized when the kinetic neutron energy of the neutron with a "-" spin state in the direction perpendicular to the interface is smaller than the necessary potential energy change. Of interest is the fact that for the spin-state "+", the third order peak is wider than the fourth order peak. This happens because in addition to the wave with the initial spin state "+", in the shifter there propagates a wave with the spin state "-" (see Eq.(2)). As a result, there appears a phase difference caused by the difference in the values of the wave vectors of waves with different spin states. It can be also seen that the spin flip probability is not higher than 4%. The calculation shows the magnetization of the magnetic layer is 2.9 kOe. It is much lower than the saturation magnetization of Co equal to 17.9 kOe. A low magnetization of the magnetic layer is due to metalic Co oxidation into CoO. The conducted calculation shows that the layers are oxidized to a considerable degree. The actual layered structure is presented as glass/1000Å(Cu)/1500Å (Ti)/500Å($7Ti_2O_3$+3Ti)/60Å(1Co+4CoO)/115Å(Ti)/195Å($7Ti_2O_3$+3Ti). Of interest is the observation of neutron interference directly by means of the angular dependence of the registered flux of the reflected neutrons. The angular dependence exists for the nonspecular reflected beam whose appearance is, as mentioned above, connected with a change in the energy at neutron transition from one sub-level to another in the magnetic field. To be precise, the glancing angle θ_{nspec} of the nonspecular reflected beam is related to the glancing angle θ_{spec} of the specular reflected beam by θ_{nspec}^2(mrad^2)= θ_{spec}^2 (mrad^2)± 0.147H(kOe)λ^2(Å^2). As a result, the periodic wavelength dependence of the intensity of the beams (on,off) and (off,on) becomes a periodic function of the glancing angle as well due to the formation of standing waves. Figure 5 illustrates the dependence on the glancing angle of the intensity of the beams "off,on" and "on,off".

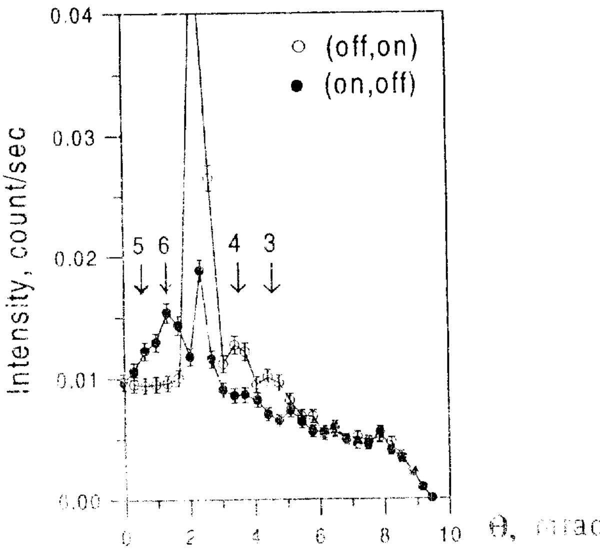

Fig. 5. The dependence on the glancing angle of the nonspecular reflected beam of the counts I(off,on) and I(on,off) for H=6.75kOe and γ=80^0, the glancing angle of incident beam 2.4mrad, and the sample to detector distance 8 m.

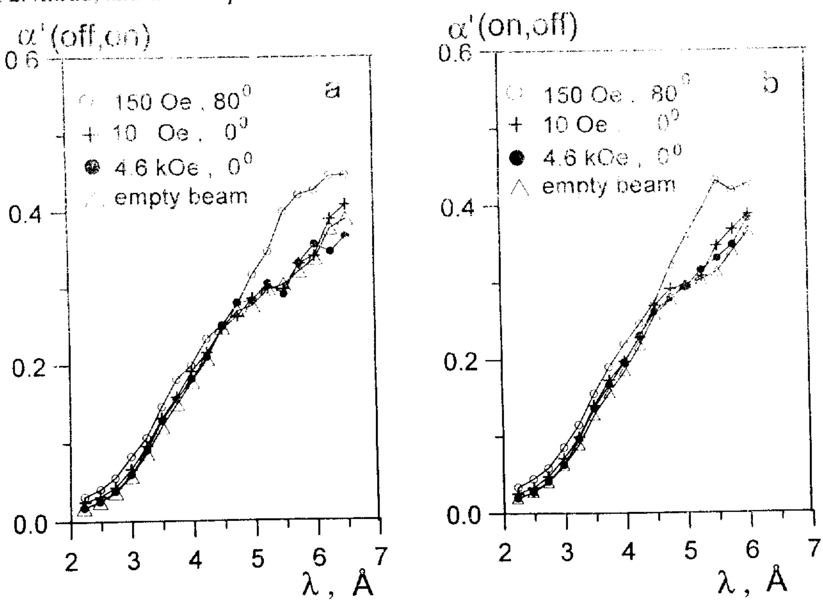

Fig. 6. The wavelength dependence of the parameters α'(off,on) and α'(on,off) for glancing angle of the incident beam 3.2mrad , the sample to detector distance 3m.

Against the background of a strong peak of specular reflected neutrons there are seen peaks of the fourth and the third absorpsion orders of the initial "+" spin-state at the reflection angles 3.69, 4.83mrad and peak of the fifth and the sixth absorption orders of the initial "-" spin-state at the reflection angle 1.5mrad.

In Figs. 6a,b there is shown the dependence of the parameters α'(off,on) and α'(on,off) for H and γ equal to 150 Oe and 80^0, 10 Oe and 0^0, 4.6 kOe and 0^0. For such H and γ the reflected beam is specular. In this connection, the parameters α' differ from the parameters α by that in the numerator of the expression for α' the summation is over the specular reflected beam interval $\Delta\theta_3$. It is seen that in contrast to the data in Fig. 4, both of the curves in Fig 6 corresponding to γ=80^0 have a maximum for the wavelength 5.6Å. This is explained by the fact that the magnetic field 150 Oe is no longer sufficient to prevent the appearance of the peak on the dependence α(on,off) (Fig.6b). At the same time, it is obvious that the transition probability increases to 0.1 due to the increase of the angle between the magnetic field vector and the magnetization vector. Fitting the experimental data shown in Fig. 6 we obtained the parameters of layers equal to their values obtained by fitting the data shown in Figs. 4-5.

5. CONCLUSION

The conducted investigation demonstrates that at total reflection a neutron standing wave with a particular spin state is generated at the distance 2000Å from the neutron reflector. For the investigated wavelength interval 2÷7Å the standing wave period is 250÷500Å. The suggested method of neutron intensity measurements after their spin transition in a magnetic field makes it possible to determine the position of a magnetic noncollinear layer with a magnetization of several hundred kiloersteds and a thickness of some angstroms. The luminosity of measurements on the beam with the flux density 10^5n/cm^2/sec is high enough to detect a change in the position of a 50Å ferromagnetic layer by the value 0.1Å in several hours of measurements. Complementary to polarization analysis, registration of the reflected neutron beam is accomplished by the method of neutron beam splitting in an external magnetic field directed at some angle to the sample plane. This increases the registration efficiency of spin-flipped neutrons.

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References

1. J.W. Knowles, Acta Crystallographica, **9**, 61 (1956).
2. D. Sippel, K. Kleinstuck, G.E.R. Schulse, Phys. Status. Solidi, **2**, 104 (1962).
3. D. Sippel, K. Kleinstuck, G.E.R. Schulse, Phys. Letters, **8**, 241 (1964).

4. F. Eichhorn, D. Sippel, K. Kleinstuck, Phys. status solidi, **23,** 237 (1967).
5. S.Sh.Shilstein, V.I.Marukhin, M. Kalanov, et al., Pisma ZhETF **12,** 80 (1970).
6. S.Sh.Shilstein, V.A. Somenkov, V.P. Dokashenko, Pisma ZhETF, **13**, 301 (1971).
7. D. Sippel, F. Eichhorn, Acta Crystallogr., **A24**, 237 (1968).
8. R. Michalec, P. Mikula, L. Sedlakova, Phys. Status solidi, **a26,** 317 (1974).
9. R. Michalec, P. Mikula, L. Sedlakova, Phys. Status solidi, **a23,** 667 (1974).
10. B.V. Batterman, H. Cole, Rev. Mod. Phys. **36**, 681 (1964).
11. B.V. Batterman, Appl.Phys.Lett. **1**, 68 (1962).
12. M.V. Kovalchuk, V.G. Kon, Usp.Fiz.Nauk **149**, 69 (1986).
13. H. Zhang, P.D. Galagher, S.K. Satija et.al, Phys. Rev. Lett. , **72** ,3044 (1994).
14. M. Maaza, B. Pardo, F. Bridou, Nucl. Instr. and Meth., **A326**, 531 (1993).
15. V.K. Ignatovich, Pisma ZhETF, **28**, 311 (1978).

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Аксенов В.Л. и др. Д3-98-369
Генерация нейтронной стоячей волны
при полном отражении поляризованных нейтронов

Осуществлен режим нейтронных стоячих волн при отражении поляризованных тепловых нейтронов от структуры стекло/Cu (1000 Å)/Ti (2000 Å)/Co (60 Å)/Ti (300 Å), помещенной в магнитное поле, направленное под углом к плоскости образца. Интенсивность нейтронов в определенном спиновом состоянии является периодической функцией длины волны и угла скольжения отраженного пучка. Показано, что режим стоячих нейтронных волн может быть использован для определения с высокой чувствительностью изменения пространственного положения магнитно-неколлинеарного слоя.

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Перевод авторов

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Generation of Neutron Standing Waves
at Total Reflection of Polarized Neutrons

The regime of neutron standing waves at reflection of polarized thermal neutrons from the structure glass/Cu (1000 Å)/Ti (2000 Å)/Co (60 Å)/Ti (300 Å) in a magnetic field directed at an angle to the sample plane is realized. The intensity of neutrons with a particular spin projection on the external magnetic field direction appears to be a periodic function of the neutron wavelength and the glancing angle of the reflected beam. It is shown that the neutron standing wave regime can be a very sensitive method for the determination of changes in the spatial position of magnetic noncollinear layers.

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

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