СООБЩЕНИЯ
ОБЪЕДИНЕННОГО
ИНСТИТУТА
ЯДЕРНЫХ
ИССЛЕДОВАНИЙ

Дубна

E14-99-227

V.L.Aksenov, S.V.Kozhevnikov, Yu.V.Nikitenko,
H.Lauter*

REFLECTION AND REFRACTION OF SPIN-FLIP NEUTRONS IN A Fe-Gd STRUCTURE

*ILL, Grenoble, France

1999

Аксенов В.Л. и др. E14-99-227
Отражение и преломление нейтронов с переворотом спина в структуре Fe-Gd

Исследовано отражение и преломление поляризованных нейтронов в пленочной структуре Fe(1000 Å)/Gd(50 Å) в режиме генерации стоячей нейтронной волны. Использован метод пространственного расщепления поляризованного пучка нейтронов. Внешнее магнитное поле, направленное параллельно плоскости пленки, составляло 18 Э ÷ 4,4 кЭ. Обнаружен процесс трех последовательных переворотов спина нейтрона. Два переворота спина нейтрона связаны с передачей момента в плоскости пленки, а третий — с передачей момента в направлении, перпендикулярном плоскости. Это может быть объяснено существованием доменной структуры, в которой вектор намагниченности направлен под углом к плоскости пленки.

Работа выполнена в Лаборатории нейтронной физики им.И.М.Франка ОИЯИ.

Сообщение Объединенного института ядерных исследований. Дубна, 1999

Aksenov V.L. et al. E14-99-227
Reflection and Refraction of Spin-Flip Neutrons in a Fe-Gd Structure

Neutron reflection and refraction in the Fe(1000 Å)/Gd(50 Å) film structure were investigated in the regime of generating a neutron standing wave. The polarized neutron beam-splitting method was used. An external magnetic field, changing within the limits 18 Oe to 4.4 kOe, was applied in the plane of the film. Three sequentially occurring neutron spin transitions were discovered. Two of them were accompanied with a momentum transfer in the plane of the film, and the third was accompanied with a momentum transfer in the direction perpendicular to the plane. This can be explained by the existence of a domain structure where the magnetization vector is directed out of the film plane.

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

Communication of the Joint Institute for Nuclear Research. Dubna, 1999

1. Introduction

The magnetism of multilayer (ML) rear-earth—transition metal (RE/TM) is unique [1]. The effects of exchange and magneto-crystalline anisotropy make the magnetic phase diagram rather complex. For the ML Gd/Fe system, spatially extended magnetic structures peculiar to "aligned Fe", "aligned Gd", and "twisted" phases were predicted [2-4]. The existence of these phases was confirmed in [5-8]. The investigation of ML (RE/TM) by polarized neutron transmission and reflection permits us to determine the spatial profile of the magnetization vector. As a result, the parameters of the exchange RE/TM interaction and magnetic anisotropy can be determined rather accurately. In the last two or three years, the effects of standing wave generation of a certain spin state [9-11] and polarized beam splitting at the interface of two media were observed in the experiments on polarized neutrons [12]. The methods based on this phenomena permit investigations of regions near separate interfaces, with a spatial resolution of 10 Å and sensitivity of 10 Oe and 1^0 by the value and direction of the magnetization vector, respectively. In this work, the first results of investigating the structure of Fe(1000 Å)/Gd(50 Å) using the methods of generating of standing waves and splitting the polarized neutron beam, performed at room temperature in the range of measurement of the strength of the external magnetic field, 18 Oe ÷ 4.4 кOe, are reported.

2. The investigation methods and instruments

In this study, the method of neutron density concentration on certain structure layers was applied. For this purpose, an investigated sample of glass/Fe(1000Å)/Gd(50Å) was prepared in a manner to form a neutron wave field in the form of a standing wave in the region around the Fe-Gd interface. A 1000 Å - thick iron layer played the role of the reflector of the incident wave. The standing wave forms for a positive spin state (spin projection along the magnetic field direction) in the range of values of the perpendicular to the interface wavelength $\lambda_\perp > \lambda_{\perp+}$ and for a negative spin state (spin projection opposite the magnetic field direction) in the range $\lambda_\perp > \lambda_{\perp-}$ ($\lambda_{\perp+}$ and $\lambda_{\perp-}$ are the limiting values of the perpendicular wavelength for the positive and negative spin states). With an increase in $\lambda_\perp$ above the limiting value, an antinode of standing wave is moving from the reflector. This fact permits one to scan the region above the reflector surface, by changing $\lambda_\perp$ and, thus, determine the location of the absorbing or spin-flipping layer.

To identify the transition type in a magnetic field with the gradient perpendicular to the interface and determine the magnetic field strength in the layer adjacent to the surface, a new method was used. The new method is based on the spatial splitting of the polarised neutron beam into a neutron beam that experienced a spin transition in the magnetic field and a neutron beam that did not. The method consists in measuring the differential angle $\Delta\theta$ between these beams. In the reflectometric measurements, the differential angle $\Delta\theta_r$ is proportional to the value of the magnetic field Hs_1 in front of the first interface of the nonmagnetic layer with the magnetic layer. After this point, there is the magnetic field gradient directed perpendicular to the interface.

In the measurements of neutron transmission through the magnetic layer, the differential angle $\Delta\theta_{tr}$ is proportional to the magnetic field Hs_2 in the nonmagnetic layer near its interface with the magnetic layer, where the magnetic field alteration stops due to the perpendicular gradient. The magnetic fields Hs_1 and Hs_2 are connected by the relation $Hs_2 = Hs_1 + \nabla H_{12}$, where ∇H_{12}

is the magnetic field alteration on the neutron path between the magnetic and nonmagnetic layer interfaces that is caused by the magnetic field gradient perpendicular to the interface. From the condition of noninterruption of the normal component of the magnetic induction on the interface, the value Hs can be connected with the boundary value of Jn of the perpendicular component of the magnetisation of a magnetic layer and the values of the tangential Ht and the perpendicular Hn components of the strength of the external magnetic field:

$$Hs = (Ht^2 + (Hn + Jn)^2)^{1/2}.$$

The measurements were carried out at the SPN polarised neutron spectrometer of the IBR-2 pulsed reactor in Dubna. The mean-square deviation of the grazing angle θ=2.5÷4 mrad of the incident neutron beam normal to the reflecting surface of the sample was equal to ±0.25 mrad. The mean-square deviation of the wavelength from the average value 1÷10Å was equal to 0.02Å. The neutron beam reflected from or refracted in the investigated sample was transmitted through the polarization analyzer and registered by a ^{3}He gas position-sensitive detector. Spin-flippers were located between the polarizer and the sample, and between the sample and the polarization analyzer. These spin-flippers changed the polarization of the beams incident to the sample and passing through the sample. Thus, four counts of neutrons reflected from the sample and four counts of neutrons refracted in the sample, corresponding to the four states "on(off), on(off)" of two spin-flippers, respectively, were registered. From those counts, the spin-dependent reflection coefficients R_{++}, R_{+-}, R_{-+}, and R_{--}, and the spin-dependent transmission coefficients T_{++}, T_{+-}, T_{-+}, T_{--} [13], corresponding to the four spin transitions "++", "+-", "-+", "--", were determined.

3. Measurement results and discussion

In Fig. 1 the contours of equal intensity for reflected and refracted beams at external magnetic field values of 110, 163, and 277 Oe for the spectrometer state "on,off". The dependencies shown in Fig. 1 were obtained after the preliminary reverse magnetization of the sample with the 4 kOe magnetic field. It can be seen that at H=110 Oe, in addition to the reflected beam, (the grazing angle is 4.14 mrad) there are non-specular reflected and refracted neutron beams caused by the "-+L" transition. In the designation of the spin transition, "L" denotes that the quantization axis is a local magnetic field H_{LOC}. At H=163 Oe, these beams are absent, while at H=277 Oe, there are already beams determined by the transition "+-L". From the sign of the transmission of the energy ΔE to the neutron, (the transition "+-L" takes place at $\Delta E > 0$ and the transition "-+L", at $\Delta E < 0$), one can make a conclusion about the type of transition.

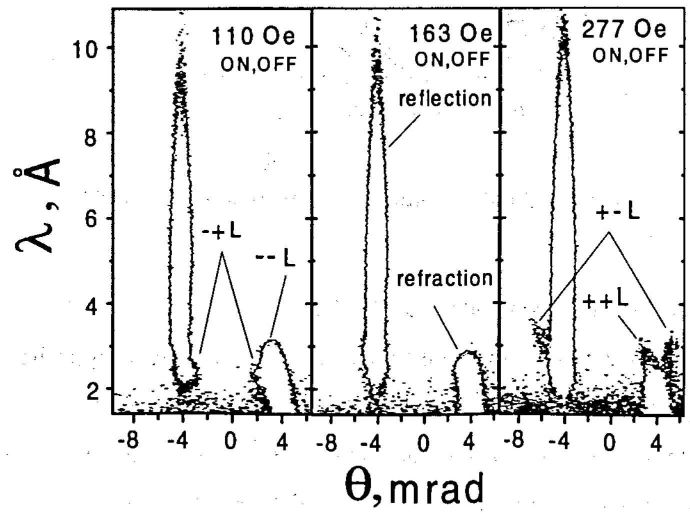

Fig. 1. Equal intensity contour.

Spectral dependencies of the reflection coefficient for spin-flip neutrons, obtained by the polarization analysis, are shown in Fig. 2. Here, the data for the case of non-specular reflection are marked by closed circles for the transition "+-L" and with open circles for the transition "-+L". It can be seen that at H=277 Oe, the states "-+" and "+-" in the external magnetic field correspond to the states "+-L" and "-+L" in the local magnetic field.

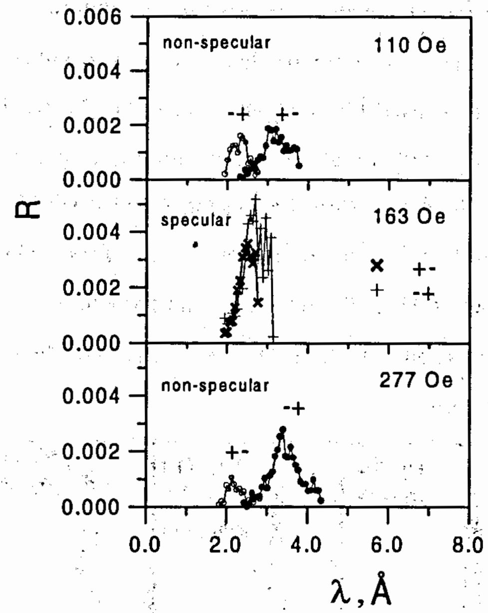

Fig. 2. Reflection coefficients for the beams "+-" and "-+".

Thus, we can conclude that at H > 163 Oe, two spin-flip processes exist, which change the initial and final neutron states to their opposites. These spin-flip processes may be connected either with the formation of a region of zero magnetic induction, where the reverse of the magnetic field induction vector takes place, or with a region where the induction vector changes in a more complicated way. In the latter case, the spin-flip is realized for the wavelength band, while in the first case, it is realized for a semi-infinite interval of the wavelength with some maximum value λ_{max}.

In Fig. 3, the dependencies for $R_{++}(\lambda)$ and $R_{--}(\lambda)$ are given. One can see that with an increasing magnetic field in the interval 110÷277 Oe, the difference $\Delta R = R_{++}(\lambda) - R_{--}(\lambda)$ changes its sign and at H= 163 Oe, it reaches the minimum value by its absolute magnitude. At this point, the probability of a spin-flip in the region of a specular reflected beam increases (see Fig. 2 at H=163 Oe). The data of Figs. 2 and 3 at H=163 Oe can be explained as a reduction of the perpendicular magnetization component Jn. The tangential magnetization component Jt tends to be directed perpendicularly to the direction of the external magnetic field. At present, precise calculations to determine the dependence of the profile of the magnetization vector on the strength of the external magnetic field are being carried out.

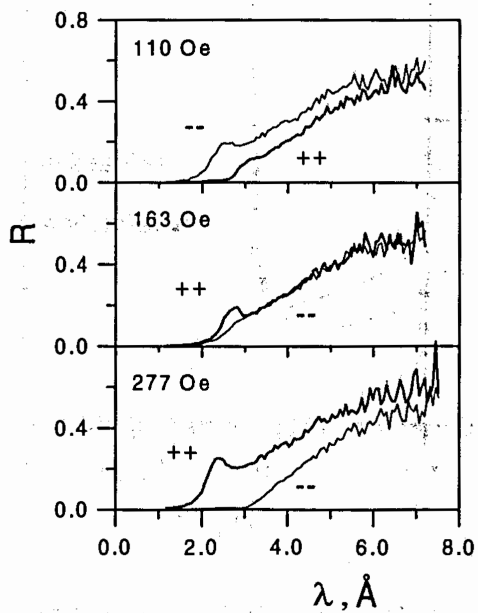

Fig. 3. Reflection coefficients for the beams "++" and "--".

In Fig. 4, the values of Jn_1 and Jn_2 versus the external magnetic field applied parallel to the plane of the sample, are shown. It can be seen that the absolute value of Jn_1 and Jn_2 practically do not change and are 10÷14 kOe at H < 150 Oe and 13÷18 kOe at H > 200 Oe. At the point $H^* = 163$ Oe, Jn_1 and Jn_2 change their signs. In the range H = 200 ÷ 700 Oe, the Jn_1 and Jn_2 alteration occurs in the opposite phase. This may be explained by the opposite correlated turning of the magnetization vectors J_1 and J_2 in respect to the direction of the external magnetic field.

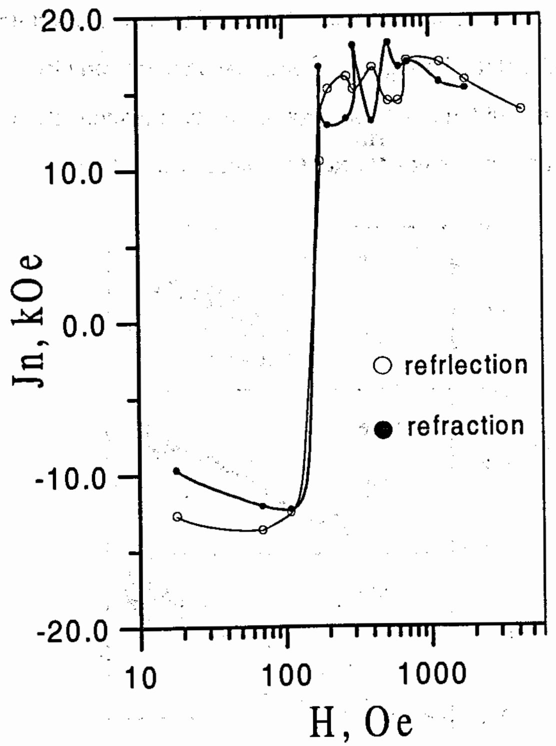

Fig. 4. The dependence of the perpendicular magnetization component in a gadolinium layer Jn_1 (open circles) and in an iron layer Jn_2 (closed circles).

Further observation shows that with increasing magnetic field strength, up to a maximum value of 4.4 kOe, the intensity of the spin-flip neutron beams decreases. The grazing angle of these beams practically does not change. Such behavior can be explained by a reduction in the cross-section of the regions (domains), magnetized normal to the interface, or by the attempt of Jt to be oriented in the direction of the external magnetic field. Finally, from the spectral position of the maxima, in the reflection coefficients of spin-flip neutrons, and minima connected with the absorption of neutrons in gadolinium when the field of neutron standing waves is generated, it follows that the region of flipping is located closer to the Fe-Gd interface than the region of nuclear neutron absorption.

The above facts and the preliminary calculations allow us to draw the following picture of the distribution of magnetization in the Fe/Gd structure. First, there are two types of regions. In the first region, the magnetization of the gadolinium layer is directed normal to the sample plane. The transmission of neutrons through this region leads to polarized neutron beam splitting. At $H = H^*$, the magnetization of this region lies in the surface of the sample.

The second region, where the cross-section area at a strength of about 300 Oe is at least ten times greater than that of the first region, is an iron layer coated by a gadolinium layer, or by a gadolinium oxide layer, and the magnetization is directed parallel to the direction of the external magnetic field. The transmission of neutrons through this region does not split the polarized beam. At $H=H^*$, the magnetization in this region lies in the sample plane and is directed normal to the direction of the external magnetic field.

Thus, the obtained results clearly demonstrate the efficiency of the joint use of neutron beam polarization analysis, the effect of polarized beam splitting, and the creation of a field of neutron standing waves to investigate layered structures characterized by the complicated spatial behaviour of the magnetization vector.

1. Z.S Shan, D.J. Sellmyer, S.S. Jaswal, Y.J. Wang, .X. Shen, Phys. Rev. B 42 (1990) 10446.

2. R.E. Camley, Phys. Rev. B 35 (1987) 3608.

3. R.E. Camley, D.R. Tilley, Phys. Rev. B 37 (1988) 3413.

4. R.E. Camley, Phys. Rev. B 39 (1989) 12316.

5. K. Cherifi, C. Dufour, Ph. Bauer, G. Marchal, Ph. Mangin, Phys. Rev. B 44 (1991) 7733.

6. Ph. Bauer, M. Sajieddine, C. Dufour, K. Cherifi, Europhys.Lett. 16 (1991) 307.

7. H. Dohnomae, T. Shinjo, M. Motokawa, J.M.M.M. 93 (1991) 477.

8. Ñ. Dufour, K. Cherifi, G. Marchal, Ph. Mangin, Phys. Rev. B 47 (1993) 14572.

9. V.L. Aksenov, N. A. Gundorin, Yu.V. Nikitenko, Yu.P. Popov, L. Cser, P3-98-374, Dubna, 1998 (in Russian).

10. V.L. Aksenov, Yu.V. Nikitenko, S.V. Kozhevnikov, F. Radu, R. Kruijs, Th. Rekveldt, D3-98-369, Dubna, 1998.

11. V.L. Aksenov, Yu.V. Nikitenko, Physica B 267-268 (1999) 313.

12. V.L. Aksenov, H. Fredrikze, S.V. Kozhevnikov, Yu.V. Nikitenko, M. Th. Rekveldt, J. Schreiber, E14-98-85, Dubna, 1998.

13. P.T. Por, W.H. Kraan, M.Th. Rekveldt, Nucl. Instr. Meth. A339 (1994) 550.

Received by Publishing Department
on August 27, 1999.