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A white beam neutron spin splitter

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Abstract

The polarization of a narrow, highly collimated polychromatic neutron beam is tested by a neutron spin splitter that permits the simultaneous measurement of both spin states. The device consists of a Si–$Co_{0.11}Fe_{0.89}$ supermirror, which totally reflects one spin state up to a momentum transfer $q = 0.04$ Å^{-1}, whilst transmits neutrons of the opposite spin state. The supermirror is sandwiched between two thick silicon wafers and is magnetically saturated by a magnetic field of 400 Oe parallel to its surface. The neutron beam enters through the edge of one of the two silicon wafers, its spin components are split by the supermirror and exit from the opposite edges of the two silicon wafers and are recorded at different channels of a position-sensitive detector. The device is shown to have excellent efficiency over a broad range of wavelengths. © 1998 Published by Elsevier Science B.V.

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1. Introduction

The advent of polarized neutron instruments at pulsed neutron sources has stimulated the production and the analysis of the polarization of a "white" beam of neutrons, covering a wide range of wavelengths. For a monochromatic beam the requirements of all component of the polarization circuit are relatively simple. Spin analysis could be done with a monochromator or even with an imperfect supermirror coating, after choosing an angle at which the structural error of the coating has minimal effects. In contrast at a pulsed source the supermirror coating has to be perfect for all neutron energies that are practically used. Neutron spin splitters have been developed for monochromatic beams [1,2] and they have been widely used to separate the spin components of the primary beam and recently the splitting of a primary polychromatic beam has been attempted [3]. In the present communication we present the results obtained by spin-splitting the "white" beam from a typical polarized neutron reflectometer. This kind of instrument, developed in recent years to study the magnetism of thin films and multilayers, has distinct characteristics. Both primary and reflected

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beams are narrow, extremely well collimated and consist of cold neutrons, with wavelengths typically ranging between 0.2 and 1.5 nm.

2. Description of the device

A sketch of the device is presented in Fig. 1. Two epipolished silicon wafers, of dimension $2 \times 50 \times 140$ mm, are coated with Si–$Co_{0.11}$ $Fe_{0.89}$ supermirrors and sandwiched between boron nitride absorbers, with the two supermirrors facing each other. The beam enters through the edge of one silicon wafer. Upon arriving to the sandwiched supermirror neutrons of one spin state are reflected, neutrons of the opposite spin state are transmitted. The two beams exit from the edges of the two silicon wafers and are simultaneously recorded at different channels of a position-sensitive detector. The supermirrors, whose surface forms an angle $\theta \sim 0.5°$ with the beam, are magnetically saturated by a magnetic field of 400 Oe parallel to the mirror's surface and perpendicular to the neutron flight path.

Suppose that the neutrons impinge on the supermirror from air. For the spin-up state, the reflectivity of the supermirror is practically unity up to a value of the momentum transfer $q = 4\pi \sin\theta/\lambda = 0.041$ Å^{-1} (λ is the neutron wavelength) or about twice the value for critical reflection from $Co_{0.11}Fe_{0.89}$. The latter quantity is simply the sum of the nuclear scattering amplitude density (bN) of the material and its magnetic induction B: $q = 4[\pi(bN + B)]^{1/2} = 0.023$ Å^{-1}. For spin-down neutrons $(bN - B)_{CoFe} = (bN)_{Si}$: the entire supermirror has the same neutron optical properties as the substrate. Both neutron spin states are reflected for $q < 4[\pi(bN)_{Si}]^{1/2} = 0.010$ Å^{-1}. However, in the case the neutrons arrive to the supermirror from the silicon side the effective scattering amplitude densities are obtained by subtracting from the local values those for silicon. Hence the spin-up neutrons are reflected for all wavelengths up to the critical value of the mirror while there is no more a critical angle for the spin-down neutrons and they are not reflected at all. In the neutron spin splitter both spin states are simultaneously measured; in principle, the two beams should be comparable since they pass through virtually the same silicon thickness.

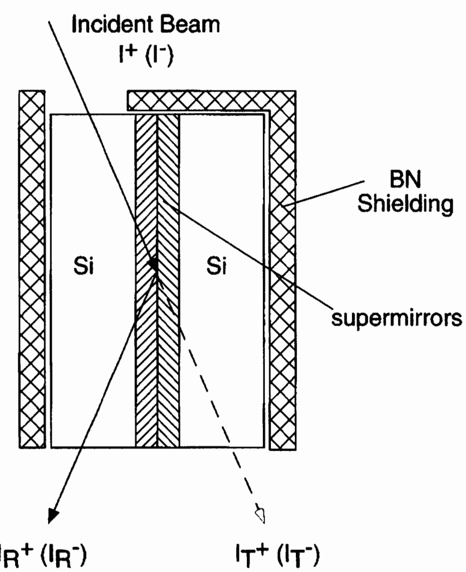


Fig. 1. Geometry of the spin splitter. Neutrons coming from the polarizer, with the flipper not energized, are called I^+; those with the flipper energized, I^-.

The composition and performance of the Si–$Co_{0.11}Fe_{0.89}$ neutron supermirrors is described in detail in Ref. [1]. They consist of 120 layers with thicknesses graded from 7–80 nm. For conventional applications (neutrons from air) the supermirror is fabricated by depositing on silicon first the thinnest layers, and ending at the surface with the thickest layer of $Co_{0.11}Fe_{0.89}$. Practical considerations dictated this choice. In the process of deposition the roughness gradually increases, deteriorating the interfaces and the reflectivity of the subsequent layers more critically if the layers are thin. In second place, the thick $Co_{0.11}Fe_{0.89}$ layer close to the surface totally reflects spin-up neutrons within the total reflection range of that material, while the thin underlying multilayers reflect – or perhaps more properly diffract – neutrons of larger q up to the maximum value characteristic of the supermirror. Only in the absence of absorption the two geometries are exactly equivalent. If the thin layers were close to the surface total reflection would take place for a critical wavelength dictated by the mean scattering length density of the $Co_{0.11}Fe_{0.89}$ and Si layers. Neutrons of wavelengths between that edge and that of total reflection for pure $Co_{0.11}Fe_{0.89}$ have to cross a thickness of supermirror of the order of 1 μm where they can be absorbed or scattered.

In our neutron spin splitter the neutrons hit the mirror from the silicon side. Therefore, the layer sequence for the first mirror had inverted geometry, with the thick layers close to silicon. For the layers of the second mirror the "normal" ordering was retained since the neutrons strike it first on the outermost layers.

3. Polarized neutron measurements

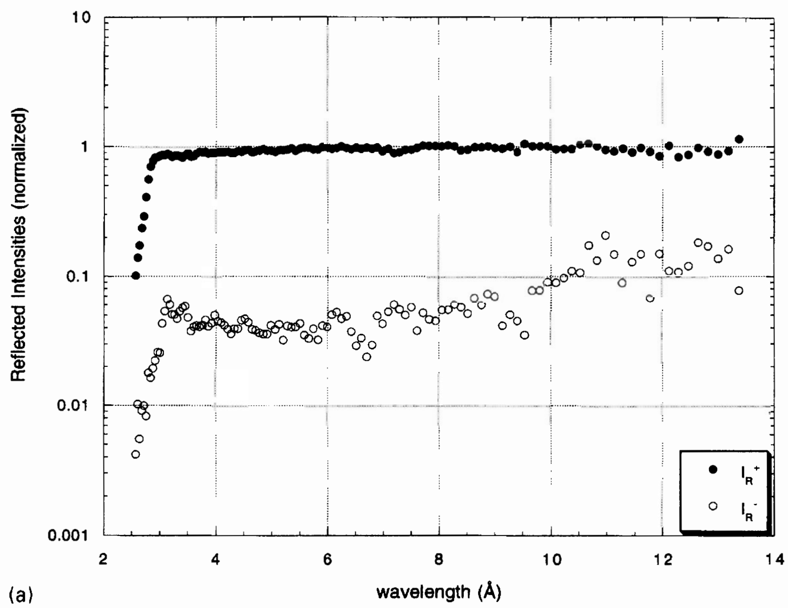
The mirrors were first tested at the Hahn–Meitner Institute (HMI), at a fixed wavelength of 4.75 Å, and then at Argonne National Laboratory. At both institutions four quantities were measured, I_R^+, I_T^+, I_R^-, I_T^- or the intensities reflected and transmitted with the incident beam polarized up or down. The measurements at HMI gave a ratio $I_R^+/I_R^- \sim 25$ for the reflected beam, $I_T^-/I_T^+ \sim 100$ for the transmitted beam up to 0.5° and ~ 25 at higher angles.

The measurements at the reflectometer [4] POSY I at the Intense Pulsed neutron Source, Argonne National Laboratory, are presented in Fig. 2a and b. The supermirror was set at the position of the polarization analyzer, downstream from the sample position. The neutron beam of POSY I originates from a solid methane moderator at 31 K. The beam is polarized after reflection by a pair of Co–Ti supermirrors [5] and then passes through a non-adiabatic Drabkin flipper [4]. The neutron beam was tightened to a height of 3 mm and a width of 0.5 mm in the reflection plane. The horizontal collimation assured that the entire beam passes through the magnetic supermirror and not merely through one of the silicon substrates of the sandwich. The range of detectable wavelengths is comprized between 0.2 and 1.5 nm. The lower limit is given by the critical wavelength for the fixed angle of the polarizing Co–Ti mirrors. At the upper limit, neutrons that are too slow need to be filtered out, since they would overlap at the detector the faster neutrons of the next pulse. The intensities were normalized to the neutron beam transmitted through the entire 140 mm silicon thickness, and rescaled so that I_R^+, I_T^- approach unity. The intensities were measured as a function of the neutron wavelength at fixed angle; in those presented at Fig. 2a and b the angle of reflection (0.6°) was kept purposely too high, to show explicitly the critical value of the supermirror.

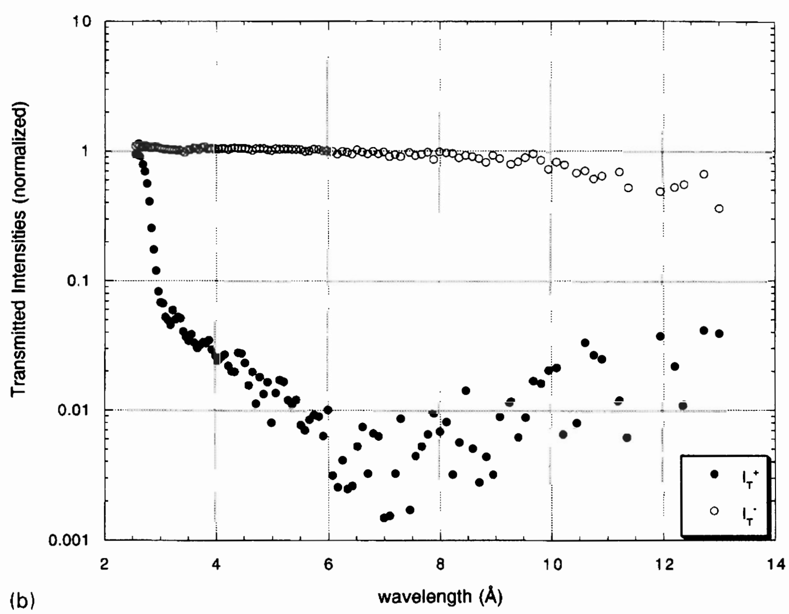
Ideally, $I_R^+ = I_T^- = 1$ and $I_T^+ = I_R^- = 0$. In practice, the supermirror was used to test the polarization efficiency of the instrument. It is easy to distinguish the efficiency of the spin splitter from that of the upstream polarization components. Suppose that the polarization is imperfect at a value λ_0. After changing the beam-splitter angle θ that feature remains at λ_0 due to other polarization elements, but if it is due to the splitter efficiency the invariant is $\sin\theta/\lambda$. Thus, the neutron spin splitter is a convenient diagnostic tool to determine the polarization efficiency of the overall instrument.

Basically, the measurements indicate that the polarization is good all over the range of wavelengths sampled. However, by inspecting Fig. 2 it becomes apparent that $I_R^- > I_T^+$ and, in absolute terms, is higher than desirable particularly for long wavelengths. This is to be attributed to the performance of the present neutron flipper soon to be exchanged with a design [6] better adapted to the geometry of a narrow beam.

It is worthwhile to add some cautionary remarks on the utilization of the beam splitter. The gain of the device, when compared to a reflection mirror, is less than a factor of two. The transmission through 14 cm of silicon was found to be 0.75 for 0.4 nm neutrons, corresponding to 0.4 barn/atom, and 0.4 for 1.2 nm neutrons, corresponding to 1.3 barn/atom. These values (and the overall $1/v$ variation of the cross section, where v is the neutron velocity) correspond well to those given in the literature for pure silicon [7]. The cross section is largely due to absorption rather than to phonon scattering [7]: by cooling the silicon to 77 K would lower the cross section by only 20%. In second place, the optical paths of the transmitted and reflected beams are not exactly identical. Fig. 3 shows the sum $I_R^- + I_T^-$ consisting mainly of the transmitted beam; its intensity is significantly lower than that of $I_R^+ + I_t^+$ particularly for long wavelengths. The transmitted beam is lower because of scattering (evidenced by a slight increase of the diffuse



(a)



(b)

Fig. 2. (a) Neutrons reflected by the splitter: full points, for incoming neutrons when the flipper is not energized. Open circles, for incoming neutrons with the flipper energized. (b) Neutron transmitted by the splitter. Full points: with the flipper not energized; open points: with the flipper energized. The intensities have been normalized by those transmitted through silicon. Notice for a wavelength of 3 Å the effect of the reflection edge of the supermirror.

background) in the supermirror layer: thus, possibly the effect can be reduced by improving the growth technique. Even with these deficiencies, the neutron spin splitter is revealing itself quite useful: for instance, it might be considered as a unit to convert an unpolarized neutrons reflectometer in a polarized one without modifying the optical path in front of the sample.

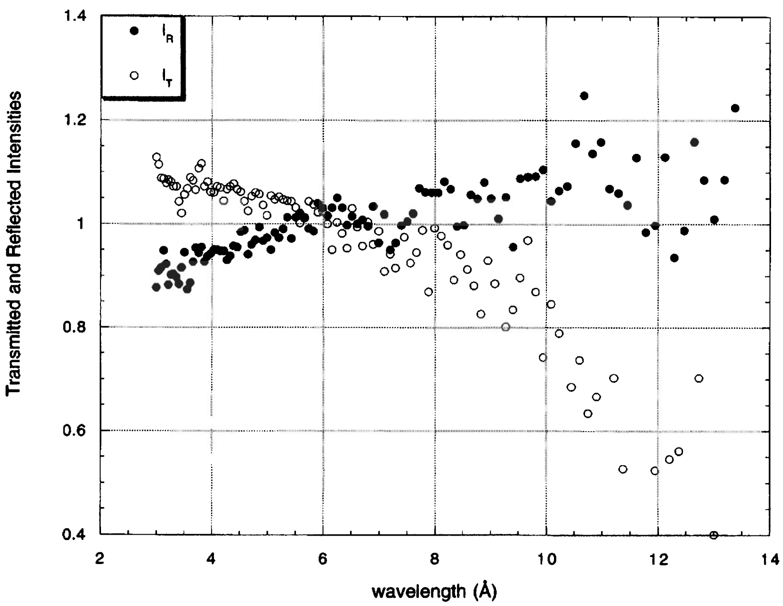


Fig. 3. The total intensities reflected by the spin flipper (full points) are compared with the transmitted intensities (open circles).

Acknowledgements

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