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PROPOSAL OF A WIDE-BAND MIRROR POLARIZER OF SLOW NEUTRONS AT A PULSED NEUTRON SOURCE

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1)INTRODUCTION

Polarizing neutron mirrors [1], supermirrors [2] and assemblies of supermirrors [3] are the well known and frequently used devices, when one needs to prepare more or less monochromatized polarized beam of slow neutrons (or to analyze its polarization). However, in the case of a white neutron beam the known applications of polarizing mirrors do not meet the requirement of reasonable polarization (eg. p>95%) in a wide range of neutron wave-lengths. This requirement, not being decisively important at steady state neutron sources, becomes essential at pulsed sources, where most efficiency springs from the usefulness of nearly all wave-lengths λ.

The reasons limiting the λ-band width are well understood (see eg. [4]) and, shortly expressed, consist in non-zero reflectivity of the mirror for the neutrons in an unwanted ("wrong") spin eigenstate, which they acquire, when have traversed the polarizing layer and met the glass substrate. In a rather narrow band the problem of suppression of unwanted reflection is solved by the proper choice of the composition of the absorbing (anti-reflecting) sub-layer, introduced between the polarizing layer and the substrate. Recently it was shown, that a remarkable progress in this direction is possible, if use the V-Cd alloy or ^{10}B containing alloys [5] as an absorbing sub-layer. However, large scale production (hundreds) of such mirrors has remained an unsolved problem yet.

Here we present another possibility of constructing a wide-band neutron polarizer, which seems to match well the pulsed neutron sources, when thinking of a small angle scattering instrument with a polarized neutron beam.

2)ORIGINS OF THE PROBLEM

It is well known, that total reflection of neutrons from a mirror occurs if the glancing angle ϑ of the incoming beam is less than the so-called critical angle ϑ_c, and that reflection ceases rather fast at $\vartheta>\vartheta_c$. The same is valid for the neutrons in two possible spin states (we use the denotations + and - in the following) and in any mirror polarizer the condition $\vartheta_{c+}>\vartheta_{c-}$ must be valid. The critical angles are determined by the condition

$$\sin\vartheta_{c+-}=\{ (U_n \pm U_m)/E \}^{1/2}, \qquad (1)$$

where U_n is the space-averaged neutron-nuclei (n-N) interaction potential;

U_m is the potential of the interaction of the neutron with magnetic field in the polarizing mirror;

E is the kinetic energy of the neutron.

Usually, by proper choice of the material for the magnetic mirror one can fulfill the requirement

$$U_n=U_m \qquad (2).$$

It means, that neutrons with the right (+) spins will meet a rather large (double nuclear) real part of the repulsive potential and (at $\vartheta<\vartheta_c$) will be totally reflected. The wrong (-) spin eigenstate neutrons then have $\vartheta_c=0$ and after traversing the magnetized layer must be absorbed in the specially introduced absorbing sub-layer (or in the specially arranged sequence of absorbing anti-reflecting layers [6]), which for these spins displays nearly pure imaginary (n-N) potential. Though with this absorbing sub-layer the total reflection is nearly absent in a strict sense of the word, some finite reflectivity, depending on the glancing angle remains there. To go not too far in the problem of reflection from an imaginary potential (or from a complex one which appears, when the real parts of the magnetized and absorbing layers are not well matching one another for wrong spins), we assume that the ϑ_{c-} nevertheless might be introduced and (with some accuracy) determined as

$$\sin\vartheta_{c-}=(W/E)^{1/2}, \tag{3}$$

where W is the imaginary part of the n-N potential. The essential property of equations (1) and (3) is that both critical angles ($\vartheta_c \ll 1$) are proportional to the neutron wave-length λ:

$$\vartheta_{c+} = \vartheta_{c1+}\,\lambda\,, \qquad \text{and} \qquad \vartheta_{c-} = \vartheta_{c1-}\,\lambda \tag{4}$$

where ϑ_{c1+-} denote the critical angles at unit wave-length. For example, in the case of the well investigated system FeCo as a magnetized mirror and TiGd as an absorbing sub-layer

$$\vartheta_{c+} = 1.8\ 10^{-3}\ \lambda, \qquad \vartheta_{c-}=0.8\ 10^{-3}\ \lambda, \tag{5}$$

where λ is the neutron wave-length in Angstroms. For the further consideration it is important, that both critical angles are increasing with λ.

If one introduces into consideration some finite collimation angle ϑ_{coll} and an average glancing angle ϑ_g of the incoming (into the polarizer) or of the outgoing beam, at some (large enough) wave-length the ϑ_{c-} becomes larger than the $\vartheta_g+\vartheta_{coll}$, both spin states being fully reflected and no polarization achieved at all. The last condition becomes very important in the small-angle neutron scattering (SANS) instruments, where just tiny collimation of the neutron beam is necessary.

As a first hand measure of the polarizer band quality one can consider the ratio $\varepsilon= \vartheta_{c+} / \vartheta_{c-}$. In the mentioned sample-case FeCo/TiGd ε=2.25, while the best known supermirrors of O. Schaerpf have ε=19.4 [6]. However, in SANS instruments the most important characteristic will rather be the ratio $\vartheta_g-\vartheta_{coll} / \vartheta_{c-}$, which must be kept greater than unity. Otherwise, the degree of polarization achieved with a collimated mirror might occur rather low. In turn it means, that before choosing a polarizer for the SANS instrument one must think about the necessary angular collimation $\sigma_{\vartheta SAS}$, which must be determined from quite independent requirements for the q-resolution (q is the length of the scattering vector in a small-angle scattering experiment, $q=k_0\ \vartheta_{SAS}$). Obviously,

$$\frac{\sigma_q^2}{q^2} = \frac{\sigma^2_{\vartheta sas}}{\vartheta^2_{sas}} + \frac{\sigma^2_\lambda}{\lambda^2} \tag{6}$$

where σ^2 denotes the dispersion of the distribution function of the subscript quantity.

The first term in the right-hand side of equation (6) usually dominates and must be kept less than 0.01 to escape large collimation distortions. Keeping this in mind we get

$$\sigma_{\vartheta sas} < 0.1\ \vartheta_{min} = 0.1\ \lambda\ q_{min}\ /2\pi, \tag{7}$$

where ϑ_{min} is the smallest observable scattering angle in the SANS instrument. If one starts to think of a modern instrument, capable of giving reasonable data down to e.g. $6\ 10^{-3}\ A^{-1}$, he immediately comes to the inequality

$$\sigma_{\vartheta sas} < 0.1\ 10^{-3}\ \lambda\ , \tag{8}$$

which is rather restrictive as compared with the main condition of total reflection even for the FeCo/GdTi mirrors:

$$\vartheta < \vartheta_{c+}=1.8\ 10^{-3}\ \lambda. \tag{9}$$

3) GIST OF THE SUGGESTION

Having in mind strict collimation determined by equation (8), let us consider a well collimated unpolarized beam, which hits the polarizing mirror at a glancing angle ϑ_g. To obtain a polarized reflected beam, the inequalities

$$\vartheta_{1c-}\ \lambda < \vartheta_g - \vartheta_{coll} < \vartheta_g + \vartheta_{coll} < \vartheta_{1c+}\ \lambda \tag{10}$$

must be fulfilled simultaneously. If one accepts $\vartheta_{coll}=3\ \sigma_\vartheta$ (a reasonable estimate for a triangular distribution), all these inequalities might be well fulfilled for a given wave-length by the proper choice of the glancing angle. However, the λ-band will be determined by the ratios

$$\lambda_{max}= (\vartheta_g - \vartheta_{coll})/\ \vartheta_{1c-} \quad \text{and} \quad \lambda_{min}= (\vartheta_g + \vartheta_{coll})/\ \vartheta_{1c+}\ , \tag{11}$$

which lead to the band-quality ratio

$$\lambda_{max}\ /\ \lambda_{min}= \vartheta_{1c+}\ /\vartheta_{1c-}\ (\vartheta_g - \vartheta_{coll})\ /(\vartheta_g + \vartheta_{coll}). \tag{12}$$

This ratio is remarkably less, than the quality factor c, introduced in sect. 1. Nevertheless, by the proper choice of the radius of curvature (an equivalent of the glancing angle in our case) of a neutron guide [7] or an assembly of mirrors [8] an acceptable compromise with a quality factor of about 3 might be realized.

The appearance of periodically pulsed neutron sources open the new possibility to overcome the mentioned difficulty. If the polarizer is placed at some distance from the neutron source, the incoming neutrons will reach the mirror at different moments of time, in dependence on flight time, which in turn is proportional to the neutron wave-length. Now one can keep the angular interval of acceptance always between ϑ_{c-} and ϑ_{c+} simply by turning the mirror synchronously with the increase of the neutron wave-length. In other words, if the glancing angle follows the equation

$$d\vartheta_g\ /dt=(\vartheta_{1c-}+\ \vartheta_{1c+}\ )\ \lambda/T/2\ \equiv\Omega \tag{13}$$

where T is the time of flight from the source to the mirror, the conditions (10) will be fulfilled for all wavelengths, starting from the smallest one, which is determined by the collimation conditions of direct vision exclusion. As far as the time of flight is proportional to the wave-length, the last equation means simply turning of the mirror with a constant angular velocity Ω. Simple estimates led to Ω of about 2 rad/sec only, which seems to be quite acceptable.

4) A MORE REALISTIC ASSEMBLY

In the above we have simplified the problem by considering a single mirror and a well collimated beam. A more realistic version which arose under the influence of double coated assemblies of supermirrors made by Prof. O.Schaerpf [6,8], is shown in fig. 1. We suggest putting the straight (not curved) Schaerpf's assembly on a turn-table, which moves according to equation (13) during a rather short time interval (of about 15 milliseconds), while the useful band of wave-lengths is passing it. As far as the repetition period of power pulses from the IBR-2 reactor is nearly 200 milliseconds, the remaining time can be spent to reverse the velocity of the whole assembly and come again to the start position. The advantage of this choice (in addition to all the merits of Schaerpf's assemblies) is the simplicity of the construction and of possible solution of kinematics. An evident demerit is in fact that the central axis of the polarizer will move across the neutron source surface during the duty time for a distance of about 5 cm, thus collecting neutrons not always from the brightest region.

More complicate systems, containing two, three etc. assemblies might be considered with the aim to escape from this inconvenience (e.g., building a full flexible S-shape construction which realizes a variable curvature during the duty time). However, in these much more sophisticated systems additional losses and complications are inevitable and that is the reason, why we stop at the simplest implementation.

ESTIMATE OF THE POLARIZED BEAM INTENSITY

We consider the polarizer-to-sample distance of 10 meters and a sample surface of 1 cm^2, the IBR-2 cold methane moderator time-averaged brightness of $7\cdot10^{11}$ n/cm^2/sec/st, the polarizer cross-section of 5*6 cm^2 and its transmission of 0.4. At these conditions the time-of-flight monochromatized neutron flux at sample will be equal to 9 10^5 n/cm^2/sec. The zero-to-zero intensity angular distribution in these conditions will be of ±3 10^{-3} radian (±10'), which in turn at λ=15 A will give the full q-uncertainty of ±1.2 10^{-3} Angstroms^{-1}. The visible (from the sample) size of the polarizer could be collimated easily to smaller dimensions, to allow one to improve q-resolution, if necessary.

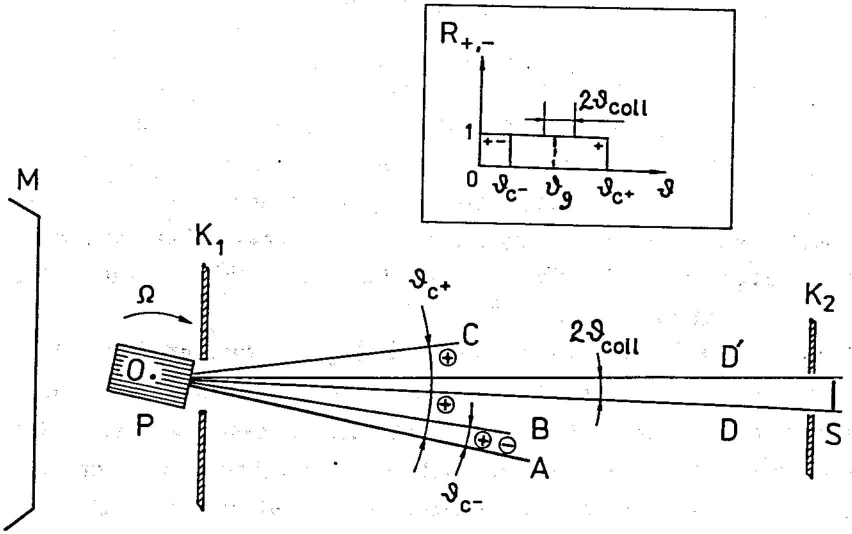

Fig.1 The sketch of an imaginary wide-band polarizing setup of a possible time-of-flight small-angle neutron scattering instrument. The letters denote: M-the pulsed source moderator; P-the multi-mirror polarizing assembly, rocking around the center O with the angular velocity Ω. The neutrons with the wanted (+) and both polarizations (+,-) fill the angles AOC and AOB, respectively. In the angle DOD', defined by the collimator K_2 , only (+) polarization exists. The rocking of P keeps the sample S (the beam DOD') in the middle of the angle BOC while the neutron wavelength and the angles AOB and AOC increase with time. The insert shows the idealized reflectivity vs. the glancing angle and the collimation angle DOD'.

CONCLUSIONS

The physical background of the polarizer described above as well as the intensity estimate seem very attractive. Though the idea of a rotating neutron mirror is rather old [9], its application to the construction of a neutron polarizer seems to be analyzed for the first time and mainly is stipulated by the progress in pulsed neutron sources and their applications.

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Широкополосный зеркальный поляризатор
медленных нейтронов

Рассмотрена схема "качающегося" широкополосного зеркального поляризатора медленных нейтронов, предлагаемая для опытов по малоугловому рассеянию. Показано, что с использованием зеркал О.Шарпфа, подобный поляризатор позволяет получить интенсивный пучок нейтронов с высокой поляризацией в интервале длин волн 2-15 Å.

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Nikitenko Yu.V., Ostanevich Yu.M. E13-92-316
Proposal of a Wide-Band Mirror
Polarizer of Slow Neutrons at a Pulsed Neutron
Source

The new type wide-band mirror-based neutron polarizer to be operated at a pulsed neutron source is suggested. The idea is to use a movable polarizing mirror system, which, be the incoming beam monochromatized by the time-of-flight, would allow one to tune glancing angles in time so, that the total reflection condition is always fulfilled only for one of the two neutron spin eigenstates. Estimates show, that with the pulsed reactor IBR-2 such polarizer allows one to build a small angle neutron scattering instrument capable to effectively use the wave-length band from 2 to 15 Å with a rather high luminosity (time-averaged flux at position being up to 10^6 n/sec/cm^{-2}).

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