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Neutron spin optics: Fundamentals and verification

N.K. Pleshanov

Petersburg Nuclear Physics Institute, NRC "Kurchatov Institute", Gatchina, St. Petersburg 188300, Russia

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ABSTRACT

Neutron spin optics (NSO) based on quantum aspects of the neutron interaction with magnetically anisotropic layers signifies transition in polarized neutron optics from 1D (spin selection) to 3D (spin manipulations). It may essentially widen the functionality of neutron optics. Among the advantages of NSO are compactness, zero-field option (guide fields are optional) and multi-functionality (beam spectrum, beam divergence and spin manipulations can be handled at the same time). Prospects in improving and developing neutron mirror spin turners (incl. flippers) are discussed. Two approaches to measurement of the efficiency of mirror flippers are introduced. The efficiency of a multilayer-backed neutron mirror flipper for monochromatic beams was found to be 97.5 ± 0.5%. Such mirror flippers can combine monochromatization of a polarized beam with flipping spins of the monochromatized neutrons. To improve their performance, account of the spin-dependent refraction in the magnetic layer should be taken. For a monochromatic beam, supermirror-backed flippers are shown to be more advantageous, with a gain in intensity up to 4 times.

1. Introduction

Polarized neutron techniques are irreplaceable as direct techniques for the study of even most non-trivial magnetic systems, not only their (atomic, electron, magnetic) structure from atomic to micron scales, but also their lattice and spin dynamics. In most cases, to realize these research techniques, polarized neutron optics is used for polarization and polarization analysis of neutron beams. Neutron spin manipulation optics was recently proposed [1,2] to essentially widen the functionality of neutron optics and contribute to the development of tools for obtaining information about the objects under study. Here the term *neutron spin optics* (NSO) is used to designate the new possibilities.

Among the advantages of NSO over the existing spin manipulation devices [3] are compactness (miniaturization is practically unlimited), zero-field option (no external fields are required, guide fields are optional) and multi-functionality (beam spectrum, beam divergence and spin manipulations can be handled at the same time). NSO devices may play an important role in developing alternative schemes of measurements, esp. with small samples, which are often of special interest for neutron studies. Therefore, the probing of the basic principles and elaboration of the basic elements for NSO are quite essential.

Quantum aspects of the neutron interaction with magnetically anisotropic layers are considered in Section 2. Basic elements for innovative neutron devices, including mirror spin turners ($\pi/2$- and π-turners, in the first place) and mirror spin precessors (compact counterparts of the precession coils used in the arms of NSE spectrometers), are introduced in Section 3. Mirror flippers open new possibilities, one of which is a beam hyperpolarization [1], when the separation of neutrons with the opposite spins is followed by the flipping of the 'wrong' spins. Experiments with a multilayer-backed spin flipper for monochromatic beams are represented in Section 4. The results obtained are discussed in *Conclusion*.

2. Spin precession by neutron reflection

NSO is based on quantum aspects of the neutron interaction with magnetically anisotropic layers and signifies the transition in polarized neutron optics from 1D (spin selection, as in conventional polarizers and analyzers) to 3D (spin manipulations).

The idea to make neutron mirror spin turners including flippers was mentioned as early as 1994 [4]. However, the idea to turn spins by reflection of neutrons seemed, at first glance, to be quite impractical. E.g., an efficient flipping under total reflection from a $Co_{64}Fe_{36}$ (170 nm) film was observed [5] in a field 5.9 mT, but the respective q-range is narrowed down to 1 point (Fig. 1). Quite disappointing and discouraging.

To be of practical interest, the spin-up (+) and spin-down (−) reflectivities $R_{\pm}$ should be close to 1, the spins rotate about one axis, and the rotation angles weakly depend on the neutron wavelength λ and the glancing angle θ, i.e. on the momentum transfer

$$q = (4\pi \ \sin\theta)/\lambda. \quad (1)$$

E-mail address: pleshanov_nk@pnpi.nrcki.ru.

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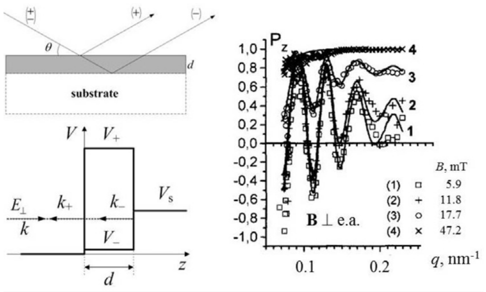

Fig. 1. On the left: the spin-up (+) and spin-down (−) neutron components with normal wavenumbers $k_\pm$ and energy $E_\perp$ undergo total reflection at different interfaces of the magnetic film (spin splitting). On the right: the measured (points) and fit (solid curves) polarization component P_z of neutrons reflected from a CoFe film with a thickness d =170 nm and potentials $V_\pm$ on a glass substrate with a potential V_s in different fields is represented as a function of q. In the neutron experiment the applied fields are perpendicular to the easy axis. Numerous details explaining the behavior of P_z in different fields are given in Ref [5].

Therefore, magnetically anisotropic layers with collinear fields are of special interest for us. The resultant spin evolution caused by reflection of neutrons from such layers can be described as precession about the fields' direction, provided that the precession condition

$$R_+ = R_- \tag{2}$$

By definition, the precession angle is positive for an anticlockwise (like Larmor) rotation of the neutron spin. To observe the precession, the spins of the incident neutrons should be inclined to the direction of the fields in the reflecting layers. However, it is only when a magnetic layer weakly reflects neutrons, it induces a Larmor precession angle, proportional to magnetic induction, total neutron path in the layer and neutron wavelength λ , i.e., decreasing as q^{-1}.

The precession angle for the total reflection (TR) of both spin components from the boundary with a magnetic medium is a shift in the phases of the opposite spin states upon total reflection [6].

$$\varphi_{\mathrm{TR}} = 2\,[\arccos(q/q_+) - \arccos(q/q_-)] \qquad (q \le q_\pm), \tag{3}$$

increasing from 0 at q =0 to a maximum 2 $\arccos(q_-/q_+)$ at $q = q_- < q_+$. Here $q_\pm$ are the critical momentum transfers corresponding to the spin-up (+) and spin-down (−) neutron potentials $V_\pm$ of the medium. The precession angle φ_{TR} can be made $\pi/2$ (when $V_+ \geq 2\ V_-$), but it can never reach π. For a given θ, the neutron with a shorter λ penetrates deeper into the non-classical under-barrier region with the field. It corresponds with a larger precession angle φ_{TR}.

For the first time the signature of the phase shifts of the wave function under total reflection of a massive particle, the neutron, has been observed by means of a thin semi-transparent film as an interference element [6]. A shift in the phases of the opposite spin states upon total reflection manifests itself in the polarization vector rotation ('quantum precession') observed by measuring one of the polarization vector components with the analyzer [5,7]. Direct evidences of the quantum precession under total reflection have been furnished with vector polarization analysis [8] and spin-echo analysis [9].

Even a more peculiar precession is induced by spatial separation of the opposite spin components ('spin splitting'), which has been studied [10] and exploited in NSE spectrometers [11] at J-PARC (Tokai, Japan). When both the spin-up and spin-down neutron components are totally reflected from different boundaries of a magnetic layer (neglecting reflection of spin-down neutrons from the first boundary) with a thickness d and potential eigenvalues $V_\pm$ (Fig. 1), the precession angle is

$$\varphi_{\mathrm{S}} = qd\,[1 - (q_-/q)^2]^{1/2} + \varphi^-_{\mathrm{TR}} - \varphi^+_{\mathrm{TR}} \qquad (E_\perp \le V_+,\ V_s), \tag{4}$$

where $E_\perp = E\ \sin^2\theta$, E is the neutron energy, $V_s > 0$ is the neutron potential of the substrate. The first term is related to different paths of the neutron waves representing the opposite spin states and the other two terms make the difference in the phase shifts caused by total reflection from (now different) boundaries. The spin-up neutron wave totally reflected from a boundary with a sufficiently thick magnetic layer decays exponentially in the layer, and only the spin-down component reaches the substrate, the respective phase shifts being

$$\varphi^+_{\mathrm{TR}} = -2\arccos(q/q_+), \quad \varphi^-_{\mathrm{TR}} = -2\arccos(q'/q'_-), \tag{5}$$

where

$$q'/q'_- = \sqrt{(E_\perp - V_-)/(V_s - V_-)} \tag{6}$$

takes account of the changes in the kinetic energy and the barrier height for the spin-down neutrons within the magnetic layer.

Again the spin precession is non-Larmor. Moreover, it is anticlockwise for most parameters, but it can also be made clockwise ('antiprecession'), e.g. when $V_-= 0$ and $qd < \varphi^+_{\mathrm{TR}} - \varphi^-_{\mathrm{TR}}$. When $V_+ = V_s$ and $V_- = 0$, the total reflection conditions for the opposite spin components are identical ($\varphi^+_{\mathrm{TR}} = \varphi^-_{\mathrm{TR}}$) and the precession angle $\varphi_s = qd$.

To summarize, the non-classical spin behavior is related to purely quantum features of the interaction, in which the probabilities to find one and the same particle in the opposite spins states may essentially differ in a region with magnetic fields. Such interaction is impossible for a classical particle, which can be found at any time in a certain point and with a certain angular momentum. To find an algorithm for building layered structures that reflect neutrons with designed precession angles is still a formidable task. Of special interest are the layered structures that induce precession with (almost) the same angle in a sufficiently wide q-range (see the subsequent Section).

The efficiency of a spin turner can be defined as the portion of neutrons reflected with the spin in the desired direction $\boldsymbol{u}$, which is achieved by turning the incident beam polarization $\mathbf{P_O}$ by a certain angle φ about the rotation axis:

$$\varepsilon(\varphi) = (1 + P_u/P_0)/2, \tag{7}$$

where P_u is the projection of the reflected beam polarization $\mathbf{P}$ onto $\mathbf{u}$ and

$$P_0 = (I_+ - I_-)/(I_+ + I_-) \tag{8}$$

($I_\pm$ are the intensities of neutrons incident in the states with the spin up (+) and down (-) the guide field). Note that Eq. (7) is a generalization of the conventional definition of the efficiency of flippers for spin turners. In particular, the efficiency of a mirror flipper is

$$f = \varepsilon(\pi) = (1 - P_z/P_{0,z})/2. \tag{9}$$

Further calculations are carried out with the *generalized matrix* method [12,13] (its later description is known as the *supermatrix* method [14]) on the assumption that the fields $\mathbf{B}_{\mathrm{in}}$ in magnetic layers and hence the precession axis are perpendicular to the incident neutron spin.

3. Basic NSO elements

As mentioned in *Introduction*, basic NSO elements include mirror spin turners and mirror spin processors. Several approaches to building mirror spin turners with R~1 and precession angles weakly depending on q were suggested and substantiated by calculations [1,2] An idea of the possibilities of different methods of stabilizing the precession angle can be perceived from the calculations of the efficiency of different π/2-turners in Fig. 2.

In the *biased total reflection* method the precession angle is stabilized by using a layer with a negative potential $V < 0$ on top of the magnetic layer totally reflecting neutrons. Then $q/q_\pm$ in (3) should be replaced with

$$q'/q'_\pm = \sqrt{(E_\perp - V)/(V_\pm - V)}. \tag{10}$$

As a consequence, the range of precession angles in the total reflection