Neutron multilayer-backed flipper: experiment, prospects

N K Pleshanov
Petersburg Nuclear Physics Institute, NRC “Kurchatov Institute”, Gatchina, St. Petersburg, 188300, Russia.
E-mail: pnk@pnpi.spb.ru

Abstract. 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 neutron spins. Supermirror-backed flippers are shown to be more advantageous with initially monochromatic beams, with a gain in the outcome intensity up to 4 times. Prospects in improving mirror spin turners, incl. flippers, are discussed. Performance of spin turners is analyzed. Scheme of a hyperpolarizer for monochromatic beam mode reflectometers is considered, its working parameters are estimated.

1. Introduction
Neutron spin manipulation optics recently proposed [1,2] may 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),
- 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.

2. Design
The necessary condition of building mirror spin turners is the equality of the reflectivities of neutrons with the opposite spins:

\[ R_+ = R_- \]  

Then the change of the spin orientation of neutrons under reflection can be described as precession about the fields in magnetic layers. A multilayer-backed spin turner [1] for monochromatic beams is the simplest for realization. Observation of the spin flipping for neutrons reflected from such a mirror flipper was recently reported [4]. It is designed (Fig. 1) as a magnetic layer weakly reflecting neutrons on top of a non-magnetic multilayer (ML). At large \( q \) (at a Bragg peak) the layers of Co, Fe and their alloys weakly reflect neutrons and may be used to build mirror spin turners. Spins inclined to the magnetic induction vector \( B_m \) in the magnetic layer undergo Larmor precession twice, before and after reflection of neutrons from ML. The precession angle depends on \( q \), so the spread of precession angles is defined by the Bragg peak width, and the efficiency of multilayer-backed spin turners is increased...
for multilayers with smaller d-spacings.

According to the Larmor precession law, the spin rotates about \( B_m \) by an angle

\[
\varphi = CB_m \frac{2d_m}{\sin \theta}
\]  

\( (C = 4\pi m_0|\mu|/\hbar^2 \approx 4.63 \times 10^4 \ \text{T}^{-1}\text{nm}^{-2}) \) proportional to \( B_m, \lambda, \) and the total (before and after reflection from ML) path length in the magnetic layer with a thickness \( d_m. \) The Bragg condition taking account of the refraction in ML can be written as

\[
4\pi \sin \theta = \lambda q_B.
\]

and one obtains the precession angle at the Bragg peak maximum (\( q = q_0 \)):

\[
\varphi = 8\pi CB_m d_m / q_B.
\]  

To turn spins of the Bragg-reflected neutrons by an angle \( \varphi = \pi, \) the required thickness of the magnetic layer can be found from (4) as

\[
d_m(\pi) = q_0 / (8CB_m).
\]

When \( B_m \) is perpendicular to the spins of the incident neutrons, the layer will work as a flipper for neutrons reflected with \( q \) near \( q_B. \)

The magnetic layer can be made from a CoFe alloy used in production of polarizing CoFe/TiZr supermirrors. From the nuclear and magnetic potentials found for CoFe layers [5], one can determine the saturation magnetization \( B_s = 2.0 \) T. Owing to pronounced easy-axis anisotropy, the residual magnetization of the layers is quite high. Assuming that it is equal to 0.95\( B_s, \) we find from (5) for \( q_B = 0.5 \) nm\(^{-1}\) that \( d_m(\pi) = 71.1 \) nm.

To produce a mirror flipper, a periodic structure of 20 pairs of quarter-wavelength non-magnetic NiMo(6.96 nm) and Ti(6.17 nm) layers was sputtered onto two glass substrates at the sputtering machine LUNA (PNPI, Gatchina, Russia). Then the NiMo target was replaced with a CoFe target, and two layers, Co\(_{40}\)Fe\(_{30}\)(71.1 nm) and Ti(30 nm), were sputtered onto one of the samples. The additional Ti layer protects [6] the CoFe layer from oxidation and prevents deterioration of its magnetic properties.

3. Experiments and analysis

Experiments with the mirror flipper were carried out at the neutron reflectometer NR-4M (beam 13, reactor WWR-M, Gatchina) with the maximum spectral density for the polarized beam at a wavelength 0.130 nm. The spin-up (+) and spin-down (-) neutron reflectivities \( R_i(q) \) for the mirror flipper in a field sufficiently strong to magnetically saturate the CoFe layer are represented in Fig. 2. One can see that the precession condition \( R_+ = R_- \) is well fulfilled for the Bragg peak with \( \Delta q/q = 7.5\% \) (FWHM) in the \( q \)-scale. However, the peak maximum is not at the designed value 0.5 nm\(^{-1}\), but at a value 0.48 nm\(^{-1}\) corresponding to thicker layers in ML.

In the low \( q \) region the spin-up and spin-down reflectivities are quite different (see Fig. 2). It can be used to study the reversal of the CoFe layer magnetization by measuring integral reflectivities at a small glancing angle. Then the integral polarizing efficiency

\[
P_m(B) = \frac{|R_{\text{off}}(B) - R_{\text{on}}(B)| / [R_{\text{on}}(B) + R_{\text{off}}(B)]}{R_{\text{on}}(B)}
\]

obtained from the reflectivities, measured with the flipper \( f_i \) switched off and on as a function of the
applied field \( B \), represents a hysteresis loop. The hysteresis loop obtained with the field \( B \) along the e.a. is represented in Fig. 3-a; the field was reduced from 60 mT to 0, then the layer was oppositely magnetized in the field -60 mT and then measurements were resumed in positive fields from 1 to 60 mT. Note that the magnetization reversal starts about 12 mT.

**Figure 2.** (a) The spin-up (+) and spin-down (-) neutron reflectivities \( R_+ \) for the mirror flipper (Fig. 1) are represented as functions of \( q \). The TOF data are obtained with the sample at \( \theta = 4.95 \) mrad in a field 47 mT. (b) The same \( R_+ \) in the linear scale for the \( q \)-range with the Bragg peaks.

**Figure 3.** (a) The dependence \( P_{\text{int}}(B) \), normalized to \( P_{\text{max}} = \max(P_{\text{int}}) \), obtained with a white beam of neutrons reflected at \( \theta = 2.18 \) mrad from the mirror flipper in the field \( B \parallel \) easy axis (in the CoFe layer). (b) The dependence \( P_{\text{int}}(B) \) obtained with a white beam of neutrons reflected at \( \theta = 2.33 \) mrad from the mirror flipper in the field \( B \perp \) easy axis (in the CoFe layer). Previously the sample was magnetized in \( B = 60 \) mT along the easy axis and turned in \( B = 0 \) about its surface normal by 90°. The field \( B \) changed as shown with the arrows: each rise from 1 mT was followed by a drop to 1 mT. As a consequence, the lower points (filled squares) in Fig. 3-b correspond to measurements in a field 1 mT after applying the field given by the field axis. One can infer that no oppositely magnetized domains form in the fields up to 20 mT. The layer behaves as a single-domain magnetic spring. It means that the mirror spin flipper, in principle, can work in guide fields up to 20 mT.

The sample magnetized in \( B = 60 \) mT was turned in \( B = 0 \) about its surface normal by 90°. The measurements obtained with the field \( B \perp \) e.a. are represented in Fig. 3-b. The field \( B \) changed as follows: 0 \( \rightarrow \) 1 mT \( \rightarrow \) 2 mT \( \rightarrow \) 1 mT \( \rightarrow \) 3 mT \( \rightarrow \) 1 mT \( \rightarrow \) ... As a consequence, the lower points (filled squares) in Fig. 3-b correspond to measurements in a field 1 mT after applying the field given by the field axis. One can infer that no oppositely magnetized domains form in the fields up to 20 mT. The layer behaves as a single-domain magnetic spring. It means that the mirror spin flipper, in principle, can work in guide fields up to 20 mT.

In the standard method of measuring the flipper efficiencies, two flippers are switched off and on, and the 4 intensities measured with an analyzer give the efficiencies of both. A mirror spin flipper
would change both intensity and direction of the beam, violating the requirement that the source and the analyzer in the measurements be the same. So the scheme is modified. Since two multilayer samples were prepared in the same sputtering process and only one was later coated with the magnetic film, both can be used, one imitating the “flipper-off” state, and the other flipping spins. The samples were adjusted on the sample unit and could be moved into and out of the beam. The same glancing angles mean the same neutron paths, therefore the efficiencies of flipper 2 and the analyzer will be identical in each set of measurements. The designed-in flipper after the sample unit was found [4] to be more efficient with small fields at the sample, than that before the sample unit. Therefore, it was used for testing the mirror flipper in measurements with the analyzer, and the mirror flipper was the first flipper in the modified scheme of measuring the flipper efficiencies.

Normalized TOF intensities (Fig. 4-a) measured for the non-magnetic sample at $\theta = 7.27$ mrad in a field 3 mT with the analyzer and flipper 2 switched off and on show that the Bragg-reflected neutrons are sufficiently polarized, even though the polarization guiding is not optimal with low fields at the sample unit of the reflectometer. Normalized TOF intensities (Fig. 4-b) measured for the mirror flipper at the same glancing angle show that the polarization of the Bragg-reflected neutrons is reversed. The mirror works as a flipper, indeed.

![Figure 4](image)

Figure 4. The TOF neutron intensities $I$ measured with (a) the non-magnetic sample and (b) the mirror flipper at $\theta = 7.27$ mrad in a field 3 mT with the analyzer and flipper 2 switched off and on are represented as functions of $q$. The intensity in each TOF channel is normalized with the direct beam intensity $I_0$ in the respective channel.

Theoretically, the efficiency of the mirror flipper in a given field does not depend on the wavelength and must be the same at the Bragg peak. The Bragg peaks for the glancing angle 7.27 mrad are at a wavelength $\lambda_B = 0.189$ nm. A narrow slit on the single detector window guaranteed setting the same angle for the reflection from the analyzing supermirror (the same efficiency of the analyzer). Because of the additional reflection and the slit, the normalized Bragg peaks in Fig. 4 are noticeably lower than the Bragg reflectivities in Fig. 2.

To evaluate the mirror flipper efficiency, the integral Bragg peak intensities (integrated only over the Bragg peaks) obtained with the non-magnetic ML ($I_{\text{off,off}}, I_{\text{off,on}}$) and the mirror flipper ($I_{\text{on,off}}, I_{\text{on,on}}$) are further used. The standard equations lead to efficiencies exceeding 1 and other contradictions, indicating that the Bragg peak reflectivities $R_0$ (for the non-magnetic ML) and $R_F$ (for the mirror flipper) are not equal. So the standard equations have been generalized [7] for $\rho = R_0/R_F \neq 1$:

$$f_1 = \frac{1}{2} \left( \frac{1 + \rho I_{\text{on,off}} - I_{\text{off,off}}}{I_{\text{off,off}} - I_{\text{off,on}}} \right),\ f_2 = \frac{1}{2} \left( 1 + \frac{\rho I_{\text{on,off}} - I_{\text{off,off}}}{I_{\text{off,off}} - I_{\text{off,on}}} \right).$$

(7)
Regrettably, the reflectivities $R_0$ and $R_F$ were not measured during the experiments. So a new approach was developed. The following equations have been shown [7] to hold:

\[
f_1 = \frac{1}{2} \left[ 1 + \frac{|\sigma_x|/\sigma_0}{1 + (P_0P_A / \sigma_0 - 1)(|\sigma_x| + \sigma_0)/(1 + \sigma_0)} \right],
\]

\[
f_2 = \frac{1 + (P_0P_A)^{-1}}{1 + \sigma_0^2},
\]

where $P_0P_A$ is the product of the efficiencies of the polarizer and the analyzer, the reflectivities $R_0$ and $R_F$ cancel out in the quantities

\[
\sigma_0 = \frac{I_{\text{off,off}} - I_{\text{off,on}}}{I_{\text{off,off}} + I_{\text{off,on}}}, \quad \sigma_v = \frac{I_{\text{on,off}} - I_{\text{on,on}}}{I_{\text{on,off}} + I_{\text{on,on}}}.
\]

Thus, knowing the product $P_0P_A$ and the four intensities, one can find both $f_1$ and $f_2$.

The product can be found by using the equation [7]

\[
P_0P_A = [(1 + \sigma^{-1})f - 1]^{-1},
\]

which holds for a flipper with an efficiency $f$ and an analyzer with an efficiency $P$; $P_0$ is the initial beam polarization: $\sigma = (J_{\text{off}} - J_{\text{on}})/(J_{\text{off}} + J_{\text{on}})$, where $J_{\text{off}}$ and $J_{\text{on}}$ are the intensities measured in the absence of the sample with the flipper switched off and on. Formula (11) used with the data [4] on measurements in the absence of the sample yields an estimation $P_0P_A = 0.98$ ($B = 3$ mT).

Using the integral Bragg peak intensities for reflection from the non-magnetic ML ($I_{\text{off,off}}, I_{\text{off,con}}$) and the mirror flipper ($I_{\text{on,off}}, I_{\text{on,con}}$), one can infer from Eqs. (8) and (9) that $f_1 = 0.975 \pm 0.005$ and $f_2 = 0.995 \pm 0.005$ for neutrons with the wavelength 0.189 nm ($B = 3$ mT). It means that the spins of about 2.5% neutrons within the Bragg peak are not flipped by the mirror flipper. In other words, the NSF portion of the Bragg-reflected neutrons is about 2.5%.

**Figure 5.** Calculated NSF portions in the Bragg peak integral reflectivity for the spin flipper as a function of the CoFe layer thickness $d_{\text{m}}$. The arrows point to the thickness $d_{\text{cor}}$ and $d_{\text{cor}}$ obtained with Eq. (5) and Eq. (12), respectively.

The NSF portion in the Bragg peak integral reflectivity (Fig. 5) is calculated for the mirror flipper as a function of the magnetic layer thickness $d_{\text{m}}$, the other parameters being as designed; the nuclear and magnetic potentials for the CoFe layer are as found in Ref. [5]; the thickness of a TiO$_x$ oxide formed on top of the Ti layer is 3 nm [6]. Here and later the NSF portions are calculated with the exact numerical method (generalized matrix method [8]). The NSF integral (solid curve in Fig. 5) is minimum (0.21%) at a thickness $d_{\text{m}} = 66.5$ nm, which is noticeably less than the designed thickness 71.1 nm, obtained according to (5). Therefore, Eq. (5) should be revised. Account of the spin-dependent refraction in the magnetic layer (Fig. 6) gives a corrected thickness for the precession by an angle $\pi$ at the Bragg maximum $q_{\theta}$:

\[
d_{\text{cor}} = x \sqrt{(q_{\theta}^2 - q^2) - \sqrt{q_{\theta}^2 - q^2}}.
\]

The correction improves the estimation: $d_{\text{cor}} = 67.8$ nm for $q_{\theta} = 0.5$ nm$^{-1}$ with the same parameters of the CoFe layer. The thicknesses not corrected ($d_{\text{cor}}$) and corrected ($d_{\text{cor}}$) for refraction are shown in Fig. 5 with the arrows. One can see that the thickness $d_{\text{cor}}$ corresponds to the NSF integral equal to 0.3%. The thickness $d_{\text{cor}}$ corresponds to 1% for the NSF integral. However, $q_{\theta}$ was found to differ from 0.5 nm$^{-1}$, its shift to 0.48 nm$^{-1}$ increases the NSF integral up to 2.5%, matching the experimental value. So one may hope that the efficiency will approach the theoretical maximum 99.8%, when the thickness is corrected.
Figure 6. Taking account of the spin-dependent refraction in the magnetic layer gives a better estimation for the optimum thickness $d_m$. Non-refracted rays are represented with dashed lines. To avoid inessential complications, the spin-independent refraction in the non-magnetic ML is not shown. The protective Ti layer on top of the structure is not shown for the same reason.

Unlike flippers based on transmission through thin Fe foils [9], multilayer-backed flippers can combine monochromatization of a polarized beam with flipping spins of the monochromatized neutrons. However, if the polarized beam is already monochromatic, it may lead to intensity loss. To avoid this, supermirror-backed flippers with reflectivities close to 1 in a wide $q$-range can be used. The NSF portion of the reflected neutrons is calculated as a function of $q$ in Fig. 7. The theoretical efficiency exceeds 99% in a $q$-range about 10%. The working $q$-range exceeds that of the multilayer-backed flipper. Due to the reflectivities close to 1 in the entire working range and due to increased angular width and wavelength spread, the gain in intensity will be up to 4 times. In addition, there is no need to precisely adjust the magnetic layer thickness with the ML spacing.

Figure 7. The calculated NSF portion of neutrons reflected from a non-magnetic NiMo/Ti ($m = 3$) supermirror backing a CoFe (66.5 nm) layer is represented as a function of $q$. Smaller oscillations due to the interference of neutron waves reflected at numerous interfaces in the supermirror are smoothed by averaging over $\Delta q = 0.001$ nm$^{-1}$.

4. Performance of mirror spin turners

The test of a neutron mirror flipper verified the feasibility of producing not only mirror flippers, but also mirror spin turners. Performance of a mirror spin turner is shown in Fig. 8. Here the $z$-axis is chosen along the incident beam polarization vector $P_0$ and the $y$-axis belonging to the $(P_0, B_{in})$ plane, the $x$-axis is perpendicular to this plane (Fig. 8). Represent the vector $P_0 = P_0 (0, 0, 1)$ as the sum of the component $P_\parallel$ parallel to the precession axis and the precessing component $P_\perp$:

$$P_0 = P_\parallel + P_\perp,$$

$$P_\parallel = P_0 \cos \chi (0, \sin \chi, \cos \chi) = P_0 (0, \sin \chi \cos \chi, \cos^2 \chi),$$

$$P_\perp = P_0 - P_\parallel = P_0 (0, -\sin \chi \cos \chi, \sin^2 \chi),$$

where $\chi$ is the angle between $P_0$ and $B_{in}$.

Assume that the polarization vector $P_0$ of reflected neutrons is a result of Larmor precession of $P_0$ about $B_{in}$. The precession plane is perpendicular to $B_{in}$ lying in the $(y,z)$ plane. Due to finite divergence and wavelength spread, precession angles vary about a designed value $\phi$. Therefore, $P_0$ results from averaging polarization vectors weighted by respective intensities over different precession angles. Note that the polarization vector $P$ obtained by precession by $\phi$ ($P = P_0$) can be written as a sum of $P_\parallel$ and a vector in the precession plane, decomposable into components along $P_\perp$ and along the orth $e_i$ perpendicular to $P_\perp$ (Fig. 8):
The neutron reflectivity for a mirror spin turner is inversely proportional to \( q \) for a given direction. The condition \( P_\perp = \sin \chi \sin \varphi = \pm 1 \) for a \( \pi/2 \) (zy) spin-turner is satisfied with \( \chi = \pm \pi/2 \), \( \varphi = \pm \pi/2 \), and the condition \( P_\parallel = \sin \chi \cos \chi (1 - \cos \varphi) = \sin(2\chi)(1 - \cos \varphi)/2 = \pm 1 \) for a \( \pi/2 \) (zy) spin-turner is satisfied with \( \chi = \pm \pi/4 \), \( \varphi = \pm \pi \). Thus, one can turn spins from the initial \( z \)-direction to \(-z\), \( \pm x\) and \( \pm y\)-directions (Fig. 9).

For a deviation \( \Delta \varphi \) from a designed precession angle \( \varphi \) the resultant polarization vector can be found by replacing \( \varphi \) with \( \varphi + \Delta \varphi \) in (15). Its projection onto the designed direction \( P/P \) is
\[
P_{\Delta \varphi} = P_{\varphi} P/P = P_0 \left[ \cos^2(\chi) + \sin^2(\chi) \cos^2(\Delta \varphi) \right].
\]
(16)
The spin turner efficiency is defined for an initially polarized beam as the portion of neutrons reflected with the spin parallel to a given direction \( P \):
\[
e(\Delta \varphi) = (1 + P_{\Delta \varphi}/P_0)/2 = 1 - \sin^2(\chi) \sin^2(\Delta \varphi/2).
\]
(17)
Since the Larmor precession angle for a mirror spin turner is inversely proportional to \( q \), one finds
\[
\Delta \varphi = -\varphi \Delta q/q_0.
\]
(18)
where \( \Delta q = q - q_0 \) and \( q_0 \) is related to the designed precession angle \( \varphi \).

In our experiment with the mirror flipper: \( \chi = \pi/2 \), \( \varphi = \pi \), hence \( e(\Delta \varphi) = \cos^2(\Delta \varphi/2) \), which is consistent with the probability of the spin projection onto \( P \). The NSF portions calculated with \( q_0 = q_0 = 0.5 \text{ nm}^{-1} \) for the Bragg peak range of \( q \), are represented in Fig. 10 by the light blue curve. The neutron reflectivity \( R \) (pink curve) and the NSF portion (blue curve) for the multilayer-backed flipper with a CoFe (66.5 nm) layer and other parameters as designed are also represented in Fig. 10. Superposition of the waves in the opposite spin states, each resulting from interplay of numerous waves reflected from numerous interfaces in the multilayer-backed flipper leads to distortion of the Larmor precession behavior (cf. blue and light blue curves). The difference between the two curves is only due to the difference in the spin-up and spin-down neutron potentials of the CoFe layer, resulting in different reflection amplitudes (modules and phases) for the opposite spin compo-
ments. The difference between the amplitudes is smaller at greater \( q \), so the performance of a mirror flipper tuned to a greater \( q_B \) will be better.

![Figure 10](image)

**Figure 10.** The neutron reflectivity \( R \) (pink curve) and the NSF portion \( 1-f \) calculated as functions of \( q \) with Eq. (21) for a purely Larmor precession in the CoFe (66.5 nm) layer (light blue curve) and with exact numerical approach for the multilayer-backed flipper (blue curve).

5. Hyperpolarizer for a reflectometer

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. Consider a scheme of such a hyperpolarizer for a neutron reflectometer with a monochromatic beam (Fig. 11).

![Figure 11](image)

**Figure 11.** Scheme of a hyperpolarizer for a monochromatic beam reflectometer. The angle \( \alpha \) between the beams formed by the polarizing filter and the mirror flipper is supposed to noticeably exceed their divergences.

Here a polarizing filter reflects only spin-up neutrons, transmitting spin-down neutrons which are then reflected at a different glancing angle by a mirror flipper. The two formed beams converge at the sample, the two specularly reflected beams are resolved by PSD. Thus, the \( q \)-range of interest can be covered in about 2 times quicker. The intensities of beams 1 and 2 can be written as sums of spin-up and spin-down neutron intensities:

\[
\begin{bmatrix}
I_+^1 \\
I_-^1
\end{bmatrix} = \begin{bmatrix}
R^+_p & 0 \\
0 & R^-_p
\end{bmatrix} \begin{bmatrix}
I_0/2 \\
I_0/2
\end{bmatrix} = \frac{I_0}{2} \begin{bmatrix}
R^+_p \\
R^-_p
\end{bmatrix},
\]

\[
\begin{bmatrix}
I_+^2 \\
I_-^2
\end{bmatrix} = \begin{bmatrix}
(1-f)R^+_p \\
(1-f)R^-_p
\end{bmatrix} \begin{bmatrix}
T^+_s & 0 \\
0 & (1-R^-_s)T^+_s
\end{bmatrix} \begin{bmatrix}
I_0/2 \\
I_0/2
\end{bmatrix}.
\]

where \( I_0 \) is the intensity of the initial non-polarized beam, \( R^\pm_p \) and \( R^\pm_f \) are the reflectivities of the polarizing filter and the mirror flipper with an efficiency \( f \), \( T^+_s \) is the transmittance of the polarizing filter substrate. Respectively, total intensities and the polarization of beams 1 and 2 are

\[
I_1 = I_0 (R^+_p + R^-_p) / 2, \quad P_1 = P^+_p,
\]

\[
I_2 = I_0 R^- s (2R^- - R^-_p) / 2, \quad P_2 = P^- p \frac{2f - 1}{2(R^-_p + R^-) - 1},
\]

where \( P^\pm_p = (R^\pm - R^\mp) / (R^\pm + R^\mp) \) is the efficiency of the polarizing filter.
The gain in the intensity obtained with such a hyperpolarizer is

\[ G_h = (I_1 + I_2) / I_1 = 1 + R_p T_s [ 2 / (R_p^+ + R_p^-) ] - 1. \]  

(24)

To achieve a good polarization \( P_2 \), the factor in square brackets should be close to 1. Therefore, the intensity gain \( G_h \) is mainly defined by \( T_s \) and \( R_p \). Note that \( G_h \) is independent of the mirror flipper efficiency \( f \). On the other hand, \( P_2 \) is proportional to \( P_f \) and \((2f-1) R_p^+ \).

For very moderate parameters \( R_p^+ = 0.9 \), \( R_p^- = 0.01 \), \( R_p = 0.9 \), \( T_s = 0.8 \), \( f = 0.975 \), the performance of the hyperpolarizer is \( P_1 = 0.978 \), \( P_2 = 0.776 \), \( G_h = 1.862 \). For advanced parameters \( R_p^+ = 0.99 \), \( R_p^- = 0.005 \), \( R_p = 0.95 \), \( T_s = 0.9 \), \( f = 0.99 \) the performance is \( P_1 = 0.99 \), \( P_2 = 0.96 \), \( G_h = 1.864 \). To improve \( P_2 \), the polarizing filter substrate can be coated on both sides. Then for the two sets of the parameters, \( P_2 \) is 0.854 and 0.975, respectively. In order to form two highly polarized beams, \( R_p^+ \) should be as close as possible to 1. Therefore, total reflection of spin-up neutrons from a sufficiently thick magnetic layer is worth considering.

Of interest is also the option of using a non-magnetic mirror instead of the mirror flipper. Then two beams of opposite polarization will be formed. Again total measurement time can be reduced up to 2 times. In this case formulas (20-24) are also applicable with \( f = 0 \). Both options (mirror flipper and non-magnetic mirror) can be built in one device.

6. Conclusion

Experiments with a neutron mirror flipper verify the feasibility of producing not only mirror flippers, but also mirror spin turners. Such spin turners can be directly used only with narrow and well-collimated beams, as used in neutron reflectometry. Further developments of multichannel designs and supermirror-based spin turners may appreciably lift the restrictions. Moreover, they can be made broad-band, which is of special interest for applications at impulse reactors and spallation sources. Combining NSO elements, one can build compact devices, including those for 3D-polarization and 3D-analysis, as well as spin manipulators and hyperpolarizers.

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