Methods and Devices for Reversing Neutron Polarization

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Abstract—The merits and demerits of the methods for reversing neutron polarization and of the devices (flipper) for neutron spin flipping relative to the magnetic field are discussed. A flipper capable of operating under problem conditions—when installed on a neutron guide and in vacuum—is described.
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INTRODUCTION

A device (a flipper) for efficient neutron spin (neutron beam polarization direction \(\mathbf{P}\)) flipping relative to the guiding magnetic field \(\mathbf{H}\) is conventionally used in experiments with polarized neutrons. Degree of beam polarization \(P\) is defined as the normalized difference in intensity between the beam with a spin opposite to the field \(I^*\) when the flipper is in the off state and the beam with a spin aligned with the field \(I\) when the flipper is in the on state,

\[
P = (I^* - I)/(I^* + I).
\]

At the early beginning of neutron experiments in 1932, Chadwick used the spin resonance method to reverse the polarization in [1]. In this method, weak RF oscillating magnetic field \(\mathbf{H}_0(\cos \omega t)\) is applied at right angle with the direction of guiding field \(\mathbf{H}\), i.e., with the polarization direction. Frequency \(\omega\) is selected to be equal to the Larmor frequency of neutron spin precession \(\omega_n = \gamma_n H\), where \(\gamma_n\) is the gyromagnetic ratio for a neutron.

The resonance method allows reversal of the polarization at certain values of guiding field \(H\), RF field amplitude \(H_0\), and time of flight \(t\) of neutrons through the area of action of RF field \(L\). The main drawback of this method is the necessity to stabilize guiding field \(H\) and frequency \(\omega\), and complete polarization reversal is possible only for a monochromatic neutron beam.

Easier-to-implement methods for reversing the polarization relative to the field are used in neutron experiments more frequently. These methods are based on nonadiabatic passage of neutrons through the region with a sharp change in the sign of magnetic field \(\mathbf{H}\) when effective field rotation frequency \(\omega_0\) is much greater than \(\omega_n\) and polarization vector \(\mathbf{P}\) does not have time to significantly change its direction in space and appears to be reversed relative to \(\mathbf{H}\).

Such a field with a drastic change of its sign is generated by a thin wide foil of nonmagnetic material, through which an electric current is passed, creating oppositely directed magnetic fields on different sides of the foil [2]. If adiabaticity factor \(K = \omega_0/\omega_n\) is <0.05, flipping efficiency \(P\) may be close to 100\%. For the field rotating angle \(\phi = \pi\) on a segment of length \(L\), the adiabaticity factor is determined from the formula

\[
K = \gamma HL/\pi \nu,
\]

where \(\nu\) is the neutron velocity.

The main drawback of such a flipper is the fact that a neutron-scattering material is placed in the beam and, should the current be high, gives rise to problems with heat removal. This difficulty was overcome in the design of Mezei’s flipper [3], which consists of flat solenoids with field \(H\) perpendicular to guiding field \(\mathbf{H}\). The polarization is reversed due to Larmor precession in the sum fields of the solenoids and guiding field \(\mathbf{H}\). Nevertheless, problems with the presence of material in the beam and with the beam monochromaticity still remain in this flipper.

The other version of a nonadiabatic flipper is based on the use of oppositely directed fields, e.g., of two Helmholtz coils disposed along the beam axis and connected oppositely (the Leningrad flipper [4]). There is no material on the beam path in this flipper, but the region of effective flipping lies near the axis of the coils, and it is therefore not so good for wide beams.

All methods for reversing the neutron polarization in which it is necessary that static magnetic fields be switched have an additional drawback that is especially perceptible if the detectors used in the flipper are sensitive to magnetic fields—the possibility of false effects.
This is particularly important for measurements of weak relative effects ($\sim 10^{-3}$ to $10^{-6}$). Fast switching of currents in devices generating the required stationary fields is also a complicated engineering problem.

An adiabatic (in coordinates of a system rotating with frequency $\omega_0$) RF flipper, for the first time designed for ultracold neutrons [5], is a device free from all above drawbacks. It has also found wide application for thermal neutrons [6–8]. In this paper, we describe its operating principle and its adaptation for mounting on the neutron guide (see patent [9]), which is in turn located in vacuum space.

**CONCEPT OF RESONANCE ADIABATIC SPIN FLIPPING IN A MAGNETIC FIELD**

The operating principle of the resonance adiabatic flipper is based on the fact that, in a coordinate system rotating with frequency $\omega_0$, the neutron spin in crossed fields (static field $H_0$ and RF field $H_1$) is affected by effective field $H_{\text{eff}} = H_0 - \omega_0/\gamma$ (Fig. 1). Under the resonance conditions in which guiding field $H_0$ is constant on segment $L$ and frequency $\omega_0 = \omega_L$, we are dealing with a standard resonance method described in the Introduction. However, if field $H_0$ has a gradient on segment $L$ along the neutron path and this gradient is such that $\omega_0 = \omega_L$ only in the middle part of this segment, difference $\omega_0 - \omega_L$ will have unlike signs at the beginning and end of segment $L$, passing through zero under the resonance conditions.

For example, if variation in the RF field amplitude over length $L$ is bell-shaped and the field value is zero at the beginning and end of segment $L$, effective field $H_{\text{eff}}$ smoothly turns through $180^\circ$ from the “plus” direction toward the “minus” direction. In this case, if standard adiabatic conditions are met for $H_{\text{eff}}$, the polarization at the end of path $L$ appears to be flipped relative to guiding field $H_0$. Flipping probability $p$ depends in this case only on adiabaticity factor $K$ [8]:

$$p = 1 - \sin^2 \left( (\pi/2) \sqrt{1 + K^{-2}} \right) / K^2 + 1$$

From this formula, it is apparent that the maximum difference of $p$ from unity at great values of $K$ is proportional to $1/K^2$. For example, at $K = 20$, we have $p_{\text{min}} = 0.9975$, and a change of, e.g., $10\%$ in one or another parameter in $K = \gamma HL/\pi v$ toward decreasing $K$ will result in value $p_{\text{min}} = 0.997$.

This means that, by contrast to the other flipper systems, operation of this flipper depends on the stability of its parameters only slightly and breaking of adiabaticity $K$ is the sole limitation (i.e., the limitation is only from the side of short neutron wavelengths). If the neutron beam spectrum is wide, the adiabaticity and flipping efficiency increase with increasing wavelength. The calculation of $p_{\text{min}}$ presented above has been carried out for the minimum $p$ value. In reality, $\sin^2 f(K)/(K^2 + 1)$ is an oscillating and decaying function of $K$, and its mean value (i.e., the difference of $p$ from unity) is significantly smaller than the above estimate.

A possible version of such a flipper for neutrons scattered from a sample is shown in Fig. 2. This flipper was produced by the Konstantinov Institute of Nuclear Physics (Gatchina, Russia) for the SANS-2 small-angle...