Depolarization of ultracold neutrons in refraction and reflection by magnetic-film surfaces

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Depolarization of neutrons on the interface between two regions with noncollinear magnetic inductions is considered.

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Ultracold neutrons (UCN) are polarized by passing them through magnetized films. The neutrons having one spin directions are completely reflected, and those with the other direction are freely transmitted,[1] so that the expected polarization is 100%. But the value obtained in the experiment[1] was only about 75%. In Refs. 2 and 3 an attempt was made to attribute this result to inhomogeneities of the field inside the film. It is shown in the present paper that the depolarization can proceed directly on the interface if the fields $\mathbf{B}_{1,2}$ inside and outside are inclined to each other, for in this case the adiabaticity condition is violated on the boundary.

In view of the continuity of the wave function and its derivative on the interface, the matrix $\hat{T}$ for the passage from medium 1 into medium 2 and the matrix $\hat{R}$ for the reflection, which connect states polarized with and against the field **B**, can be expressed in the form

$$\begin{aligned} \hat{T} &= \hat{\Phi}_2^{-1} (\hat{k}_{\phi 1} + \hat{k}_{\phi 2})^{-1} 2\hat{k}_{\phi 1}\hat{\Phi}_1, \\ \hat{R} &= \hat{\Phi}_1^{-1} (\hat{k}_{\phi 1} + \hat{k}_{\phi 2})^{-1} (\hat{k}_{\phi 1} - \hat{k}_{\phi 2})\hat{\Phi}_1. \end{aligned} \tag{1}$$

$$\begin{aligned} &\hat{k}_{\phi i} = \hat{\Phi}_i \hat{k}_i \hat{\Phi}_i^{-1} = q_{i+} + q_{i-}(\sigma \mathbf{e}_{Bi}); \quad \mathbf{e}_{Bi} = \mathbf{B}_i / B_i, \\ &\hat{k}_i = q_{i+} + q_{i-}\sigma_z; \quad q_{i\pm} = k_{i+} \pm k_{i-}; \quad k_{i\pm} = \sqrt{k_0^2 - u_i \pm k_{Bi}^2}, \\ &u_i = 4\pi N_i b_i; \quad k_{Bi}^2 = 2m\mu | B_i / \hbar^2; \quad k_0^2 = 2mE_\perp / \hbar^2, \\ &\hat{\Phi}_j = \exp[i\phi_j(\mathbf{n}\sigma)]; \quad j = 1,2; \quad \mathbf{n} = [\mathbf{B}_1 \times \mathbf{B}_2] / |\mathbf{B}_1 \times \mathbf{B}_2], \\ &\phi_1 - \phi_2 = \theta/2; \quad \theta = \arccos(\mathbf{e}_{B1}\mathbf{e}_{B2}); \quad \phi_j = \theta_j/2. \end{aligned} \tag{2}$$

The notation used in (1) is defined in (2), where $E_\perp$ is the energy of the motion perpendicular to the interface, m is the mass, μ is the magnetic moment of the neutron, N_i is the density of the nuclei, b_i is the coherent scattering length of the neutron by one nucleus (we can assume in general the matter is present on both sides of the interface), and θ_i is the angle between $\mathbf{B}_i$ and the z axis, which is directed along the line of intersection of the interface with the plane of the vectors $\mathbf{B}_i$. Expressions (1) make it possible to find the fraction μ_- of the neutrons leaving the foil with the spin flipped, and μ_+ is the fraction with the spins unflipped:

$$\mu_- = 4k_{1+}k_{2-}|k_{1-}+k_{2+}|^2\sin^2(\theta/2)/Q,$$

$$\mu_+ = 4k_{1+}k_{2+}|k_{1-}+k_{2-}|^2\cos^2(\theta/2)/Q, \tag{3}$$

$$Q = k_{1+}k_{1-}+k_{2+}k_{2-}+2(q_{1+}q_{2+}-q_{1-}q_{2-}\cos\theta).$$

The polarizing ability of the film is in this case $P=(\mu_+-\mu_-)/(\mu_++\mu_-)\approx\cos\theta$. At an external field $B_2=400$ G the internal field is $B_1=20\,000$ G and a polarization 75% corresponds to $\theta\approx 40°$, and $\theta_1\approx 1°$.

Opinions differ on the manner of obtaining P from the polarization ratio ϵ.[1,4] This question was first posed by Taran.[3] The answer depends on the experimental conditions. In the stationary flow-through variant[1] it is necessary to take into account the effect of accumulation between the polarizer and the analyzer.[3] For simplicity we assume the flipper effectiveness to be equal to unity and the polarization in the intermediate region to be zero, and introduce an abstract loss coefficient λ. We can then write $\epsilon=(\alpha_++\alpha_--\beta)/(\alpha_++\alpha_-+\beta)$, where $\alpha_\pm=\mu_\pm^2/(2\mu_\pm+\lambda)$, and $\beta=2\mu_+\mu_-/(\mu_++\mu_-+\lambda)$. As $\lambda\to\infty$ we have $\epsilon\approx p^2$, and as $\lambda\to 0$ and at $\mu_-\ll\mu_+$ we get $\epsilon=(\mu_+-\mu_-)^2/[(\mu_++\mu_-)^2+4\mu_+\mu_-]\approx 1-8\mu_-/\mu_+$. If we use the relation $p=\sqrt{\epsilon}$, then p is underestimated, but the polarization in the interval between the polarizer and analyzer differs from p as $\lambda\to 0$. In the time-of-flight procedure no accumulation takes place[4] and therefore if the films are symmetrical we have $P=\sqrt{\epsilon}$.

The depolarization at the interface can be verified experimentally, since it takes place coherently, and the initially polarized neutrons undergo birefringence and double reflection. The angle of reflection of the beam with the flipped spin differs from the incidence angle ψ by an amount $\delta\psi=\pm\tan\psi\mu B/(E\pm\mu B)$, where B is the external field and E is the total energy of the neutron. The $\pm$ sign corresponds the different initial polarizations. The intensity of the nonspecular beam can be easily found from (1). It is proportional to $\sin^2\theta$. If the noncollinearity of $\mathbf{B}_i$ is due to anisotropy, then it should depend both on the inclination of the field to the external field and on the temperature.

When polarized neutrons pass through a magnetized foil, birefringence takes place inside the foil if the internal and external inductions of the magnetic field are not collinear. On the exit surface of the foil, each of the beams again undergoes birefringence, and it turns out that beams having like polarization acquire inside the foil a phase difference $\chi=(k_+-k_-)H$, where H is the foil thickness. By varying this phase difference in one manner or another, it is possible to observe interference beats of intensities with different polarizations. This effect is of greatest interest for neutrons with energies close to the UCN energy, for in this case the angle between the diverging components with opposite polarizations on the field **B** is large, and the interference picture can not be interpreted as ordinary spin precession.

If the magnetized foil is not plane-parallel, then two beams of like polarization will diverge slightly after passing through the foil, and by examing the interference of the slightly diverging beams it is possible to obtain information on the coherence length of the neutron itself.

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