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Neutron Interferometry Method of Study of Parity Violation in Cold Neutron Transmission

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The possibility of using an extremely sensitive neutron interferometry technique to carry out precise measurements of the parity non-conservative effects in neutron spin rotation is discussed. An accuracy of about 10^{-5} rad could be achieved in the determination of spin direction dependent phase shifts. The method, free from some systematic effects limiting present polarization techniques, can be used as another way for the study of parity non-conservation effects in weak interactions.

KEYWORDS: Parity non-conservation, Neutron Interferometry

The parity non-conservation in weak interaction provides a possibility to investigate the nature of the weak force in the presence of the much stronger electromagnetic and strong interactions, and is the subject of permanent interest during decades. In this work it is attractive to study the transmission of cold neutron beams through the matter, in which case coulomb scattering is absent and the strong interaction manifestes itself as the neutron-nucleus forward scattering.

Weak currents result in small parity-nonconservation (PNC) effects under the propagation of neutrons through the ordinary matter. The most sensitive linear PNC effect has first been considered by Michel.[1] This effect appears in forward elastic scattering as the optical rotation of the transverse component of the neutron spin around the propagation direction. Stodolsky[2] proposed to look for an electron contribution to this effect, that can be comparable to the nuclear one. Later, Forte[3] has proposed that PNC effects can be enhanced in the vicinity of a neutron resonance even at thermal neutron energies.

The scattering amplitude in this case can be written as the sum of parity conservative and non-conservative terms:

$$f(\vartheta) = f_{PC}(\vartheta) + f_{PNC}(\vartheta) \qquad (1)$$

For polarized neutron beam transmission through a non-polarized target the weak term in neutron - nucleus interaction results in an average interaction, that depends on the neutron spin $\vec{\sigma}$ and the momentum of the beam $\vec{p}$.

$$f_{PNC}(0) = C\langle\vec{\sigma}\cdot\vec{p}\rangle \qquad (2)$$

where the complex coefficient C is expected to be proportional to G, the weak interaction coupling constant. The real part of the coefficient C, which is constant at low energy, results in a helicity dependence of ϕ_{PNC}. It was shown[4] that for a neutron beam with polarization vector $\vec{P}$, the rotation angle of this vector around $\vec{p}$ is

$$\phi_{PNC} = -4\pi \cdot N \cdot l \cdot \mathrm{Re}(C)$$

where the positive sign of ϕ_{PNC} corresponds to a right hand rotation of $\vec{\sigma}$ around $\vec{p}$.

The experimental approach used in a number of experiments, where such effects were observed,[5, 6] is neutron polarimetry, that is the measurement of the angular rotation of the neutron beam polarization vector ϕ_{PNC}. A major problem in these experiments was the separation of a small PNC effect from the neutron precession in the residual magnetic field. In order to extract a net PNC signal from this background, a spin flip coil was inserted in the centre of a low field region. Measurements were carried out with the sample alternately placed before or behind the spin flip coil: the sign of ϕ_{PNC} was changed for these two sample's positions, whereas the angle of the neutron precession in the residual magnetic field did not change sign; it allowed the compensation of the large systematical effect.

A new wave of interest to such kind of experiments appeared last years, when Heckel[7] reported a non-zero result for natural lead. Such effect can be explained by the valent model,[8] so that experiments with lead are looked upon as tests of two different models of weak interaction. It was proposed that the isotope ^{207}Pb could be 'responsible' for this effect. A set of careful experiments has been carried out at Hahn-Meitner Institute, Berlin by a Berlin - Moscow - Seatle collaboration.[9] These experiments also showed that the problem of stray magnetic fields is not yet solved. Because of small-angle neutron scattering in the sample and the divergence of the neutron beam, the target makes trajectories of neutrons different for the two target positions (before and behind the spin flip coil). The angles of the neutron spin precession in stray magnetic fields before and behind of this coil are generally different. Thus, because the change of sample positions induces an uncompensated systematical error, it limits the accuracy of experiments.

Here a new method for studying the PNC effects on neutron spin rotation is proposed. It is based on methods of neutron interferometry and principally does not require the change of the sample position in order to identify a small PNC effect above the neutron precession in magnetic field, so that it is free from the systematical error discussed above.

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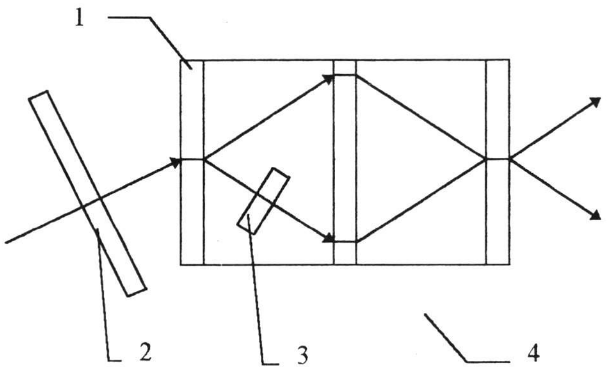

Fig. 1. Layout of the experiment. 1 - neutron interferometer, 2 - flipper, 3 - sample, 4 - shifter

As it was already mentioned above, the neutron-nucleus weak interaction results in the helicity dependence of the coherent forward scattering amplitude $f(0)$. It can also be described by the neutron refraction index n

$$n = \left[1 + \frac{\lambda^2 N}{\pi} f(0)\right]^{1/2}$$

where λ is the neutron wavelength and N the atomic density. If $f^+(0)$ and $f^-(0)$ are the amplitudes for helicity +1 and -1, respectively, then one can write, using Eq. (1):

$$n^+ = 1 + \frac{\lambda^2 N}{2\pi}\left[f^+_{PC}(0) + f^+_{PNC}(0)\right] = n^+_{PC} + n^+_{PNC}$$

$$n^- = 1 + \frac{\lambda^2 N}{2\pi}\left[f^-_{PC}(0) + f^-_{PNC}(0)\right] = n^-_{PC} + n^-_{PNC}$$

so that the neutron refraction index consists of a parity conservative part n_{PC} and a comparatively small parity nonconservative part n_{PNC}.

Let us consider a neutron interferometry experiment, where a sample is placed in one of the interferometer arms and the spin state of the polarized incident beam is controlled by a flipper, installed in front of the interferometer (Fig. 1). Total phase shifts, acquired by the transmission through the sample, of neutron waves with opposite spin states $|\uparrow\rangle$ and $|\downarrow\rangle$, parallel and antiparallel to the neutron momentum, are

$$\Phi^+ = p \cdot t \cdot n^+ \qquad (3a)$$

$$\Phi^- = p \cdot t \cdot n^- \qquad (3b)$$

so that the phase difference between beams I and II (see Fig. 1), which is actually measured by the interferometer, can be written as

$$\varphi^+ = p \cdot t \cdot (n^+ - 1) = p \cdot t \cdot n^+_{PC} + p \cdot t \cdot n^+_{PNC} = \\ = \varphi^+_{PC} + \varphi^+_{PNC} \qquad (4a)$$

$$\varphi^- = p \cdot t \cdot (n^- - 1) = p \cdot t \cdot n^-_{PC} + p \cdot t \cdot n^-_{PNC} = \\ = \varphi^-_{PC} + \varphi^-_{PNC} \qquad (4b)$$

Here, parity nonconservative parts of the phase shift are

$$\varphi^{\pm}_{PNC} = p \cdot n^{\pm}_{PNC} \cdot t \qquad (5)$$

where t is the sample thickness.

Two different ways determining φ_{PNC} in a neutron interferometry experiment are the use of the transversally or longitudinally polarized incident neutron beams.

In the first case, the experiment is just neutron interferometry analogue of PNC experiments described above and principally is the measurement of the rotation angle of the spin of transversally polarized incident neutron beam, that is the rotation of the polarization vector. The phase shift φ_{PNC} can be defined by the angle of the PNC spin rotation, as

$$\varphi_{PNC} = \phi_{PNC} / 2 .$$

In the second case, the neutron spin is parallel or antiparallel to the momentum, so it does not lead to any rotation of the polarization vector. However, opposite helicities +1 and -1 will result in parity nonconservative phase shift (Eq. (4)).

In both cases the parity conservation part φ_{PC} (Eqs. (4a) and (4b)) consists of nuclear and magnetic phase shifts

$$\varphi_{PC} = \varphi_{nucl} + \Delta\varphi_m$$

Here

$$\varphi_{nucl} = (1 - n_{nucl}) \cdot p \cdot t = N \cdot \lambda \cdot b_c \cdot t$$

(b_c. is the coherent scattering length of the sample under the study) and $\Delta\varphi_m$ is the difference of the neutron spin precession angles in the residual magnetic field, which can have a rather small value of about 0.5 mG (defined by a proper magnetic shielding), but which principally can be different for each of interferometers' arms.

Reversing the spin states of the incident beam changes only the signs of the PNC effect and the magnetic phase shift, so that one can write (φ_0 is an initial phase shift)

$$\varphi_{|\uparrow\rangle} = \varphi_0 + \varphi_{nucl} + \Delta\varphi_m + \varphi_{PNC} \qquad (6a)$$

$$\varphi_{|\downarrow\rangle} = \varphi_0 + \varphi_{nucl} - \Delta\varphi_m - \varphi_{PNC} \qquad (6b)$$

Thus, in this case one avoids the use of the spin flip coil in the low field region to change sign of the PNC effect, and problems connected with it. The effect caused by residual magnetic field slightly violates the symmetry of the experiment, but it can be corrected for measurements without sample (Eq. (6)), and therefore one can easily evaluate such asymmetry.

The crux of the matter is that the change of trajectories of neutrons because of the scattering in the sample will result in very much reduced systematical error. Indeed, the scattering violates extremely rigid interference conditions, so that scattered neutrons will not contribute to the interference pattern, but only to the background, and slightly reduce the interference pattern visibility. Only neutrons scattered within a small angular acceptance $\Delta\theta \approx$ 1 sec of arc will still contribute to the interference pattern, but the artefact they can cause is proportional to $(\Delta\theta)^2$ and is negligible.

Thus, only one of the considered effects mimics the PNC spin rotation. However, in the proposed method the measuring process is confined to the size of the interferometer, so that the length of the magnetic field-free space is about 6 cm, in contrast to the conventional polarimetry technique, where it amounts up to 30 cm. This fact reduces significantly the problem of residual magnetic field in the neutron interferometry method.

Moreover, in our case the change of the spin state of the neutron beam is realized by a flipper which is placed *not inside* , but *outside* of the apparatus. Thus, recording two interference patterns (Eqs. (6a, b)), which correspond to the spin-up and spin-down states of the incident beam, one can determine $\Delta\varphi_{PNC}$. Certainly, the accuracy of determination of $\Delta\varphi_{PNC}$ is defined by the accuracy of phase measurements in neutron interferometry experiment and the latter depends on the visibility of interference pattern and count rate. Simulations show that for a 30 day experiment on the neutron interferometer installed at the reactor of HMI (P = 10 MW),[10)] the neutron optical activity at the level of $5 \cdot 10^{-5}$ can be determined. Certainly, the use of more intensive neutron sources will allow improvement of this value. For the high-flux reactor of ILL this level can be down to 10^{-5} for the same time of data collection. This is comparable with the sensitivities reached in experiments,[5-7,9)] which was about $5 \cdot 10^{-6}$.

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