New approach to test a neutron electroneutrality by the spin interferometry technique

I.A.Kuznetsov, V.V.Voronin

Petersburg Nuclear Physics Institute,
Gatchina, Leningrad distr., 188300, Russia

Abstract

New method to measure a neutron electric charge is described. The main idea is to use SESANS technique, which provides a spacial splitting of neutron onto two eigenstates with different projection of spin on magnetic field. After passing through working area with applied uniform electric field E these two eigenstates are coupled back. Therefore, the phase of interference pattern, i.e. azimuthal spin direction, is defined by phase difference of two neutron eigenstates accumulated in the working area. This phase will be determined by the nonzero neutron electric charge. Preliminary estimations demonstrate that using this technique can improve the current constrain on neutron electric charge at least on one order of magnitude.

1 Introduction

Electroneutrality of the free neutron is commonly accepted. Modern experimental constrain is lying on the level $q_n < 10^{-21}e$ [1]. But the zero neutron electric charge is not a request of Standard Model containing an abelian $U(1)_Y$ gauge symmetry, even after taking into account quantum anomaly cancellations [2]. Majorana masses of the neutrinos and, of course, a non-abelian gauge group of grand unification support charge neutrality of atoms and neutrons, but there remain problems [3].

Overall, only a few hints exist for physics beyond the Standard Model, and the neutrality of neutrons [1] and of atoms [4], both of order $10^{-21}e$, is such a hint, since in the SM this would require an incredible fine-tuning. Some models beyond the SM that violate boson - lepton (B- L) symmetry could accommodate a nonzero neutron charge $q_n = \varepsilon(B - L) \neq 0$, too, with the interesting signature that the charge of the hydrogen atom (which has B $= L$) would remain zero [2].

From other hand, some variants of theories with additional extra dimensions (see, for example [5, 6] and references therein) give the possibility to have non-zero neutron electric charge. In any case, the improving of accuracy of the neutron electroneutrality verification seems to be rather interesting and important.

2 Method description

The main idea of this approach is to use the spin interferometry technique, which is realized in SESANS (spin-echo small angle neutron scattering) installations, see for instance [7, 8].

The principle of such interferometer is shown on fig.1. The installation consists of two regions K1 and K2 of magnetic field with inclining edges. Magnetic field in the first region is opposite in direction to the second one. Such regions can be organized by different ways: with parallelogram magnet poles, with current coils of appropriate form or with system of two resonant coils, placed on some distance between.

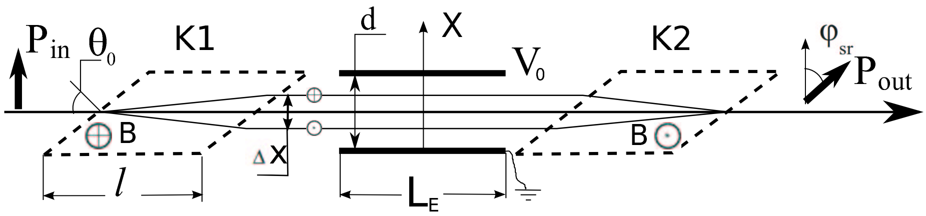

Figure 1: Scheme of the experiment

Neutron beam polarization **P** is directed perpendicularly to guiding magnetic field $B \parallel Z$ by the $\pi/2$ spin-rotators, which are not shown in the figure. As a result, the neutron wave function can be written in form

$$\psi_{in} = \frac{1}{\sqrt{2}} \begin{pmatrix} e^{-\frac{i\varphi_0}{2}} \\ e^{+\frac{i\varphi_0}{2}} \end{pmatrix}, \quad (1)$$

where φ_0 - neutron spin direction in azimuthally plane. Hereinafter let's consider **P** parallel to X-axis ($\varphi_0 = 0$).

Then, the spatial splitting of neutron wave onto two eigenstates with different projection of spin on magnetic field takes place in the first coil K1 with inclining magnetic field edges. The value of spatial splitting Δx is proportional to magnetic field and can be varied by changing the current in the coil. After passing through the working area these two eigenstates are coupled back with the second coil K2, which has the same parameters as

K1, but opposite in magnetic field direction. The phase of the interference pattern, i.e. azimuthal spin direction on the exit of K2 is defined by phase difference of two neutron eigenstates, accumulated in working area.

Then, let's apply the inhomogeneous spatial distribution of some potential $V_{sr}(x)$ in working area. In this case two neutron eigenstates with opposite spin direction will pass through this area with different kinetic energies. And the phase difference between these two eigenstates will be

$$\varphi_{sr} = (V_{sr}(x_0) - V_{sr}(x_0 + \Delta x))/\hbar \cdot \tau, \tag{2}$$

where τ is the time of neutron stay in $V_{sr}(x)$ potential.

As a result, the neutron wave function on the exit of coil K2 will be

$$\psi_{out} = \frac{1}{\sqrt{2}} \begin{pmatrix} e^{-\frac{i\varphi_{sr}}{2}} \\ e^{+\frac{i\varphi_{sr}}{2}} \end{pmatrix} \tag{3}$$

Polarization vector of passing neutron beam P_{out} can be defined as

$$P_{out} = \frac{< \psi_{out}|\boldsymbol{\sigma}|\psi_{out} >}{< \psi_{out}|\psi_{out} >}, \tag{4}$$

where $\boldsymbol{\sigma}$ are the Pauli matrices.

As a result we have:

$$P_x = \cos\varphi_{sr},\ P_y = \sin\varphi_{sr},\ P_z = 0. \tag{5}$$

If an electric potential $V_E(x) = E_0 \cdot x$ is applied in working area then the spin rotation angle will be:

$$\phi_e = \frac{E_0 q_n \Delta x}{\hbar} \cdot \tau \tag{6}$$

where τ is the neutron time-of-flight through the working area ($\tau = L_E/\mathrm{v}_n = \frac{L_E \lambda_n m_n}{\hbar 2\pi}$), λ_n is the neutron wave length, m_n and q_n are the mass of the neutron and it's electric charge.

The value of spatial splitting Δx in a spin interferometer is defined as [7]

$$\Delta x = \frac{\mu B}{E} l \tan\theta_0 \tag{7}$$

where l is the K1 and K2 coils length, θ_0 is the angle between the neutron velocity and normal to coil edge, is the value of magnetic field inside the coil, μ is the magnetic moment of neutron and E is it's energy. Finally, the angle of spin rotation due to neutron charge will be equal to

$$\phi_e = E_0 q_n l L_E B \tan\theta_0 \gamma \frac{\lambda_n^3 m_n^2}{8\pi^3 \hbar^3}, \tag{8}$$

where γ is the neutron gyromagnetic ration.

Numerical estimations show, that under the conditions ($B = 0.1$T, $L_E =$ 1m, $l = 1$m, $E_0 = 100$ kV/cm, $\tan\theta_0 = 10$, $\lambda_n = 30$Å)

$$\phi_e = 7 \cdot 10^{16}\, e_n. \tag{9}$$

where $e_n = q_n/e$ is the neutron electric charge in elementary charge unit. If the measured accuracy is $\Delta\phi_e \simeq 10^{-5}$ then the accuracy of neutron electric charge measurement will be $\sigma(e_n) \simeq 1.4 \cdot 10^{-22}$ of elementary charge that is about one order better the modern accuracy [1].

3 Conclusion

New approach to test the neutron electroneutrality is described. It is based on using spin interferometer technique realised in the SESANS apparatuses. The sensitivity of the proposed technique can be $\sim 10^{-22}$ e, that is about one order better the current accuracy [1]. The possibility to modify and improve the method accuracy on a few orders based on a neutron Laue diffraction in a perfect crystal is proposed. The demonstration experiment to test the possibility to measure phase shift caused by neutron refraction in media was done. The results fully coincide with the theoretical expectation.

This work is supported by the RFBR (Grant Nos. 12-02-00441 and 11-02-12161) and Science and Education Ministry of Russian Federation.

References

[1] Baumann J., R. Goehler, J. Kalus, W. Mampe, Phys. Rev. D, **37**, 3107 (1988)

[2] Foot R., H. Lew R.R. Volkas, J. Phys. G, **19**, 361 (1993)

[3] Witten E., Phys.Lett. B **86**, 283 (1979)

[4] Dylla H. Frederick, John G. King, Phys.Rev. A **7**, 1224 (1973)

[5] Rubakov V.A., Physics-Uspekhi, **44**, 871 (2001)

[6] I. Antoniadis, N. Arkani-Hamed, S. Dimopoulos and G. Dvali, Phys. Lett. B **436**, 257 (1998)

[7] W.G.Bouwman et al, NIM A **586** (1), 9 (2008)

[8] E.Knudsen, L.Udby, P.K.Willindrup, K.Lefmann, W.G.Bouwman, Physica B, **406**, 2361 (2011)