Nuclear Instruments and Methods in Physics Research A 778 (2015) 26–30

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Improved instrument for the determination of the neutron electric charge

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ARTICLE INFO

Article history:
Received 4 November 2014
Received in revised form
5 January 2015
Accepted 5 January 2015
Available online 13 January 2015

Keywords:
Neutron charge
Electric charge quantization
Ultracold neutrons

ABSTRACT

We present an improved instrument for the determination of the neutron electric charge with ultracold neutrons. Several technical upgrades with respect to a former experiment will be discussed in detail. As a first test, we applied the apparatus to investigate the influence of gravitational attraction by means of a massive block of lead. The calculated sensitivity for a charge measurement is $\delta q_n \approx 2.14 \times 10^{-20} e/\sqrt{\text{day}}$. Planned modifications increasing the sensitivity up to $\delta q_n \approx 1.34 \times 10^{-21} e/\sqrt{\text{day}}$ are demonstrated.

1. Introduction

The Minimal Standard Model (MSM) describing the fundamental interactions in particle physics is not able to explain the electric charge quantization (ECQ) inherently [1]. Moreover, this is put in by hand. Within MSM, a slight deviation of the electric charge of e.g. neutrons or atoms from zero is allowed. Extending the MSM with respect to neutrino masses, ECQ could be explained in case of majorana neutrinos [2]. On the other hand, if neutrinos were dirac particles, ECQ can be destroyed via

$$\delta Q = \varepsilon(B - L),$$

with B the baryon number and L the lepton number, respectively [3]. This means that e.g. hydrogen would be neutral, while the neutron or neutrinos could carry a tiny charge ε. The majorana character of neutrinos has not been observed yet [4]. So, the question of ECQ is still unanswered from this point of view. Hence a search for the electric charge of the neutron and the search for neutrinoless double beta decay approach this problem from two different sides.

In 1988, the electric charge of the neutron q_n was determined to

$$q_n = (-0.4 \pm 1.1) \cdot 10^{-21} e$$

with a neutron optical device using cold neutrons (100 m/s–300 m/s) [5]. e is the electric charge of the electron. This experiment still holds the most stringent, direct bound on the free neutron charge. In the last years, the problem of a charged neutron has attracted attention again, thus several new experiments are planned [6–8], using free neutrons.

The neutron electric charge could also be determined using bulk matter [9,10], molecules [11] or atoms [12]. Proposed experiments using atom-interferometry, probing the electric neutrality of atoms and neutrons, promise sensitivities up to the level of $q_n \sim 10^{-28} e$ [12]. As neutrons in atoms and free neutrons may have different charges [13], it is important to test the neutron charge with both, bound and free neutrons at comparable sensitivities.

In 1987, the neutrality of the free neutron was tested using ultracold neutrons (UCN), but only at a level of $(-4.3 \pm 7.1) \cdot 10^{-20} e$ [14]. Since then, UCN have not been used for the test of neutrons' neutrality. We picked up the idea to use UCN for the neutron electric charge measurement in 2008 [8]. In the following, we will refer to the experiment [14] as the "former experiment", as we compare it with our setup.

2. Method

The principle of measurement is shown in Fig. 1.

A grating is illuminated by UCN. A cylindrical concave mirror images the input grating onto an exit grating in a $2f$ configuration. Neutrons that pass the exit grating will be detected. If a force (e.g. an electric field in case of $q_n \neq 0$) acts perpendicular to the optical axis, the neutrons will be deflected. Thus the image will be shifted, which results in a change in the count rate. Shifting the exit grating along the x-axis results in a modulation of the count rate. The count

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http://dx.doi.org/10.1016/j.nima.2015.01.015
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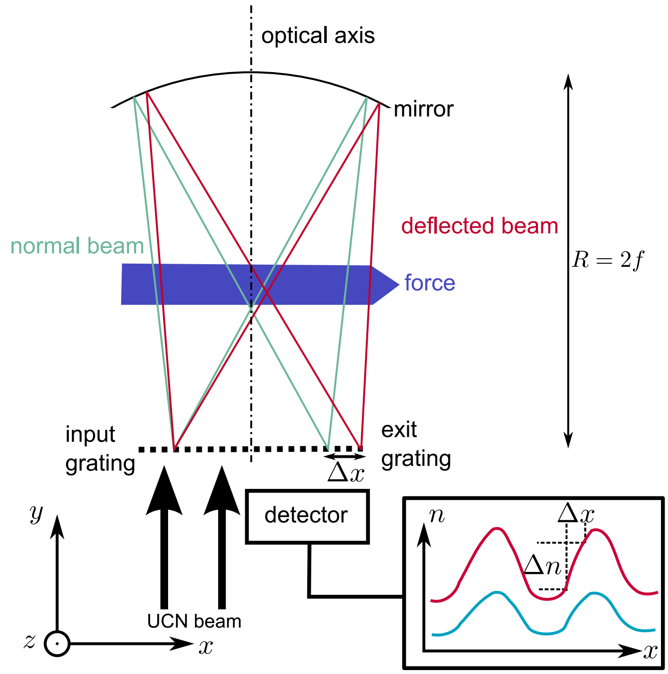

Fig. 1. Principle of measurement: the scan of the exit grating yields a modulation in the count rate n. A force perpendicular to the optical axis shifts the image. This results in a change in the count rate.

rate corresponds to the spatial convolution of two multiple rectangle functions. At the point of the steepest slope $\partial_x n$, the sensitivity for shifts of the neutrons along the x-axis is the highest. This is the bias point of the apparatus. Flux fluctuations would mimic forces. Therefore, we perform a differential measurement using two stacked exit gratings, one is set at the positive slope, the other one at negative slope. A shift Δx of the neutron image is given by

$$\Delta x = \frac{1}{2}\left(\frac{\Delta n_1}{\partial_x n_1} + \frac{\Delta n_2}{\partial_x n_2}\right). \tag{1}$$

A force difference ΔF acting on the UCN beam could be detected by the change in count rate in the differential measurement:

$$\Delta F = \frac{m_N}{t^2}\left(\frac{\Delta n_1}{\partial_x n_1} + \frac{\Delta n_2}{\partial_x n_2}\right), \tag{2}$$

with the mass of the neutron m_N, t the mean flight time of the UCN through the optical system and $\Delta n_i = n_{i+} - n_{i-}$ the difference in the neutron flux in the differential channel i between a change of force. The statistical uncertainty of such a measurement amounts to

$$\delta(\Delta F)_{\text{stat.}} = \frac{m_N}{2t^2\sqrt{\tau}}\left(\frac{\sqrt{2n_1}}{\partial_x n_1} + \frac{\sqrt{2n_2}}{\partial_x n_2}\right), \tag{3}$$

with τ the total measurement time, assuming that $n_{i+} \approx n_{i-} = n_i$.

3. Technical aspects

In the following, the technical aspects of our apparatus will be explained. Several new features compared to [14] are described in detail.

3.1. Overview

Fig. 2 shows a sketch of the final setup. The electrode system for electric field generation is not shown. The overall length of the optical system is $2f = 1.5$ m.

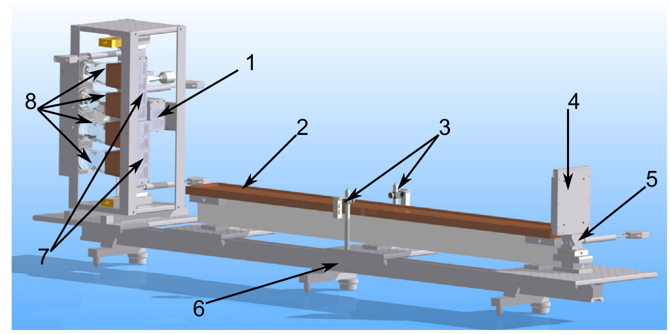

Fig. 2. Overview of the optical system. The optics is elongated in x- and y-direction compared to the former experiment.

The UCN enter the experiment via the input grating (1). All gratings are manufactured by laser cutting of a 200 μm thick Ni-foil and have a width of 45 mm. A horizontal UCN mirror consisting of liquid Fomblin (2) increases the solid angle of the UCN flux. The liquid follows gravity automatically, hence no alignment is needed. The cylindrical mirror (4) (NiV-93/7 coated glass, curvature $R = -1500$ mm, 100 mm in width, 150 mm in height) is mounted on a motorised goniometer (5) for alignment. It reflects the UCN and images the input grating onto the two stacked exit gratings (7, each 145 mm in height). Two linear laser levels (3) are used to align the gratings. The neutrons passing the exit gratings are detected by Li-doped glass scintillators (8) adapted to photomultiplier tubes. The optics is mounted onto a breadboard rail system (6), allowing basic alignment. The system is installed in a vacuum chamber.

3.2. Fomblin as liquid mirror

Fomblin is a trade name for a chemical class of perfluoropolyether oils. Those oils contain no hydrogen and are therefore well suited for the reflection of UCN. So far, Fomblin has been used for UCN storage experiments for a long time [15]. In this experiment, Fomblin is used as a specular UCN reflector for the first time.

This class of oils has a high resistibility against large electric fields [16], making it a good candidate for the charge experiment. We used "Fomblin Y-HVAC 140/13" in. by Solvay-Solaxis. The low vapor pressure of 6.7×10^{-13} mbar predestines it for vacuum applications [17]. The high viscosity of $\nu = 1508$ cSt reduces the appearance of macroscopic and capillary waves. The intrinsic roughness of ≈ 5 Å[1] indicates an excellent specularity for UCN reflection.

3.3. Geometry

Due to imperfections of the horizontal mirrors like waviness, roughness and misalignment, UCN performing too many reflections blur the image. Dependent on the slit width of the gratings, they only contribute to the background. For this reason, the upper horizontal mirror (see [8]) is omitted and the lower mirror is degraded by 15 cm against the input grating. The UCN have "more time" to fall, which decreases the number of mean horizontal reflections by a factor of ≈ 13. Fig. 3 shows the distribution of horizontal reflections in both setups.

Even though the flight path is longer, the horizontal reflections are sharply peaked around one reflection. The enhancement of the flight path from $L = 1041$ mm to L = 1500 mm increases the time of flight and thus the sensitivity by a factor of 2.25 (see Eq. (3)).

[1] The measurements were carried out at the Max-Planck-Institute for Polymer Research in Mainz (MPIP) with X-Ray diffraction methods (to be published).