Nuclear Instruments and Methods in Physics Research A 792 (2015) 38–46

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

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

Spectrometer for new gravitational experiment with UCN

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ARTICLE INFO

Article history:
Received 14 January 2015
Received in revised form
3 April 2015
Accepted 6 April 2015
Available online 23 April 2015

Keywords:
Ultra-cold neutrons
Gravity
Moving diffraction grating
Time-of-flight spectrometry

ABSTRACT

We describe an experimental installation for a new test of the weak equivalence principle for neutron. The device is a sensitive gravitational spectrometer for ultracold neutrons allowing to precisely compare the gain in kinetic energy of free falling neutrons to quanta of energy $\hbar\Omega$ transferred to the neutron via a non stationary device, i.e. a quantum modulator.

The results of first test experiments indicate a collection rate allowing measurements of the factor of equivalence γ with a statistical uncertainty in the order of 5×10^{-3} per day. A number of systematic effects were found, which partially can be easily corrected. For the elimination of others more detailed investigations and analysis are needed. Some possibilities to improve the device are also discussed.

1. Introduction

Apparently, neutrons are the most suitable objects to investigate the gravity interaction of elementary particles. Although gravitational experiments with neutrons have a more than half a century history [1], the existing experimental data are quite scanty, and their accuracy is many orders of magnitude inferior to the accuracy of gravitational experiments with macroscopic bodies and atomic interferometers [2–6].

Almost fifteen years after the first observation of the neutron fall in the Earth's gravitational field [1], the gravitational acceleration was measured in a classical experiment with an accuracy of about 0.5% [7]. However, the fact of gravitational acceleration of the neutron was already earlier considered as obvious and used for precise measurements of the coherent scattering length of neutrons by nuclei. In the Maier–Leibnitz–Koester gravitational refractometer [8,9], the initially horizontal neutron beam moved parabolically, fell from height h on a liquid mirror, reflected from it, and arrived at a detector. Varying the incidence height, one could determine the critical height h_0, at which the condition of the total neutron reflection was satisfied. In this case, $mgh_0 = V$, where

$$V = \frac{2\pi\hbar^2}{m}\rho b \tag{1}$$

is the effective or optical potential of the mirror, m is the neutron mass, g is the gravitational acceleration, ρ is the volume density of atoms, and b is the coherent scattering length.

Up to the mid-1970s, data on the coherent scattering lengths of neutrons on nuclei were obtained from the measurement of the neutron–atom scattering cross-section, i.e., by a method that is not connected with the gravitational interaction. This allowed Koester to compare the data on the scattering length obtained by two methods and thereby to verify the fundamental principle of the equivalence of the inertial and gravitational masses of the neutron [10]. He obtained the value $\gamma = 1.0016 \pm 0.00025$ for an equivalence factor that he defined as $\gamma = (m_i/m_g)(g_n/g_0)$, where m_i and m_g are the inertial and gravitational neutron masses, respectively, and g_n and g_0 are the gravitational acceleration of the neutron and the local gravitational acceleration of macroscopic bodies, respectively. More recently, Sears [11] made a number of important remarks concerning that study and repeated Koester's processing. For the equivalence factor γ, which is now defined as the ratio of the coherent scattering lengths measured by two methods, he presented a value of $1-\gamma = (3 \pm 3) \times 10^{-4}$. Much more recently, a similar analysis was performed by Schmiedmayer [12], who obtained the equivalence factor with an accuracy twice as good as that obtained in [10]. Note that the correction of the scattering of neutrons by atomic-shell electrons was introduced in [10,12], where data on the nuclear scattering lengths were extracted from experiments on the scattering of neutrons by atoms. This correction is in the order of 1%. At the same time, even modern data on the neutron–electron scattering length are somewhat contradictory [13,14] and it is unobvious that their accuracy is adequate to

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http://dx.doi.org/10.1016/j.nima.2015.04.009
0168-9002/

the stated accuracy of the studies mentioned above, particularly [12] whose author noted that he used averaging of statistically incompatible data on the n–e scattering length.

The first quantum neutron gravitational experiment was performed in 1975 by Colella et al. [15], who observed the gravitationally induced phase shift of the neutron wave function in an experiment with a neutron interferometer. Results of first experiments [15,16] basically corresponded to theoretical predictions. However, further investigations revealed certain discrepancies. In the latest work [17], the difference between the experimental and theoretical phase shifts was equal to 1% with an error smaller by an order of magnitude. The cause of this discrepancy, which remains unknown, was discussed in many theoretical studies (see, e.g., [18]). Results of a more recent experiment [19] whose accuracy was equal to 0.9% do not remove this problem. Very recently the experiment with a neutron spin-echo spectrometer was performed [20]. Authors reported that their experimental result for the gravitation induced phase shift agrees within approximately 0.1% with the theoretically expected result, while the overall measurement accuracy is 0.25%.

Another quantum gravitational experiment with neutrons was performed recently [21,22], while the possibility of this experiment was predicted earlier in [23]. Nesvizhevsky et al. [21,22] reported the observation of the quantization of the vertical-motion energy of ultracold neutrons (UCNs) stored on a horizontal mirror. It is possible to hope that detailed investigation of this effect or a similar phenomenon accompanying the storage of UCNs over the magnetic mirror [24] will be very useful for studying the gravitational interaction of the neutron as a quantum particle.

Very promising results were recently obtained by Jenke et al. [25]. They observed transitions between quantum states of UCN being stored on a plane mirror. An original approach to the testing the equivalence principle for neutrons was proposed recently in [26]. The idea was based on the huge sensitivity of the neutron-diffraction method to the force acting on a neutron.

In the experiment [27] the change in the energy of a neutron falling to a known height in the Earth's gravitational field was compensated by a quantum of energy $\hbar\Omega$ that was transferred to the neutron via a non-stationary interaction with moving diffraction grating. The aim of the experiment was the determination of the value $\gamma=(mg)/(mg)_{\exp}$ where m is the neutron mass recommended by PDG [27], g is the local free fall acceleration and $(mg)_{exp}$ the gravity force acting on a neutron found in the experiment. In the experiment the value of the equivalence factor was found to be $1-\gamma=(1.8\pm2.1)\times10^{-3}$.

In the present paper we describe the experimental set up for a new experimental test of the equivalence principle for neutrons. Results of the test experiment and some future prospects of improvements of the device are also discussed.

2. Moving diffraction grating as a nonstationary device for the neutron energy transformation

As in [28] in the new experiment the change in energy mgH of a neutron falling from a known height in the Earth's gravitational field is compared to a known quantum of energy$\hbar\Omega$, which is transferred to the neutron by a non-stationary device. As latter a moving diffraction grating playing the role of a quantum phase modulator is used. The phenomenon of energy quantization via diffraction of the neutron by a moving grating was first predicted in [29] and experimentally observed in [30–32].

We present here briefly the theoretical description of the corresponding quantum mechanical problem. In the laboratory system of reference a plane neutron wave $\Psi_{in}(x,z,t)=A_0\exp(ik_0z-i\omega_0t)$ is assumed to propagate along the z-axis towards a periodic grating,

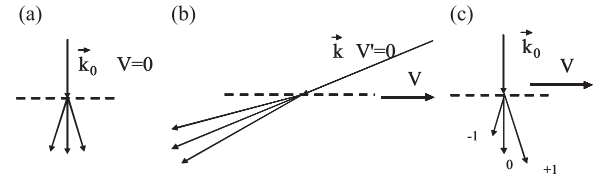

Fig. 1. Diffraction by a grating. (a)—Grating at rest, $\omega_j=\omega_0$; (b)—reference frame is moving together with grating, $\omega_j=\omega'$; (c)—moving grating in laboratory frame of reference, $\omega_j=\omega_0+j\Omega$.

which is assumed to be normal to the neutrons propagation axis (Fig. 1a). We denote with $k_0=mv_0/\hbar$ the neutron wave number, where m is the neutron mass, $\hbar$ the Planck constant and $\omega_0=\hbar k_0^2/2\,m$. The grating is moving with constant speed V along positive direction of the X axis (Fig. 1b) and grating grooves are oriented along Y axis. Following Ref. [29] we shall solve the problem in the moving frame of reference (x',z) where the grating is at rest. In this system, the angle of incidence on grating is oblique:

$$\Psi'_{in}(x',z,t)=A_{in}(x')\exp\left[i(k_0z-\omega't)\right] \tag{2}$$

with $A_{in}(x')=A_0\exp(-ik_Vx')$, $k_V=mV/\hbar$, $\omega'=\omega_0+\omega_V$, $\omega_V=\hbar k_V^2/2m$. After passage of the grating in the region $z>0$ we have

$$\Psi'_{in}(x',z,t)=A_0\int_{-\infty}^{\infty}F(q)\exp(iqx'+ik_zz-i\omega't)dq \tag{3}$$

where $k_z=(k_0^2+k_V^2-q^2)^{1/2}$. $F(q)$ is the Fourier transform of the product $F(x)=A_{in}(x)f(x)$ and $f(x)$ is the grating transmission function. For a periodical function $f(x)=\Sigma_j\,a_j\,\exp(iq_jx)$ where j are integer numbers, $q_j=2\pi j/L$, and L is the space period of the grating, we obtain for the Fourier transform$F(q)=A_0\sum_j\delta\left(q-q_j+k_V\right)$, and the Fourier coefficients are

$$a_j=\frac{1}{L}\int_0^L f(x)\exp\left(iq_jx\right)dx,\quad j=0,\pm1,\pm2, \tag{4}$$

Passing back to the laboratory frame of reference $x=x'+Vt$ we obtain a superposition of plane waves with amplitudes b_j, discrete frequencies ω_j and wave vectors $\mathbf{k}_j=(q_j,k_{zj})$ (see Fig. 1c):

$$\Psi(x,z,t)=\sum_j b_j\exp\left(iq_jx+ik_{zj}z-i\omega_jt\right), \tag{5}$$

where $b_j=a_j\left[(k_0)^{1/2}/\left(k_0^2+2k_Vq_j\right)^{1/4}\right]$, $k_{zj}=(k_0^2+2k_Vq_j-q_j^2)^{1/2}$, $\omega_j=\omega_0+j\Omega$, $\Omega=2\pi/T$, $T=L/V$.

Let us consider a grating with a rectangular groove profile with width $L/2$ and depth d, such that the phase difference $\Delta\varphi=k_0(1-n)d=\pi$, where n is the refraction index for neutrons. In the case of normal fall the amplitudes a_j are

$$a_j=\begin{cases}0 & \text{at } j=2s-1\\ i(2/\pi j) & \text{at } j=2s-1\end{cases} \tag{6}$$

It is obvious that the amplitudes for the even diffraction orders, including the zero, vanish and that the major part of the flux concentrates in ±1 orders.

Obviously, for larger values of the spectral splitting $\Omega=2\pi V/L$ it is necessary to increase the grating speed V and (or) decrease the space period L. But due to the oblique incidence in the moving reference frame the phase profile varies with increasing velocity and takes the form of trapezium [33] (see Fig. 2).

From (4) it follows that amplitudes a_j are now

$$a_j=\begin{cases}cB_j & \text{at } j=2s\\ -B/j & \text{at } j=2s-1\end{cases} \tag{7}$$