New UCN Experiment for Test of the Equivalence Principle for Free Neutrons

A.I. Frank[1], P. Geltenbort[2], M. Jentschel[2], S.V. Goryunov[1], G.V. Kulin[1], D.V. Kustov[1,3], A.N. Strepetov[4]

[1] *Joint Institute for Nuclear Research, Dubna, Russia*
[2] *Institut Lauer-Langevin, Grenoble, France*
[3] *Institute for Nuclear Research, Kiev, Ukraine*
[4] *Institute of General and Nuclear Physics, RCC «Kurchatov Institute», Moscow, Russia*

Abstract

We report here the status of the new neutron experiment for the test of the equivalence principle. The main idea of it is to compensate the change in the energy of the ultracold neutrons falling in the Earth's gravitational field (mgH) by the quantum of energy ($\hbar\Omega$) transferred to the neutron by nonstationary interaction with a moving phase grating. The controlled variation of the neutron energy was measured by a peculiar time-of-flight method. For this experiment a new spectrometer with neutron interference filters (NIF) has been built and tested.

1. Introduction

The equivalence of the gravitational and inertial masses is one of the most fundamental physical principles. The present-day approach of testing it is based on the employing different test bodies whose important properties, such as the binding energy per unit mass, atomic mass, and ratio of the number of neutrons to the number of protons, differ as much as possible. From this point of view, investigation of the gravitational interaction of a free neutron is of particular interest. Although gravitational experiments with neutrons have a more than half a century history, 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.

Almost fifteen years after the first observation of the neutron falling in the Earth's gravitational field [1], the gravitational acceleration was measured in a classical experiment with an accuracy of about 0.5% [2]. However, the fact of the acceleration of the neutron in the gravitational field, which was considered as obvious, was even earlier used by Maier-Leibnitz and Koester [3] for precise measurements of the neutron coherent scattering of nuclei. Later on, there appeared data on coherent scattering lengths for neutron–nucleus interaction that were obtained by measuring cross sections for neutron scattering on atoms. This made it possible to compare scattering length data obtained by two methods and to test thereby the equivalence principle for the neutron [4] to a precision of about 3×10^{-4}. Much later, Schmiedmayer [5] performed a similar analysis and obtained the equivalence factor with an accuracy 1×10^{-4}.

The first quantum gravitational experiment with neutrons was performed in 1975 by Colella, Overhauser, and Werner [6] with a neutron interferometer. They observed the gravitation induced shift of the phase of the neutron wave function. However, further investigations revealed certain discrepancies. In the latest work [7], the difference between the experimental and theoretical phase shifts was equal to 1% with an error smaller by an order of magnitude. The results of a more recent experiment [8] whose accuracy was equal to 0.9% do not remove this problem.

Nesvizhevsky et al. [9] 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 [10] will be very useful for studying the gravitational interaction of the neutron as a quantum particle. Very promising results were obtained recently by Jenke et al. [11], who observed transitions between quantum state of neutron in the Earth gravity field.

In 2006 we performed free fall experiment with UCN for the test of the equivalence principle by new methods. In some sense this experiment placed intermediate position between classical and quantum experiment. The energy change in neutron energy due to free falling in the Earth's gravitational field was measured as in classical experiment. But the experimental approach for this measurement was based on quantum methods. The change in energy due to gravity (mgH) was compensated by the quantum of energy transferred to the neutron ($\hbar\Omega$) in the nonstationary interaction with a moving phase grating. And for the UCN spectroscopy neutron Fabry-Perrot interferometers were used. For the equivalence factor γ it was obtained $1-\gamma=(1.8\pm2.1)\times10^{-3}$. It was recognized later that systematical errors of such experiment may be decreased at least by the order of magnitude by some modification of experimental approach [13]. For realization of this idea a new gravitational UCN spectrometer with Fabry-Perrot interferometers (neutron interference filters) has been built. Here we shall give a short description of this device and present first results of its experimental test.

2. Spectrometer and procedure of the new gravity experiment

New experimental installation is shown in figure 1. As in the previous experiment [12], the Fabry-Perrot Interferometers (FPI) are used as a spectrometric device and the controlled

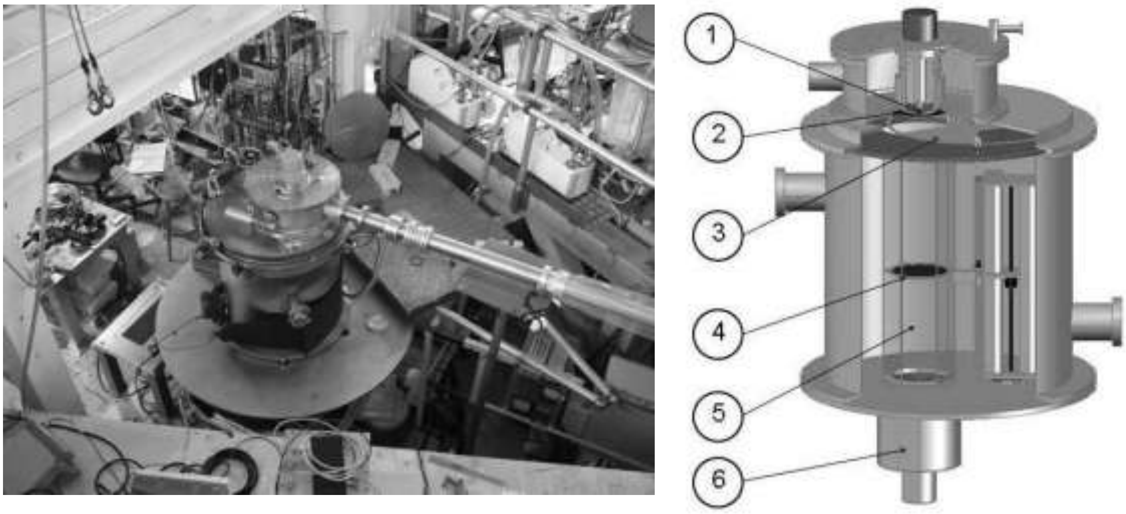

Fig.1. Experimental installation. At the left: Spectrometer at the PF2 beam position at ILL (Grenoble, France). At the right: device structure. 1 - Fabry-Perrot monochromator, 2 – diffraction grating, 3 - rotor of the chopper, 4- movable Fabry-Perrot interferometer-analyzer, 5 – vertical glass neutron guide, 6 – detector

variation of the neutron energy realizing by diffraction by a moving grating. But the energy of the neutron is measured now by a peculiar time-of-flight method. For this purpose the neutron flux is modulated by a chopper and the detector measures the corresponding oscillation of the count rate. The phase of the count rate oscillation

$$\Phi = 2\pi f\tau \quad (1)$$

is defined by the frequency of the chopping f and the time of flight τ. The main benefit of this approach is that the modulation phase does not depend on UCN beam intensity and therefore does not sensitive to fluctuations of the background or the detector efficiency.

The experimental procedure may be divided into two independent parts. The first step is the calibration part. At this stage FPI is placed in a movable carriage (see pos.4 in fig.1) and dependence of the count rate oscillation phase $\Phi_{an}(H)$ is measured as a function of the analyzer position H.

At the second step – the main part of the experiment, FPI-monochromator is placed in the upper part of spectrometer as shown in fig 2. Before entering the vertical neutron guide (5 in fig. 1) UCN passed through the rotating phase grating. It provides high-frequency neutron wave modulation resulting in the appearance of sidebands in neutron spectrum [14]. To transmit to the detector only neutrons with diffraction order -1, shifted in energy by $h\Omega$, the 9-layers analyzer filter [15] with relatively wide transmission band is placed in the movable carriage. Here $\Omega = 2\pi f N$, f is the frequency of grating rotation and $N = 75\,398$ is the number of grooves.

During this phase of the experiment the dependence of the count rate oscillation phase $\Phi_{mon}(\Omega)$ is measured as the function of the position H of the wide analyzer. For a number of measurements with different frequencies Ω_i it is possible to determine those H_i, which satisfy the equation $\Phi_{mon}(\Omega_i) = \Phi_{an}(H_i)$, and finally obtain a set of equations

$$\Delta H_i = h\Omega_i / mg_n \quad (2),$$

where mg_n is the gravity force acting on the neutron.

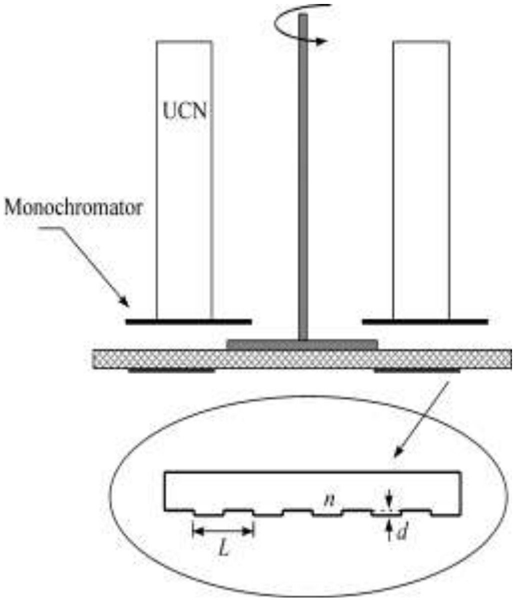

Fig.2. Upper part of the spectrometer. The ring corridor providing UCN to the spectrometer, FPI- monochromator and grating are shown

3. Test experiments

The experiment was performed at the UCN source at ILL (Grenoble, France). The spectrometric quality of the device was tested by classical time-of-flight method. For this purpose a disc with two slits shown in a figure 3 was used for short chopping of the UCN beam. At rotation frequency 1200 rpm the duration of neutron pulse was about 2.8 ms (FWHM). The time of flight spectrum was measured with standard FPI-monochromator.

Fig. 3. The disc of the chopper for classical time-of-flight method

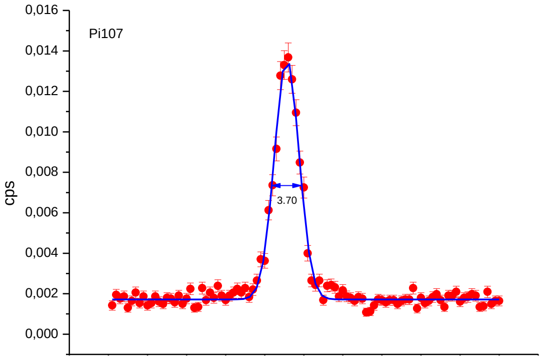

Fig. 4. Time of flight spectrum of neutrons, passed through FPI-monochromator plotted at the one period of chopper rotating. Full time of flight was about 140 ms

For the testing of both phases of the gravity experiment, the disc of the chopper shown above was replaced by rotor-modulator, shown in figure 5. The chopper disc might be rotated with a frequency up to 1800 rpm providing the UCN flux modulation as fast as 90Hz. Stability of the modulation frequency was of the order of 10^{-4}. Due to high degree of monochromatization the count rate of the detector oscillates with enough large amplitude even in the case when neutron time of flight many times large of modulation period. It is demonstrated in fig. 6.

Fig.5. Chopper-modulator

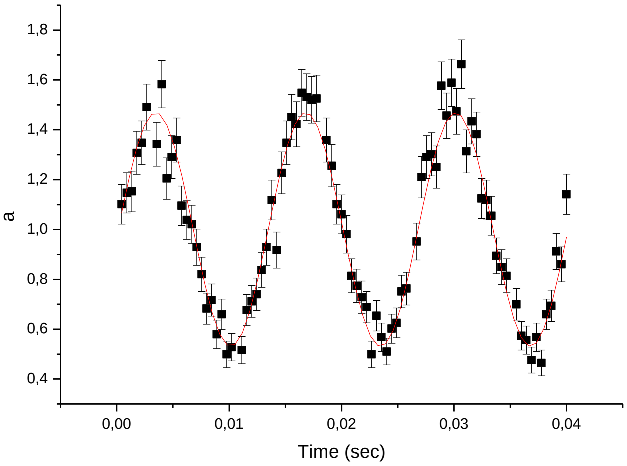

Fig.6. Oscillation of the count rate. Modulation frequency 75Hz, neutron time of flight 150 ms

The absolute value of the time of flight may be defined for any position of the monochromator by measuring the count rate oscillation phase dependence at different modulation frequencies. An example of such measurement is displayed in fig.7.

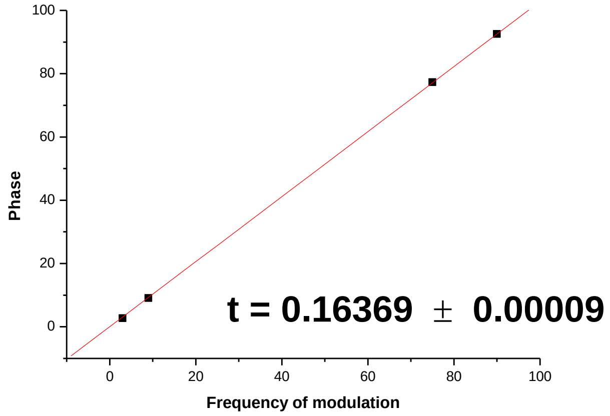

Fig.7. Dependence of the count rate oscillation phase on the modulation frequency. The absolute value of time of flight may be easily extracted from linear fit.

The phase of the count rate oscillation also was measured depending on the position of the monochromator in height as it must be done in the first stage of the gravity experiment. Results of the measurement are shown in figure 8. Notice that error bars there are less than the size of points. They were typically 0.03-0.05 radian while total phase was more than 70 radian.

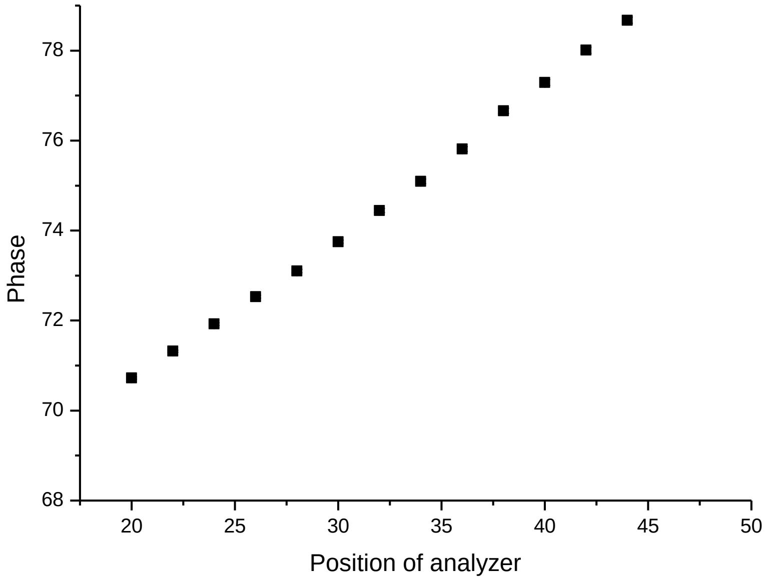

Fig.8. Phase of the count rate oscillation in the dependence of the vertical position of monochromator.

In figure 9 results of the experiment which was performed in conditions of the second phase of the experiment are displayed together with results of the first stage. Now the energy of the quasi-monochromatic neutrons was shifted due to the diffraction by a grating rotated with frequency 6300 rpm. The phase of the count rate oscillation was measured in the dependence of the vertical position of analyzer with wide transmission band.

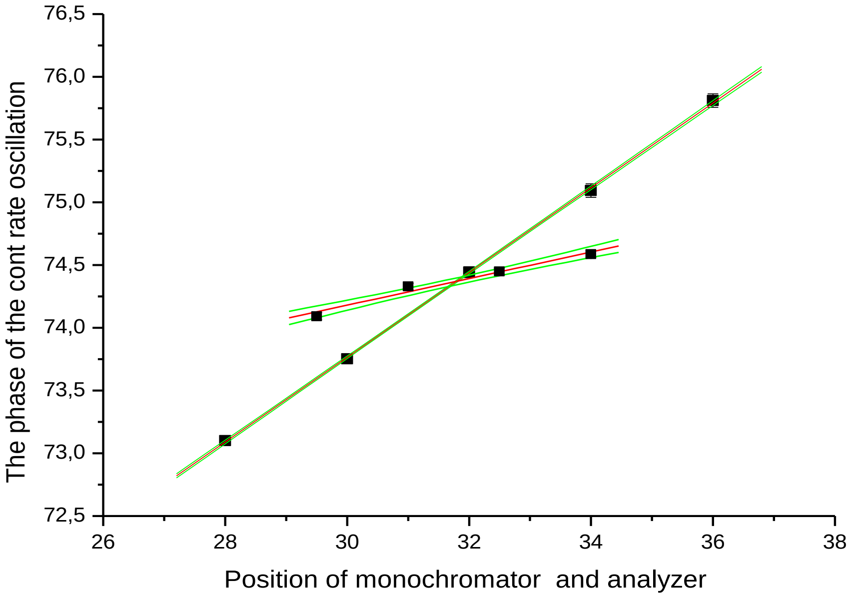

Fig. 9. Phases of the count rate oscillation measured in two steps of experiment. The point of the crossing of fitting lines is the aim the measurement. Such measurement must be repeated with different grating rotation frequencies.

4. Summary

New UCN spectrometer for the experimental test of the equivalence principle was built and successfully tested. Test experiments were performed in both modes which will be used in main gravity experiment. With the present installation the intensity of the PF2 UCN sources for 55 days the accuracy on the level $2x10^{-3}$ is possible. Some modification of the device is needed to reach the better accuracy.

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