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

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Abstract

We report here the status of a 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 (ħΩ) 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.

The collection rate of statistical accuracy was as high as 5×10^{-3} per day instead of 1.5×10^{-2} per day in previous cycle of 2011. At the same time some systematic effects were found.

1. Introduction

The equivalence of gravitational and inertial masses is one of the most fundamental physical principles. Gravitational experiments with neutrons have more than a half century history, but existing experimental data are quite scanty. Accuracy of gravitational experiments with neutrons is many orders of magnitude less than with macroscopic bodies and atomic interferometers.

Best experimental result for neutrons was attained by Maier-Leibnitz and Koester who reached the precision for equivalence principle validity [1] of about 3×10^{-4}. Much later, it was reestimated by Schmiedmayer [2] and he obtained the accuracy for the equivalence factor equal to 1×10^{-4}.

The first gravitational experiment with a neutron interferometer was performed in 1975 by Colella, Overhauser, and Werner [3], where the gravitationally induced phase shift of the neutron wave function was observed. In the latest work [4], the discrepancy equal to 1% was demonstrated, while the error was smaller by an order of magnitude. Results of a more recent experiment [5] with accuracy equal to 0.9% do not remove this problem.

Nesvizhevsky et al. [6] reported the observation of the quantization of the vertical-motion energy of ultracold neutrons (UCNs) stored on a horizontal mirror. In the work of Jenke et al. [7] transitions between quantum states of neutron in the Earth's gravitational field were observed. One may hope that experiments of this type can be very useful for studying the gravitational interaction of the neutron as a quantum particle.

In 2006 [8] we performed free fall experiment with UCN for the test of the equivalence principle by new methods. In some sense this experiment occupies an intermediate position between classical and quantum experiments. The change in energy due to the gravity (mgH) was compensated by the quantum of energy transferred to the neutron (ħΩ) by the nonstationary interaction with a moving phase grating. 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 [9]. For this aim a new gravitational TOF spectrometer with neutron interference filters has been built and in 2010 for the first time the spectrometric propertied of a new installation was tested [10].

In 2011 the first full scale test of a new experiment on the test of the equivalence principle for free neutron was successfully performed [11]. The test experiment was performed in the modes that will be used in main gravity experiment. The main problem, that was found in the beam-time of 2011 year, was very law accuracy collection rate, only 1.5×10^{-2} per day.

2. The spectrometer and the procedure of the new gravity experiment

The experimental installation is shown in figure 1. As in experiment of 2006 year, the Fabry-Perrot Interferometers (FPI) were used as a spectrometric devices and the controlled variation of the neutron energy was realized by a moving diffraction grating. But the energy of the neutron was measured by a peculiar time-of-flight method. For this purpose the neutron flux was modulated by the chopper and the detector measured the corresponding oscillation of the count rate. The phase of the count rate oscillation

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

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 stages. The first stage is the calibration part. At this stage FPI was placed in a movable carriage (see pos.4 in fig.1) and dependence of the count rate oscillation phase $\Phi_{an}(H)$ was measured as a function of the analyzer position H.

At the second stage – the main part of the experiment, FPI-monochromator was placed in the upper part of the spectrometer as shown in fig 2. Before entering the vertical neutron guide (p. 5 in fig. 1) UCN passes through the rotating phase grating. It provides high-frequency neutron wave modulation resulting to the appearance of sidebands in neutron energy spectrum. In order to transmit to the detector only neutrons with -1 diffraction order, is was shifted in energy by $-\hbar\Omega$, the 9-layers analyzer filter with relatively wide transmission band was placed in the movable carriage. Here $\Omega=2\pi fN$, where 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 $\Phi_{mon}(\Omega)$ was measured as a function of the position H of the 9-layers analyzer with wide spectrum of transmission. For a number of measurements with different frequencies Ω_i it was 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

$$\Delta H_i=\hbar\Omega/mg_n\ , \qquad (2)$$

where mg_n is the gravity force acting on the neutron.

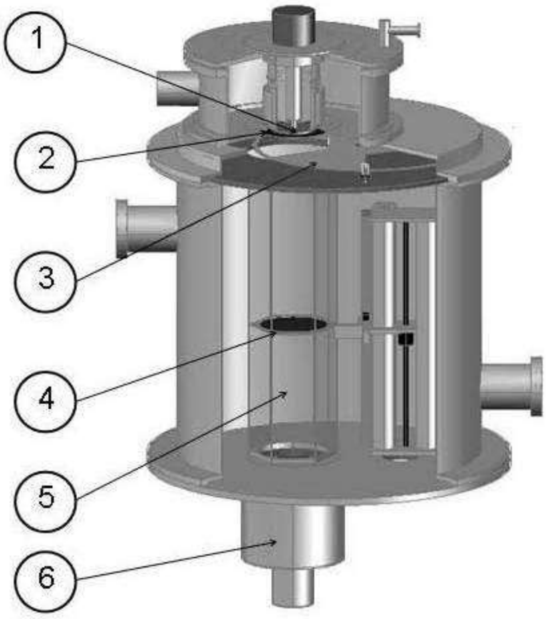

Fig.1. Experimental installation.
1 - Fabry-Perrot monochromator, 2 – diffraction grating, 3 - rotor of the chopper, 4- movable Fabry-Perrot interferometer-analyzer, 5 – vertical glass neutron guide, 6 – detector

3. Beam time of 2012

The beam time of 2012 year was used for investigation of the main sources of intensity losses, background nature, optimization of the effect to background ratio and test of two stages of gravity experiment. For this purposes several modifications of the spectrometer were done.

The diameter of the feeding neutron guide at the entrance to the spectrometer was increased from 70 to 80 mm, that doubled the count rate. Unfortunately, the initial count rate at PF2 UCN beam in 2012 was less than in 2011 by a factor of 1.5.

To decrease the total thickness of material on the way of UCN new multilayer structures including FPI-monochromator, 9-layer wide analyzer and superwindow were manufactured in the Institute for Physics of Microstructures RAS (Nizhny Novgorod, Russia) on the Si wafers 0.3mm thick instead of old multilayer filters that were made on 0,6 mm wafers. This allowed us to decrease the thickness of material by a factor 2 in geometry of the calibration and by a factor 1.6 in geometry of main measurements that led to the gain in the count rate approximately by a factor of 2-2.5.

Some steps were taken to suppress the background related to transmission UCN and VCN through region of carriage in bypass of the analyzer.

All efforts mentioned above allowed us to get the statistical conditions of measurements much better then in the previous cycle, see figures 2-4.

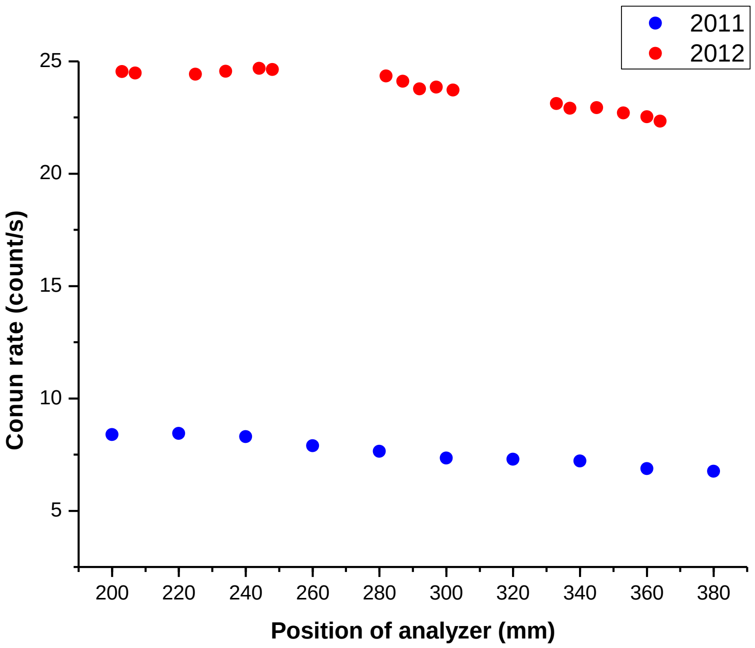

Fig. 2. Count rate in the geometry of calibration in 2011 (dark point) and 2012 (light dark points) with rotating chopper-modulator.

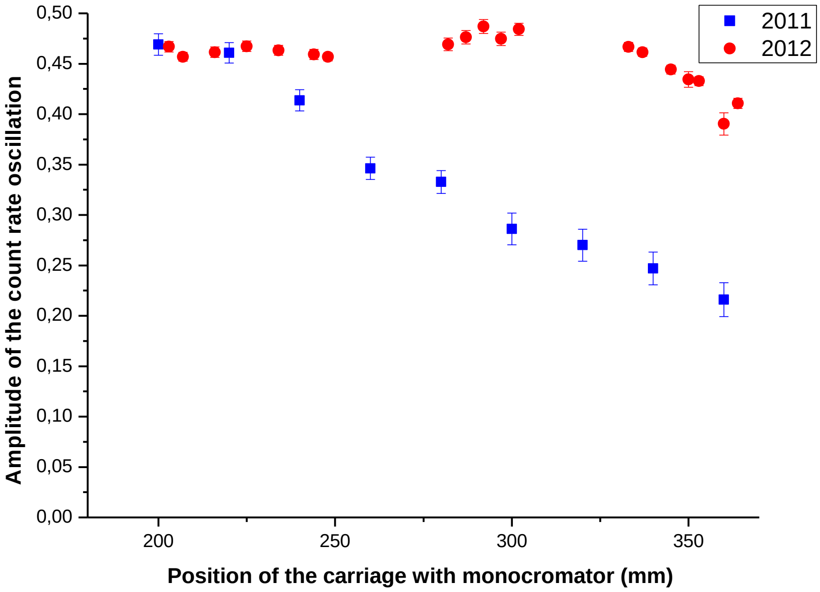

Fig. 3. Amplitude of the count rate oscillation depending on the position of the analyzer. Geometry of calibration. Square and round points correspond to 2011 and 2012 respectively.

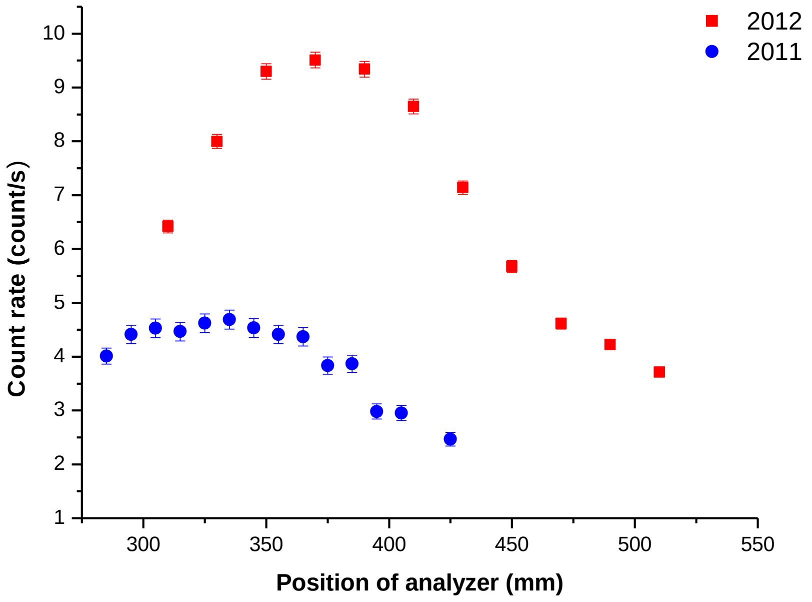

Fig. 4. Scanning curve of -1 diffraction order with the grating spinning at 6300 rpm. Round points – filters used in 2011. Square points new filters used in 2012. Modulator was fixed in the open position.

Both stages of the experiment in new conditions were tested. The frequency of modulation was 84 Hz. The main stage of the experiment was performed at the same modulation frequency and with the grating rotating at 3600, 3900, 6000 and 6300 rpm.

New monochromator was characterized by a narrower transmission spectrum what permitted us to increase the operation frequency of the chopper-modulator without decreasing the modulation amplitude. The width of 9-layer analyzer transmission band was increased to 12 neV that either increased the count rate in the main stage of experiment or, what is more important, increased an angle between two crossing lines of phases, obtained in two stages of the experiment. That increased the sensitivity of measurements. Results of measurements in conditions of the second phase of the experiment for different grating frequencies are displayed on the figures 5 together with results of first (calibration) stage. The point of the crossing of fitting lines is the aim of measurements.

Results of 2012 beam time shown, that the collection rate of statistical accuracy is 5×10^{-3} per day.

At the same time a problem was found. As that clearly seen in fig. 5 some groups of phase measurements with their fitting lines do not cross the calibration curve. That happened because the position of crossing point did not correspond to theoretically estimated values.

The nature of the systematic effect is an admixture of zero order to the spectrum of minus first order. There are at least two reasons for the appearance of UCNs of zero's diffraction order. First one is trivial and it consists in the possibility for UCN to bypass the grating on they way from the monochromator to vertical glass neutron guide. The second source of the zero order appearance is more fundamental. It is known that phase π–grating is characterized only by odd diffraction orders and zero order must be absent. But in the moving frame of the grating with rectangular shape the profile is no longer π –grating and zero order may appear.

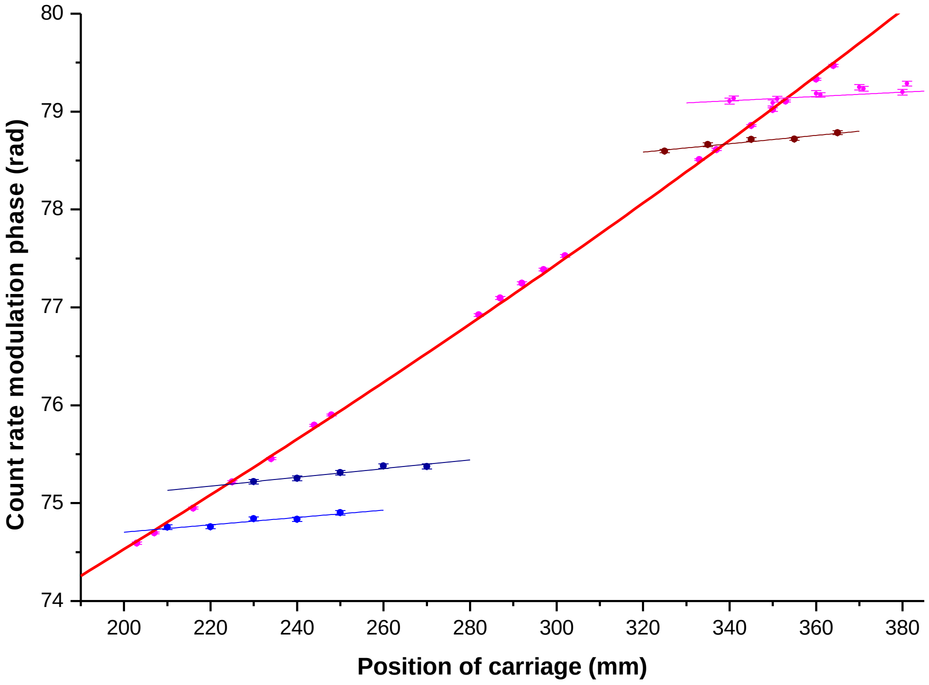

Fig. 5. Phases of the count rate oscillation measured in two stages of the experiment. Modulation frequency is 84Hz. Frequencies of the grating rotation are 3600, 3900, 6000, 6300 rpm

Summary

The main result is that very large improvement in sensitivity was achieved. The collection rate of statistical accuracy, was as high as 5×10^{-3} per day instead of 1.5×10^{-2} per day in 2011. The gain in statistic collection time is about 9. This rate is enough to collect statistical accuracy of the order of $5\text{x}10^{-4}$ for 80 days (two cycle) of statistic collection.

At the same time the serious source of systematic error in our experiment was found. At this moment theoretical and experimental investigations of that problem is required. We plan to do in the nearest future.

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