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ON EXPERIMENTAL VERIFICATION OF VALIDITY OF THE WEAK EQUIVALENCE PRINCIPLE FOR THE NEUTRON

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1 Introduction

Experimental verification of the weak principle of equivalence for atoms and elementary particles has become the issue for discussion long ago, particularly in connection with elucidation of the gravitational properties of antiparticles [1]. The weak equivalence principle states,that in a given gravitational field all bodies with equal velocities move with equal accelerations [2]. The most natural way for carrying out experimental verification of this principle is to perform the experiment of Galilei-type with atoms and elementary particles,e.g.to measure their free fall acceleration and then compare it with those of massive bodies for the same site on the Earth surface.

Difficult and very interesting from the experimental viewpoint attempts [3] to perform such experiments with electrons (as preliminary for those with positrons)[4] failed to give any definite result due to accessory effects in the electrostatic shielding, which themselves are of considerable interest(see the recent review[5]). In the last years experiments with antiprotons[6] have been in plans and those with antihydrogen atoms under discussion[7].

2 Experiments with neutrons

The only elementary particle which free fall acceleration was measured up to now is the neutron. The most precise experiment of the Galilei-type where the fall of neutrons travelling primarily horizontally with a known velocity along a given path was measured – is rather an old experiment[8]. The precision of the experiment is $3 \cdot 10^{-3}$. The equivalence principle for neutrons was also verified by the method of Koester[9].The best result of the processing of the data from this experiments has the precision $2.5 \cdot 10^{-4}$[10]. This method is based on comparison of the neutron scattering lengths obtained in two types of experiments: with and without account for gravitation. In the latter case the most reliable data are usually provided by precise measurement of the total neutron cross-sections in the electronvolt region and by the neutron-interferometric measurements with ideal crystals. This experimental data must be corrected for the scattering momentum dependence of the electromagnetic components of the total scattering amplitude: the amplitude of polarization scattering, neutron-electron scattering, Schwinger scattering and to take into account the influence of the resonance scattering. The latest and most exhaustive summary of the neutron scattering lengths and the corresponding references are given in [11].

In Koester's measurements of neutron scattering lengths the gravitation refractometer is used.In it the horizontal beam of neutrons under the action of Earth gravitation falls onto the surface of a liquid mirror and being reflected comes into a detector. The critical height of the total reflection depends on the optical potential of the mirror,which is the characteristic of the interaction of a neutron with a liquid. The value of the potential is defined by the mean potential energy of the neutron in the medium:

$$V_0 = 2\pi\hbar^2 N b m_i^{-1} + \vec{\mu}\vec{B}, \tag{1}$$

where N is the number of nuclei in a unit volume of a mirror, b is the coherent scattering length on a bound nucleus of the liquid;m_i is the inertial mass of the neutron,μ is magnetic moment of the neutron,B-the value of magnetic induction in the medium. It is evident that the critical height of the total reflection equals:

$$h = V_0/m_g a, \tag{2}$$

where m_g is the gravitational mass of the neutron,a is the neutron free fall acceleration. What is actually measured is the height profile of the reflection coefficient and it is compared with the calculated one after the corrections are made for the capture and diffuse scattering of neutrons in a liquid, modification of the optical potential due to local field effects, inertial forces and angular divergence of the initial beam, etc. If one neglects the difference between the gravitational and inertial masses entering equations (1) and (2), it is possible to determine the neutron scattering length on the nuclei in a liquid.

For detailed consideration of the basis of this method see [12]. There it is shown that in fact the ratio of the scattering lengths, determined by the gravitational and nongravitational methods is equal to:

$$\gamma = b_g/b = [\frac{m_g\left({}^{12}C\right)}{m_i\left({}^{12}C\right)}]^2\frac{A}{a}, \tag{3}$$

where A is the free fall acceleration of a macroscopic body, $m_g\left({}^{12}C\right)$ and $m_i\left({}^{12}C\right)$ are the gravitational and inertial masses of carbon atoms,which are used as standard in the measurement of atomic and nuclear masses.

Strictly speakinq if it is established that $\gamma = 1$, then A=a under condition of equality of the gravitational and inertial masses of the atoms, i.e., if the equivalence principle holds for the atoms.

Second, the quantum formula (1) is a consequence of the averaging of the Fermi quasipotential:

$$V = 2\pi\hbar^2\frac{b_\nu}{(m_i)_\nu}\delta(\vec{r} - \vec{r}_\nu), \tag{4}$$

which is choosen to have it matched to a correct value of the scattering amplitude in the first order Born approximation. The second order of the perturbation theory for this potential gives a divergence. The formula (1) has never been tested out experimentally with the precision claimed in the papers [9] and [10] to be the precision of verification of the

equivalence principle for neutrons. The Galilei-type experiments [8] are straightforward, free of the use of quantum consequences and have better defence against the above cited arguments.

The verification precision of the equivalence principle for macroscopic bodies achieved the level $\delta g/g < 10^{-12}$ [13] in the experiments using astronomical distances between the gravitating mass and the test body, and a level of $\sim 10^{-13}$ [14] and $2 \cdot 10^{-14}$ [15] in the laboratory experiments with the distance between the gravitating mass and the test body egual to several centimeters. One can hardly hope that the precision of the verification of the equivalence principle for microscopic particles can ever achieve the like level. However, experiments with macroscopic and microscopic objects are supplementary in a sense [12], because the mass ratio of test bodies in both types of experiments is $\sim 10^{27}$. Therefore, the possibility of increasing the precision of direct experiments of the Galilei type by a factor of several orders of magnitude can be of interest.

3 Proposed method

In a Galilei-type experiment one measures the time, t, it takes a test body to fall in the Earth gravitational field through the difference of heights h:

$$h = v_v t + at^2/2. \qquad (5)$$

Here v_v is the vertical component of the velocity of a test body (a neutron) at a moment t=0. Should one attempt to improve the precision of determination of acceleration a to several orders of magnitude as compared with the result of the experiment [8], the precision of all other quantities in (5) must be of the same order. For example, in the experiment [8] the neutron horizontal flight distance was 180m. When travelling it the neutron with the velocity $\sim 10^5 cm \cdot s^{-1}$ fell down to 20 cm; and if one wants to have the precision in $a \sim 10^{-5}$ the height difference of the splits of the detector and the source (collimator) has to be measured to a precision of 1μ, the angular collimation of the initial beam must be within $10^{-7} - 10^{-8}$.

Here the scheme of an experiment is proposed, which permits one to increase the precision of verification of the equivalence principle up to several orders of magnitude as compared to the level achieved in the experiments [8]–[10]. The idea consists in precise measurement of the time of flight of neutrons with a preliminary formed resonant spectrum of velocities in the Earth gravitational field. This spectrum is proposed to be formed with the help of an interferential filter (the Fabri–Perot interferometer), and the time-of-flight spectrometry accomplished using a thin film ferromagnetic shutter.

The schematical layout of the experiment is shown in fig.1. Ultracold neutrons

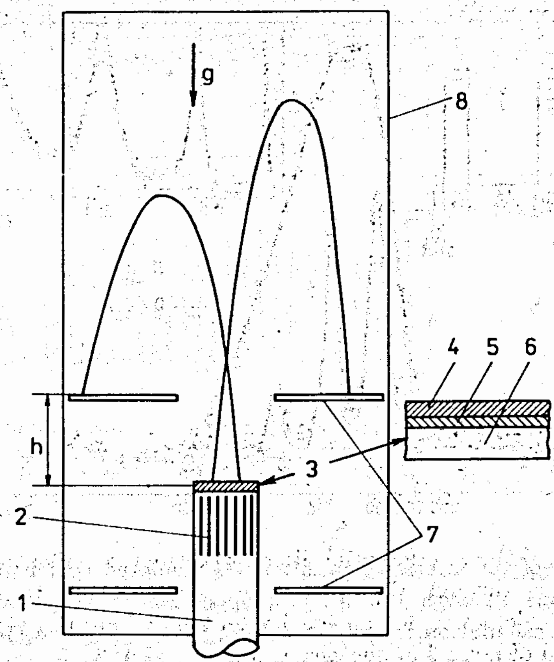

Fig.1 The scheme of the proposed experiment on the measurement of the free fall acceleration of a neutron: 1.neutronguide, 2.collimator, 3.thin film system for the formation and modulation of the neutron flux, 4.thin film interferential filter, 5.thin film ferromagnetic shutter, 6.polished silicon plate, 7.neutron detector, 8.vacuum volume

from the neutronguide 1 through the collimator 2 come to the assembly 3, consisting of a thin film interferential filter 4 and a thin film ferromagnetic chopper 5, both evaporated on the surface of a polished silicon plate 6.The neutrons outgoing vertically upwards fall down in the gravitational field onto the surface of a horizontally positioned detector of neutrons 7, having the form of a disc with a hole in the center. The detector may be shifted vertically. The whole of the installation is placed inside a cylindrical vacuum vessel (it is suffice to maintain the vacuum better than 1 Torr).

The interferential filter is a plane three-layer thin film system, in which the layers have different refraction indices for neutrons. In this system between two potential barriers a gap is located with a lower potential for neutrons. The interferometer exploits the resonant phenomena, arising on transmission of waves through two or more low transparent, weakly absorbing layers(potential barriers),

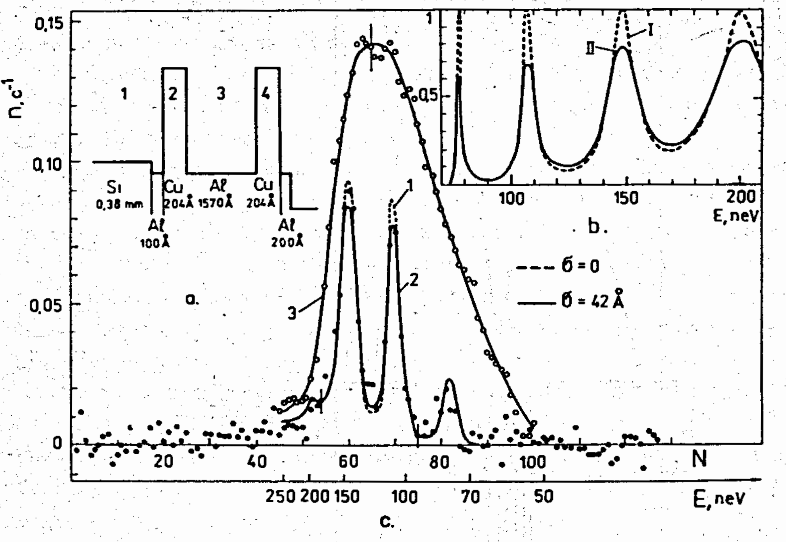

Fig.2 a.Scheme of the interferential filter, b.Calculated coefficient of the transmission of neutrons through the filter, c.Spectrum of the transmitted neutrons:1.theoretical calculation for an ideal filter,2.matching the Gaussian distribution in the depth of layer 3 at the dispersion $\sigma = 42\AA$, 3.spectrum of neutrons transmitted through the plate

allowing for formation of standing waves. Under resonance the transparency of this layered system increases drastically. For neutrons the role of potential barriers and gaps between them can play thin films of substances with different values of scattering lengths,determining according to equation (1) the values of potential for neutrons. Apparently the possibility of application of multilayered thin film structures (to increase the neutron reflection coefficient) was first mentioned in the publication of V.F.Turchin [16](see also [17]). In [18] a thin film layered system was used for the first time in experiment (in reflection geometry at thermal neutrons glancing incidence). The possibility of application of multilayered interferential filters to formation of resonant spectra of ultracold neutrons was shown in [19]. There is direct analogy between the interferential structures for neutrons and the planar potential superlattices for electrons [20], playing an important role in modern microelectronics. In [21] the simplest case of a double-humped barrier was considered and in the experiments [22] and [23] the operation of this simplest interferential filters was demonstrated with the use of a gravitational spectrometer and the time-of-flight method. Figure 2a shows the structure of the interferential system, formed after thermal evaporation on the polished silicon plate of the layers: Cu–Al–Cu and the sequence of the potentials for neutrons, arising in this

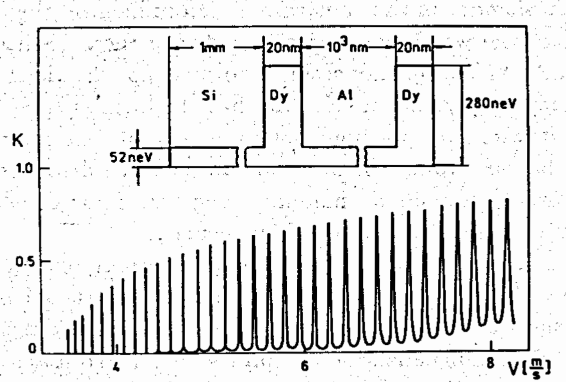

Fig.3 The scheme of filter and the calculated coefficient of neutron transmission

structure. Figure 2b shows the calculated transmission coefficient through such a structure as a function of the neutron energy in two different assumptions concerning the homogeneity of the thickness of Al-layer in the structure:the Gaussian distribution of the thickness of this layer on the surface of the interferential filter with the dispersion $\sigma = 42\AA$; and ideally homogeneous layer ($\sigma = 0$). Figure 2c shows the experimental transmission coefficient, measured with the method of time of flight correlation spectrometry [23]. Figure 3 shows the scheme and the calculated velocity spectrum of neutrons for the interferential filter with a relatively large gap between potential barriers, which permits one to form a respectively large number of resonances in the spectrum, what is essential for the proposed method of measurement of the free fall acceleration of a neutron. For the device shown in fig.1 the time of flight of the neutron from the filter with the shutter to the detector in the Earth gravitational field is determined by the formula:

$$t_i = \left(v_i + \sqrt{v_i^2 - 2ah}\right)/a, \tag{6}$$

where the index i corresponds to the number of a resonance in the spectrum, v_i is the velocity of neutrons in this resonance. If the spectrum contains n well resolved resonances and m runs of measurement are performed at different positions of the detector, one obtains m·n equations with m+n+1 unknown values:n is the number of resonant velocities, m is the number of different values h in equation (6) and the free fall acceleration a.At the number of resonances in the spectrum n=10 and the number of different heights of the detector m=2 one has 20 equations with 13 unknown values.

The position of the resonance in the spectrum is determined by the height of the potential barriers and the width of the gap, l, between them. Sensitivity of the position of a resonance on the velocity scale, v, to this gap variations for most valuable in this experiment high neutron velocities has the form $\delta v/v \sim \delta l/l$. For the relative dispersion of resonance positions not to exceed 10^{-3} at the thickness of the gap between the barriers $1\mu m$, it is necessary to have the dispersion of the gap $\sim 1nm$. Contemporary methods of manufacturing thin films developed for the purposes of electronics can guarantee such homogeneity.

Modulation of a neutron flux for the time-of-flight spectrometry can be realized with the help of a thin film ferromagnetic shutter [24] for ultracold neutrons, especially suitable for the correlation-type spectrometry. [25]. The principle of this shutter consists in fast remagnetization of thin ($\sim 10^3 \AA$) ferromagnetic films and respectively fast changing of magnetic part of the potential in equation (1). The correlation method gives the largest gain in statistical accuracy as compared with the conventional one, especially when one has several large peaks in the spectrum. The structure of the spectrum shown in fig.1, meets this requirement well.

4 Quantitative estimate of the sensitivity

The flux density of ultracold neutrons currently available is $\sim 10^4 cm^{-2} \cdot s^{-1}$ and there is hope for futher progress [26],[27]. Let us assume that the maximum velocity of the ultracold neutrons used in the measurement is 6 $m \cdot s^{-1}$, the diameter of the vacuum cylinder is 1m,and consequently the neutron collimation angle is equal to $\pm 4°$ (condition that the neutrons cannot leave the cylinder due to horizontal motion when flying up and falling down). If the working area of the shutter and interferometer is $50cm^2$ and the incoming neutron flux has isotropic angular distribution, then the neutron flux at the detector is equal to $2.5 \cdot 10^3 s^{-1}$(in fact, in the mirror neutronguides the angular distribution of ultracold neutrons is significantly focused in the forward direction, which must essentially increase the experimental count rate). If the flux reduction on passing through a ferromagnetic shutter equals 0.3 [24], and due to correlation ~ 0.5, the neutron flux at the detector will be equal to $4 \cdot 10^2 s^{-1}$. The typical spectrum of the ultracold neutron flux has the form $n(v) \sim v^3$. Therefore the main part of the intensity is concentrated at the end of the time-of-flight spectrum $n(t) \sim t^3$. If the number of channels in the time of flight spectrum is equal to $\sim 10^3$ and if one takes into account the 10 most intensive resonances with the FWHM equal to ~ 5 channels,then according to the model estimates the mean number of counts under the peak will be equal to $2 \cdot 10^6$ per day with the dispersion $\sim 6 \cdot 10^3$. As the approximate analysis shows in this case the position of the peak in the time scale can be determined with the

precision $2 \cdot 10^{-3}$ of the channel width.This gives the precision of determination of $\delta a/a \sim 2 \cdot 10^{-6}$ for a round day measurement.

To guarantee the necessary time resolution, the thickness of the working layer of the detector has to be as small as possible. The most appropriate variant of the detector is the scintillation detector of ultracold neutrons [28], which can have the thickness of the working layer as small as several microns. The strict horizontality of the working layer of the detector is of great importance in this experiment, because it is necessary to guarantee minimal dispersion of the value h in eq. (6)– the difference of the heights of positions of the chopper and the detector. This horizontality can be achieved in the device having the working and scintillating layers deposited on the surface of the transparent disc, floating on the surface of a transparent liquid(oil).Scintillations are counted by photomultipliers located under the back side of the disc.

In the method proposed here the corrections to the free fall acceleration due to the rotation of the Earth globe according to:

$$a = a_0 - v^2/R - 2v\omega \cdot cos\varphi \cdot cos\psi, \tag{7}$$

where a_0 is the local gravitational acceleration, v is the horizontal component of the neutron velocity relative to the Earth, R is the local radius of the globe, φ is the latitude and ψ is the angle between the neutron's velocity horizontal component and east direction,are very small as compared to the experimental methods of [8],[9],[10].

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