New experiment for the test of the dispersion law for very slow neutrons

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Abstract

Results of the experiment on passing UCN through a rotating disc of silicon single crystal are reported. They demonstrate the sample transparency constancy while moving parallel to its own surface. Neutron velocities range in sample reference frame was 6 ÷ 38 m/s. It was found that real and imaginary parts of the effective potential are constant with accuracy 3×10^{-3} .

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Introduction. It's well known, that slow neutrons dispersion law in matter is described with good accuracy by relation [1-3]

$$k^2 = k_0^2 - 4\pi\rho b, \qquad b = b' - ib'' \tag{1}$$

where k is the wave number in matter, k_0 is the wave number in vacuum, ρ is the number of atomic nuclei in matter volume unity and b is the coherent scattering length. The fact that the square of the wave number changes at the boundary by a constant $\chi^2 = 4\pi\rho b$, lets us to assign effective potential to matter:

$$U = \frac{2\pi\hbar^2}{m}\rho b, \tag{2}$$

where m is the neutron mass.

The important question of validity (1), (2) has been discussed in the literature [5-11]. Being initially a purely theoretical, this problem assumed ever greater importance due to the advent of high-precision techniques of potential value measurement (2) [12]. Discovering of ultra-cold neutrons (UCN) [13,14] having ability to totally reflect from the boundary of the medium at all angles of incidence, increased the interest in this problem. The probability of UCN extinction seen in storage experiments, usually was higher than the calculated value, derived from the data of the imaginary part of the potential U. One could assume, that true dispersion law is different from (1) [5,9]. Subsequently, in theory were indeed found some of

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the factors that lead to slight deviations from (1) [6-9]. However, the calculations indicated that in the case of UCN the magnitude of the corrections should be very small.

The problem of establishing the true form of the dispersion law and now remains largely theoretical, since the experimental data in this area are scanty. In Köster's work [15], the purpose of which was to test the equivalence principle for neutron, the effective potential of neutron mirror was compared with the energy of neutrons incident on it from a certain height. The value of the scattering length *b*, a part of the equation (2), was determined from measurements of the scattering cross section. Taking as its starting point the validity of the equivalence principle, this experiment can be interpreted as a test of the validity of relation (2). Then, from the data [15] follows, that for neutrons with wave length 20 nm formula (2) is valid with accuracy $(2\div3)\times10^{-4}$. However, at the moment of the work there wasn't any reason to doubt the validity of (1). Works [6-8], that predicted the existence of so-called coherent field corrections, appeared much later, and the expected value of these corrections was of the same order as the accuracy of the experiments [12,15].

Deserve a separate discussion experiments carried out later with moving samples that will be considered in the next section.

In this paper, we report on a new experiment, the purpose of which was to test the validity of the dispersion law for neutron waves for ultracold neutrons.

A distinctive feature of the potential dispersion law and the idea of the experiment. On the strength of equivalency of relations (1) and (2), the dispersion law described by them can be called as "potential". Its distinctive feature is the dependence of the normal component of the wave number in the medium only on the normal component of the wave number in vacuum [5]. Meanwhile all physically measurable quantities are independent of the so-called lateral velocity component of the neutron, directed along the medium interface.

For any other type of the dispersion law it isn't true. Indeed, let the wave is refracted at the boundary of a medium, which is characterized by the dispersion law

$$k^2 = k_0^2 - \xi_0^2 + \varepsilon(k_0^2)\,, \tag{3}$$

where $\varepsilon(k_0^2)$ – nonpotential correction of any nature. Then for the normal components of the wave vectors in vacuum and in the medium occurs:

$$k_\perp^2(k) = k_{0\perp}^2 - \xi_0^2 + \varepsilon(k_0^2)\,. \tag{4}$$

Consequently, the presence of nonpotential term in the dispersion law (3) always leads to a dependence of the normal component of the wave number in the medium $k_\perp$ on k_0 [16]. This is true even if the component $k_{0\perp}$ is constant.

Another formulation of the same statement is contained in [17], where it was shown, that in the case of validity of the potential dispersion law, the phase of the neutron wave passing through the sample depends on the movement of its surfaces, and not on the motion of the scattering centers that make it up. Experiments with neutron interferometer [18], in one arm of which a rotating disk was placed, confirmed the validity of this conclusion. When providing a disk in rotation the phase of the wave passing through it normally to the surface, remained constant within experimental accuracy. The question of the validity of the potential dispersion law was not discussed by the authors.

In the subsequent paper [19] it was noted that since the total wave number in the reference system of the sample depends on its velocity, the presence of non-potential changes to the dispersion law [6-8] should also lead to the effect of the phase shift. But the sensitivity of the "zero-Fizeau experiment" [18] was simply insufficient for its observations.

Notice that in usual optics analogous experiment [20] manifested observable effect due to significantly differ dispersion law. Positive effect surely was demonstrated later in the similar neutron experiment [21]. True, the deviation from (1) has been associated with the selection of special substance as a sample, characterized by *a fortiori* non-potential dispersion law caused by the proximity of neutron resonances.

Thus, the dependence of the normal component of the wave vector in the medium on the lateral velocity of the sample really may be a sign of the distinction from the dispersion law (1). In paper [16] it was proposed to apply this approach to test the dispersion law for ultracold neutrons. Instead of interferometer with spatially separated waves, it was proposed to use a neutron analog of Fabry-Perrot interferometer, the so-called neutron interference filter [22-24]. In case of distinction from the dispersion law (1) filter's motion parallel to its borders should lead to a change in $k_\perp$ component of the wave vector in the material and the displacement of the position of quasi-bound state level, near which the structure is transparent. Such a shift can be registered by measuring the spectrum of ultracold neutrons passing through the interferometer.

The corresponding experiment was carried out [25] and the shift of the filter's line was indeed observed when the lateral speed of neutrons was changing. Later, however, it became clear that in case of a resonant tunneling such effect may occur due to the huge increase of the process of neutron scattering by optical inhomogeneities of the medium [26]. The interference of the transmitted and forward scattered waves leads to a distortion of the transmission line, and the magnitude of the effect depends on the total wave number. Thus Fabry-Perot interferometer turned out not entirely suitable target for such experiments.

However, a useful result can be obtained in a simpler experiment. The fact is that in general case of complex, but potential, dispersion law, the transmission of a homogeneous sample also should not depend on the lateral speed of neutrons or movement of the sample parallel to its borders. This was demonstrated in [27], in which one used a thin film of natural gadolinium as a strongly absorbing sample. The constancy of the complex potential was due to the fact that because of UCN's low energy the law 1/v for the absorption cross section was valid in this case, even for substances that have resonances in the thermal energy region [28].

The same approach is obviously possible in the case of relatively transparent samples. The idea is to check the independence of the transmission of the sample from the neutron component of the velocity parallel to the surface without measuring the absolute value of the absorption cross section. The constancy of transmission would indicate both the invariance of the normal component of the wave number in the medium defined by the real part V of the potential U, and the constancy of the imaginary part of the effective potential W responsible for absorption. Such an experiment is described below.

Experimental setup, measurement procedure and main results. The experiment was carried on the UCN source of the Institute Laue-Langevin (Grenoble, France) [29], with the same UCN spectrometer as in paper [27]. The disk of a single silicon crystal with a diameter of 150 mm and a thickness of 1.85mm was used as a sample. It could be set in rotation by a motor. UCN got to the sample passing through the ring-shaped gap and the monochromator (see fig.1). As the latter there was used interference filter [24] – neutron Fabry-Perot interferometer. He transmitted the neutrons with a narrow spectrum of vertical velocities ($\Delta v/v \approx 0.02$) (fig.2) with maximum at 4.52 m/s, that corresponds to energy $E_z = mv_z^2/2$ =107 neV. Transmission of the sample was approximately 0.3. After passing through the sample neutrons fell into a vertical mirror neutron guide that transported them to the detector.

In the experiment the number of neutrons passing through the sample at rotational speeds of disc 3 and 100 rot/s was measured. Rotational speed changed every 200 s, although the periodic repetition was not strictly. The linear velocity of the sample in the field of neutrons passing through it was at two different rotational speeds ~1.1 and 37.5 m/sec respectively. The dispersion of linear velocities determined by the width of the ring-shaped diaphragm and was about ± 10%.

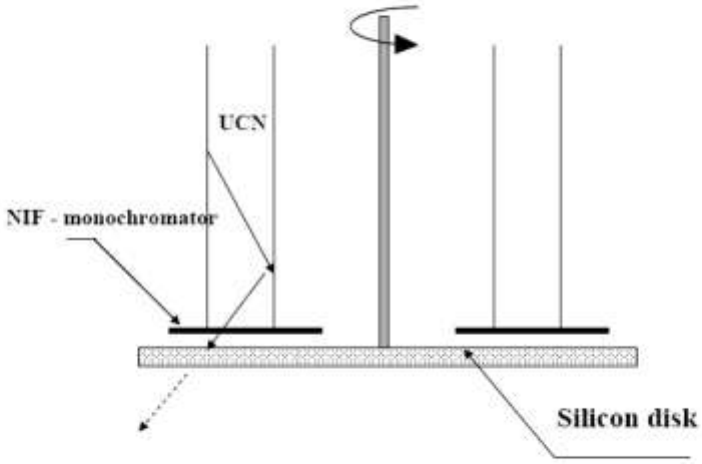

Fig. 1. Idea of the experiment.

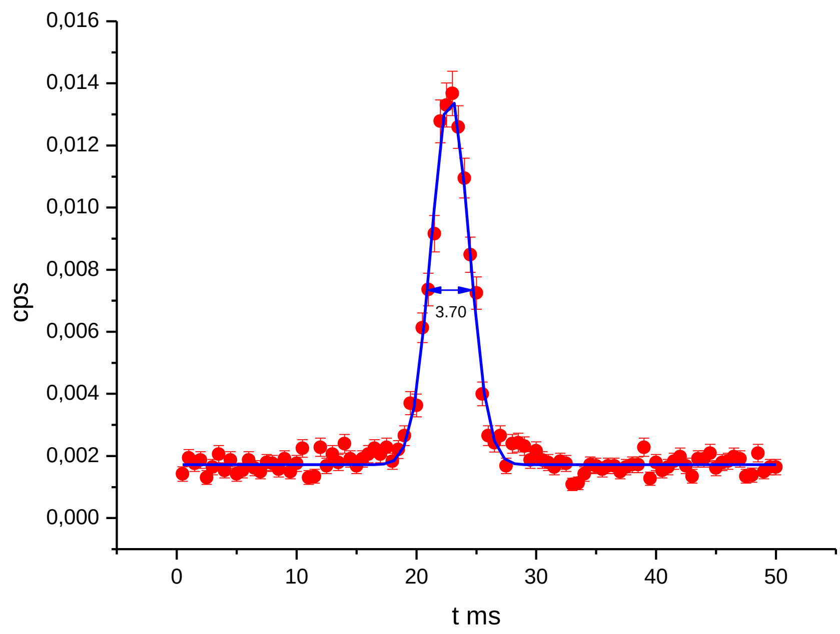

Fig. 2. TOF spectrum of neutrons after the monochromator. The total time of light was about 139 ms. Time 50 ms on the abscissa – significantly shorter period of one cycle of the beam interruption.

Note that used in the experiment monochromator transmitted UCN with specified vertical component of speed, while the horizontal velocity remained not definite. It, however, could not exceed the boundary speed limit of vertical glass neutron guide (~4.3 m/s). Thus at low rotational speed full speed of the neutron in the reference system of the sample was in the range 5-7 m/s, while at a frequency of 100 Hz it reached a value of about 38 m/s.

For each pair of measurements the change of count rate on the sample rotation frequency was calculated. The distribution of results corresponds to a normal one. On fig. 3 results of one of the two series of measurements are presented. Count rate somewhat different in the two series, making up about 24 count/s. Full collecting time was about 10^5 s. Any corrections didn't make in results of measurements. The reason for the observed in [27] systematic "turbine effect" has been understood and this effect was excluded.

For relative change in count rate $\Delta n/n$ in two measurement series it was obtained $\Delta n/n = (0.8 \pm 2.0)\times 10^{-3}$ and $\Delta n/n = (0.5 \pm 1.9)\times 10^{-3}$. Joint processing of all the data led to the result $\Delta n/n = (0.6 \pm 1.4)\times 10^{-3}$. The transmission of the sample is constant with the same precision.

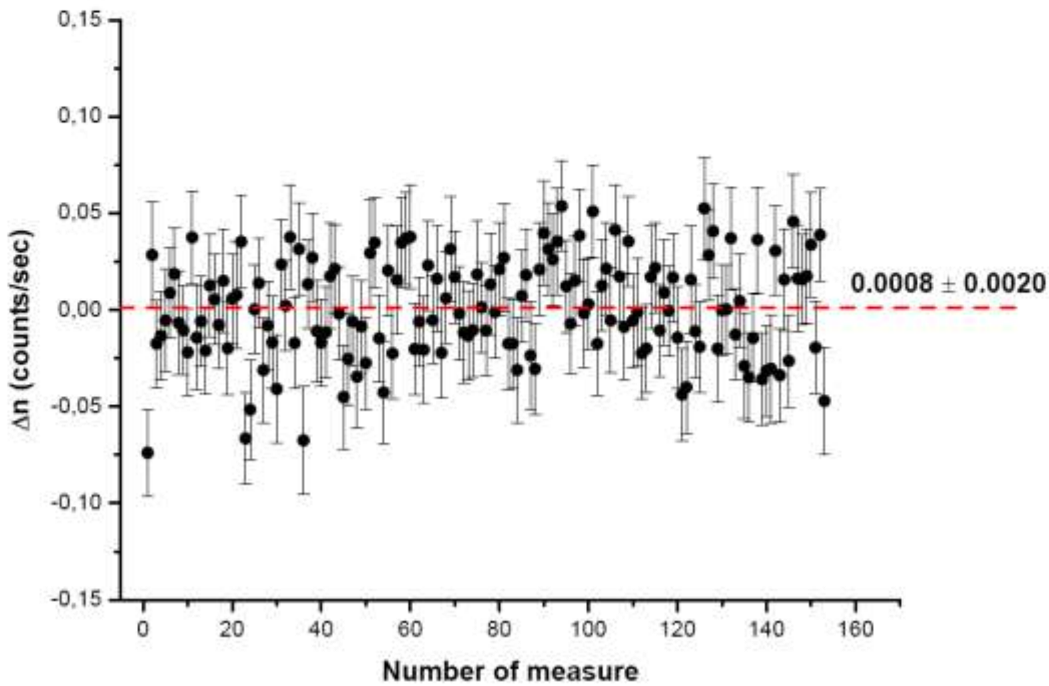

Fig. 3. Results of a series of measurements. The variation of count rate with increasing rotational speed of the sample from 3 to 100 rotations per second is shown.

Association between values of the transmission T and parameters of the effective potential $U = V - iW$ established by calculation. For small changes in the real or imaginary part of the potential U relative change in the transmission $\Delta T/T$ appeared to be close to values $-\Delta V/V$ or $-\Delta W/W$, but simultaneous change $\Delta V = -\Delta W$ can give, in general, a compensation of effects.

To analyze this result we can write, following [5-7], the effective potential in form $U = (2\pi\hbar^2/m)\rho(1+J)b$, meaning that the correction J can be complex $J \approx J' + iJ''$.

Assuming first that the change in the transmission of the sample can be due only to the real part J', we estimate the possibility of its changing when the speed of the neutron varies in the range mentioned above as $\delta J' \leq 3\times10^{-3}$ at 90% confidence level. For a similar estimation of the imaginary part J'' it should be noted that when $J'' \neq 0$ the imaginary part of the potential W is proportional to $b''(1+J')+b'J'' \approx b''+b'J''$ [5]. Then it follows from results of the experiment that, given the above change in the velocity of neutrons possible change in the value $\delta J''$ is limited by $\delta J'' \leq (3\times10^{-3})\cdot\eta$, where $\eta = b''/b'$. Taking into account that for silicon $\eta \approx 10^{-5}$, we obtain the limitation $\delta J'' \leq 3\times10^{-8}$ on the assumption that it is not compensated by the simultaneous and 10^5 times greater change of $\delta J'$.

Conclusion. In the experiment described above it was done an attempt to evaluate possible change in the effective potential of the interaction of ultracold neutrons with a silicon single crystal when the neutron velocity in the reference system of the sample altered from 5-7 to about 38 m/sec. The sensitivity of the experiment was sufficient to register a change in the transmission of the sample due to the variation of the real or imaginary parts of the effective potential at the level 3×10^{-3}. From the constancy of sample transmission the conclusion about the absence of indications of such a change at 90% confidence level was made. It appears that the sensitivity of the experiment can be significantly increased.

Note also that in our experiment with rotation frequency of about 100 samples/sec nuclei were moving with a giant centrifugal acceleration 10^3g. Although it is difficult to expect any effects in this case, but the potential nature of the dispersion law in the case of high accelerations is not obvious. This work was supported by RFBR grant 11-02-00271-a.

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