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FIRST EXPERIMENTAL TEST
OF THE UCN DISPERSION LAW

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Introduction. It is well known that the dispersion law for slow neutrons is described with a high accuracy by the relationship [1]

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

where k is the wave number of the neutron in the medium, k_0 is the wave number in vacuum, ρ is the number of nuclei in a unit volume, and b is the coherent scattering length. The effective potential

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

corresponds to that relationship. The issue of the extent of the validity of relations (1), (2) is of great interest because they are widely used in neutron optics [2] and in the physics of ultracold neutrons (UCN) [3,4].

The "potential" dispersion law (1) may not be exact. In the case of thermal and cold neutrons, very small corrections to it may have to be taken into account due to the existence of correlation between the positions of the scatterers [5,6]. These corrections have not been observed experimentally [7].

Equation (1) is derived using the Fermi pseudo-potential [8] that describes well the scattering of the neutron by a single nucleus in the Born approximation. However, as shown in [9], as the neutron wavelength tends to infinity the effective number of nuclei participating in the coherent scattering increases and reaches the value at which repeated scattering events on one and the same nucleus become important. This prevents using the point-like pseudo-potential at extremely low energies and restricts the applicability range of dispersion law (1). In practice the important question is determine the wavelengths for which slight deviations from the potential dispersion law appear. This article presents preliminary results of the experiment designed to give the answer to this question.

The idea of the experiment is described in [10]. It is based on specific properties of the potential dispersion law noted in [11-13]. Consider a neutron refracted from a boundary of a medium and suppose that the dispersion law includes a correction term $\varepsilon(k_0^2)$

$$k^2 = k_0^2 - \kappa_0^2 + \varepsilon(k_0^2), \quad \kappa_0^2 = 4\pi\rho b . \tag{3}$$

If the medium is homogeneous along its surface, the wave number component k_{0t} parallel to the plane of the interface does not change in refraction. Subtracting $k_{0t}^2 = k_t^2$ from both sides of Eq. (3) we obtain

$$k_\perp^2 = k_{0\perp}^2 - \kappa_0^2 + \varepsilon(k_0^2). \tag{4}$$

It can be concluded that the existence of the non-potential term $\varepsilon(k_0^2)$ results in the appearance of the dependence of the normal component of the wave number in the medium $k_\perp$ on the value of the wave number in vacuum k_0. The goal of the experiment is to find that dependence.

The main element of the instrument is an interference filter [14,15], the neutron analogue of the Fabry-Perot optical interferometer. In the simplest case, it consists of three thin films made of two different materials, deposited on a substrate. The scattering density ρb (and the corresponding effective potential)

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for the top and bottom films are larger than for the intermediate film (and for the substrate). As a result, the structure of the potential of the filter may be represented by two potential barriers with a gap between them. For a sufficient thickness of the middle film the width of the gap is large enough for quasibound states to be formed. As a result, the transmission function of the filter has an essentially resonant behaviour.

The width of the resonance is determined by the penetrability of the outer films and its position may be obtained by matching the wave functions at the boundaries. Note that in the outer layers (films) the wave functions under the barrier decreases exponentially and this corresponds to an imaginary value of the wave number. Since this is a one-dimensional problem, all characteristics of the resonance depend only on the normal components of the real and imaginary wave numbers.

The neutron velocity relative to the filter can be changed if the filter is set into motion in the direction parallel to its surface. It is obvious that this does not change the normal component of the wave number of the incident wave $k_{0\perp}$. However, inside the medium, the normal component of the wave number, $k_\perp$, does change in the case of a nonpotential dispersion law (4), and consequently, leads to a shift of the resonance. It can be detected by measuring the energy of the neutrons transmitted through the filter.
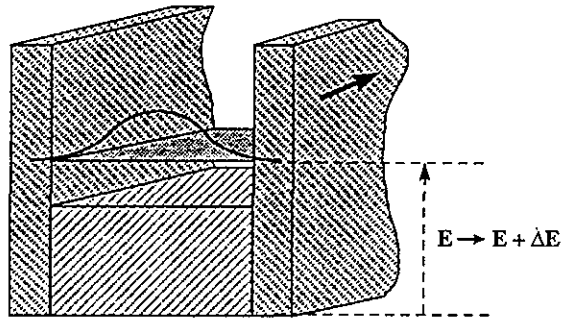
$$E \to E + \Delta E$$

Fig.1. The potential structure of the interference filter and the quasi-bound state level. In the case of a non-potential dispersion law, setting the filter into motion leads to a displacement of the resonance position.

Experimental test of the UCN dispersion law. The experiment was performed with the UCN source of the Institute Laue-Langevin (Grenoble, France) [15]. The experimental layout is shown in Fig. 2. Ultracold neutrons from the feeding neutron guide go to the entrance chamber and, after a number of reflections, to a cylindrical corridor leading them to the 158 mm diameter filter-monochromator. The inner and outer diameters of the corridor are 110 mm and 130 mm, respectively. As a result, UCN irradiate only a annular zone of the filter. The filter is rotated about the vertical axis by a motor. The UCN transmitted through the filter with a sufficiently narrow energy spectrum with the maximum 107 neV

and half-width of the order of 4 neV go to a hexahedral glass mirror neutron guide with the vertical walls 40 cm high. Moving along the neutron guide in the gravitational field of the Earth the UCN are accelerated. The change in the energy is 1.026 neV/cm. A second analysing filter with the maximum transmission about 127 neV is positioned ~20 cm below the first filter. The 107 nev neutrons falling inside the neutron guide from the first to the second filter, increase their energy to ~127 nev and are transmitted by the letter. We can change the vertical position of the analysing filter in a very small increment. This allows us to conduct energy scanning and measure the transmission of the system over a sufficiently large energy interval. The neutrons transmitted through the spectrometer are measured with a He^3 proportional detector.
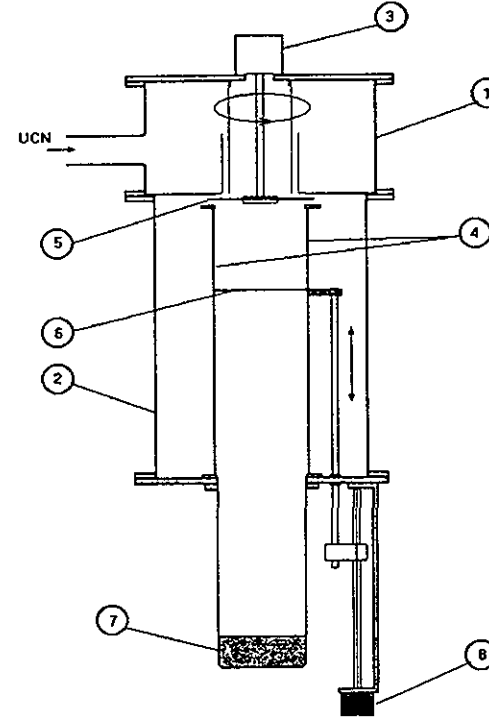
Fig.2 The experimental layout.

1 - entrance chamber, 2 - vacuum chamber, 3 - filter rotating motor, 4 - mirror neutron guide, 5- rotating filter-monochromator, 6 - filter -analyser, 7 - detector, 8 - step motor

The interference filters are prepared by magnetron sputtering on silicon substrates 0.6 mm thick. Two materials are used: a Ni(N) paramagnetic compound with a high scattering amplitude density and a Ti/Zr alloy with nearly zero ρb. To further reduce background, a special multilayer (over hundred

layers) filter was mounted under the scanning filter. This multilayer filter (the superwindow), transmits UCN but reflects effectively neutrons with the energy from 200 to 700neV.
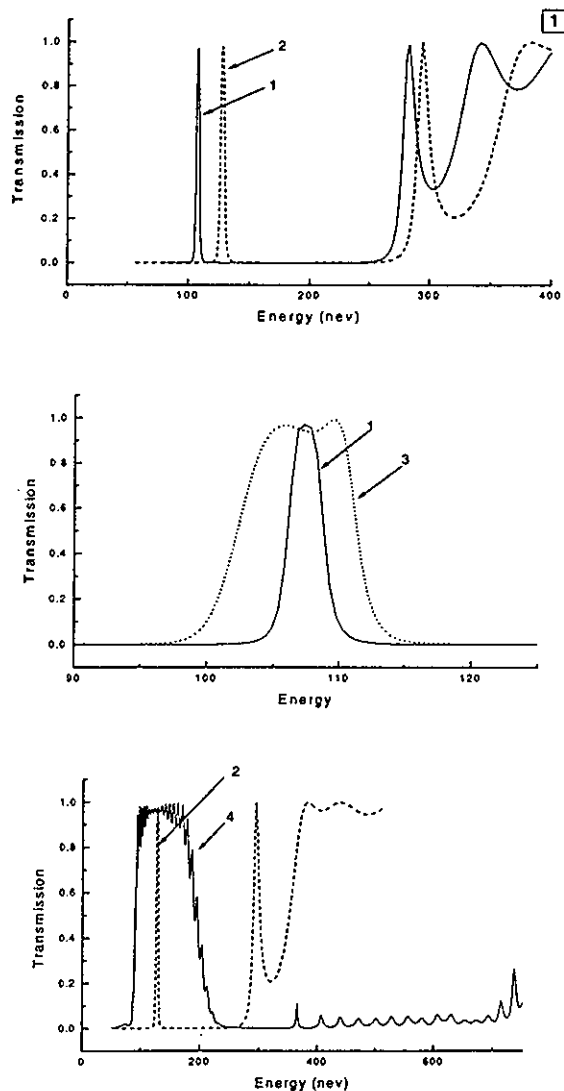

Fig.3. Calculated transmission curves for the interference filters, used in the experiment.
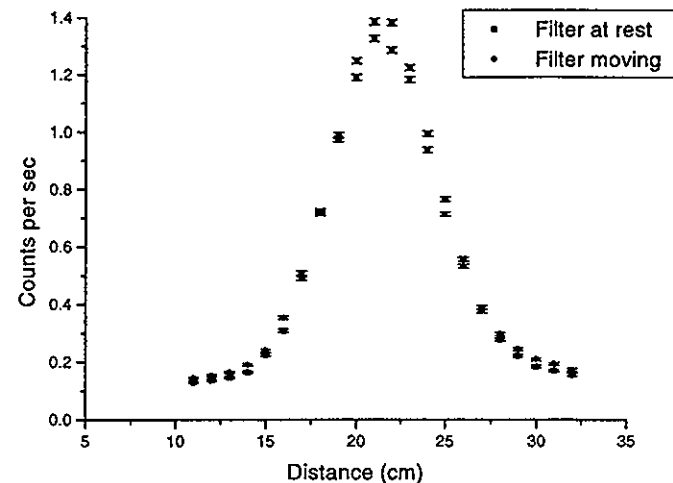1 - monochromator, 2 - analyzer, 3 - wide-window filter for the test experiment, 4 - superwindow.

Fig.4 Obtained scanning curve.

The scanning curve has a half-width of about 6.6 neV. The maximum counting rate is 1.4 counts/sec against a background of 0.12 counts/sec. When the filter is rotating the background increases by approximately 0.02 counts/sec, which is possibly due to the scattering of neutrons on the moving inter layer roughness. In addition, a slight decrease (2-5%) in the integral under the scanning curve was observed.

For each position of the analyser, multiple measurements of the counting rate were conducted with the filter-monochromator at rest and in rotation. After that the analyser was moved to the next position. The linear velocity of the filter in the UCN accessible region was about 35 m/sec. The direction of rotation was periodically changed. Two series of measurements consisting of 5 and 12 runs, respectively, were conducted. The data on centroid displacements

$$\delta <x> = \frac{\sum_i x_i n_i'}{\sum_i n_i'} - \frac{\sum_i x_i n_i}{\sum_i n_i} \qquad (5)$$

obtained in separate scans were then averaged. (Here n_i' and n_i are the counting rates in the position of x_i). The measured displacement were - 0.100±0.031 cm (+) and -0.158±0.046 cm (-) for the first series and - 0.060±0.019 cm (+) and -0.084±0.025 cm (-) for the second series (the brackets denote the direction of rotation). The χ^2 -test on the second series gave the value: $\chi^2 = 1.11$ per degree of freedom.

The negative sign of the effect corresponds to the displacement of the analyser downwards, i.e. an increase in the neutron energy. Averaging over the rotation

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directions yields -0.118±0.024 cm and -0.069±0.014 cm. To go from the centroid shift of the experimental curve to the shift of the spectrum itself, the data given above must be multiplied by a factor which takes into account the portion of the background under the scanning curve. As a result, we obtained for the two series of runs the energy shifts: $\Delta E_1 = + 0.150\pm0.032$ and $\Delta E_2 = +0.090\pm0.018$ neV. The scanning curves were normalised after subtraction of the background. The inset in fig.5 shows the differential behavior of the effect, the differences between the counting rates with motor on and off, determined at each point of the scanning curve.

We have also determined the positions of the maxima of the normalised scanning curves by fitting them with several function. This procedure leads to essentially the same values of the shift.

The experimental conditions were somewhat different in two series. In the first one the superwindow had a fixed position in the lower part of the neutron guide. In the second series it was attached to the filter-analyser and moved together with it in the process of scanning. A subsequent analysis showed that in the first case, a weak additional effect due to line broadening caused by filter rotation could possibly appear and we have include it in the systematic error. As a result, for two runs of measurements we obtained that the average neutron energy shift, if the filter is set into rotation, is $\Delta E_1 = +0.150 \pm 0.032$ (stat) ± 0.025 (syst) and $\Delta E_2 = +0.090 \pm 0.018$(stat) neV, and the average $\Delta E = +0.100 \pm 0.016$ neV.
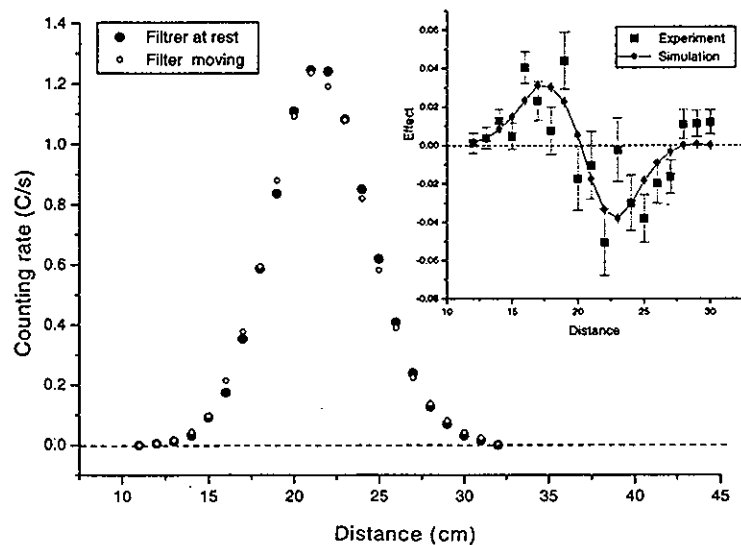

Fig.5. The normalized scanning curves obtained in the second run of measurements. The background is subtracted. The errors are specified because they are less than the size of the point. In the insert, the behavior of the differential effect, the difference between the scanning curves, is shown.

The test experiment and false effects. To exclude from consideration the hypothesis about possible changes in the neutron energy due to interaction with a rotating structure, a special test experiment was carried out. In this experiment the monochromator was fixed and was positioned immediately above the spinning filter. The monochromatic neutrons prepared in this way were transmitted through a special spinning filter with a transmission width larger than the width of the spectrum. The experimental and data processing procedures were the same as in the main experiment. The data obtained in separate measurements correspond to the normal distribution ($\chi^2 = 1.40$). No changes in the neutron energy due to the moving filter are observed: $\Delta E = +0.009 \pm 0.024$ neV. However calculations show that some parasitic effects may exist whose presence is not covered by the test experiment. The estimates based on the experimental data lead to values of this effects much less than the experimental results.

Correction to the dispersion law. It is of interest to estimate the correction for the dispersion law under the assumption that the measured effect is due to resonance shift. Since the potential of the inner Ti/Zr layer is close to zero, it is natural to expect, that effect is due to the change of the $k_\perp$ in the outer Ni(N) layers. Solving the quantum problem of the transmission of a filter we find that this change must be of the order of $(\Delta k_\perp)_{exp} \approx -i \cdot 1.2 \cdot 10^3 cm^{-1}$ ($\Delta k_\perp / k_\perp \approx 1.5 \cdot 10^{-3}$) when filter is set into motion to be in agreement with the observed effect.

The resonance line shift is connected with the real part of the correction to the square wave number $u(k_0^2) = Re[\varepsilon(k_0^2)]$. On the basis of the estimates in [9] it is easy to obtain for an arbitrary incidence angle,

$$\Delta k_\perp \cong -\frac{i}{2} \frac{\kappa_0^6 a^2}{k_0^2 \sqrt{\kappa_0^2 - k_{0\perp}^2}} \qquad \kappa_0^2 > k_{0\perp}^2 \qquad (6)$$

where a is the interatomic distance. From Eq.(6) we obtain the estimate $(\Delta k_\perp)_{th} \approx -i \cdot 0.6 \cdot 10^3 cm^{-1}$.

Conclusion. Having conducted the experiment to search for the resonance line shift of an interference filter caused by the motion of the filter parallel to its surface. We conclude that the observed effect can be interpreted as a change in the energy of the neutrons transmitted through the filter. The statistical confidence level of the result is sufficiently high. We have found no false effects that might be responsible for the result. However, we were not able to exclude completely the possibility of their existence.

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