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New experimental test of dispersion law for very slow neutrons

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ABSTRACT

The results of an experiment on transmitting UCN through a rotating disc made of silicon single crystal are reported. They demonstrate that the transmission of the sample remains constant if it moves parallel to its surface. The range of neutron velocities in the system of reference associated with the sample is 6–38 m/s. It is found that the real and imaginary parts of the effective potential are constant to within 3×10^{-3}.

1. Introduction

It is well known that the law of dispersion of slow neutrons in matter is described within good accuracy by the relation [1–3]

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

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

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

where m is the neutron mass.

The important question of the validity of (1), (2) has been discussed many times [5–11]. Being initially purely theoretical, the problem has acquired ever greater importance due to the advent of high-precision techniques of potential value (2) measurements [12]. The discovery of ultracold neutrons (UCN) [13,14] with their ability to be totally reflected from a medium boundary at any angle of incidence has increased the interest to the problem. As a rule, the probability of UCN extinction observed in storage experiments is higher than its value calculated from the data on the imaginary part of the potential U. One could assume then that the true dispersion law is different from (1) [5,9]. Later, theory found some factors that led to slight deviations from (1) [6–9]. Calculations, however, indicated that for UCN the corresponding corrections must be very small.

The problem of establishing the true form of the dispersion law still remains largely theoretical since the experimental data in this area are scarce. In Köster's work [15], the purpose of which was to test the equivalence principle for neutrons, the effective potential of the neutron mirror was compared with the energy of neutrons incident on it from a certain height. The value of the scattering length b in (2) was determined by measuring the scattering cross section. Accepting, as a starting point, that the equivalence principle is valid, this experiment can be interpreted as verification of the validity of relation (2), as well. Then, from the data [15] it follows, that for neutrons with the wave length 20 nm the formula (2) is valid to within $(2\text{–}3) \times 10^{-4}$. However, at the time of the work there seemed to be no reason to doubt the validity of (1). Papers [6–8] predicting the existence of the so-called coherent field corrections appeared much later with the expected values of such corrections being of the same order of magnitude as the accuracy of the experiments [12,15]. Later experiments with moving samples, to be considered in next section, deserve special discussion.

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

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2. The distinctive feature of the potential dispersion law and the idea of the experiment

In view of the equivalence of relations (1) and (2), the dispersion law they describe can be called "potential". The distinctive feature of the law is that the normal component of the wave number in medium depends on the normal component of the wave number in vacuum alone [5]. At the same time, 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 dispersion law this is not true. Indeed, let the wave be refracted at the boundary of a medium characterized by the dispersion law

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

where $\varepsilon(k_0^2)$ is the nonpotential correction of any nature. Then, for the normal component of the wave vector in vacuum and medium:

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

Consequently, the appearance of the nonpotential term in the dispersion law (3) will always result in dependence of the normal component of the wave number in medium $k_\perp$ on k_0 [16]. This is true even if $k_{0\perp}$ is constant. A different version of the statement is in [17] where it is shown, that if the potential dispersion law is valid, the phase of the neutron wave passing through the sample depends on the motion of its surfaces but not on the motion of scattering centers composing it. Experiments with the neutron interferometer [18], with a rotating disk being located in one of its arms, confirmed the above conclusion. As soon as the disk is set in rotation the phase of the wave passing through it normal to the surface remains constant within experimental accuracy. The question of the validity of the potential dispersion law is not discussed by the authors. In the subsequent paper [19] it is noted that since the total wave number in the reference system of the sample depends on its velocity, non-potential corrections for the dispersion law [6–8] should also lead to the effect of phase shift. However, the sensitivity of the "zero-Fizeau experiment" [18] is simply insufficient to observe it.

Note that in conventional optics an analogous experiment [20] manifested an observable effect due to a significantly different dispersion law. Actually, the positive effect was demonstrated later in a similar neutron experiment [21]. However, deviation from (1) is associated with selection of a special substance as a sample characterized by *a fortiori* non-potential dispersion law due to proximity of neutron resonances. Thus, dependence of the normal component of the wave vector in medium on the lateral velocity of the sample may really point to that the dispersion law differs from (1). In [16] it is proposed to apply this approach to verify the dispersion law for ultracold neutrons. In place of the interferometer with spatially separated waves, it is proposed to use a neutron analog of the Fabry–Perot interferometer, the so-called neutron interference filter [22–24]. If there is deviation from the dispersion law (1), filter's moving parallel to its borders should lead to a change in the $k_\perp$ component of the wave vector in the material and to displacement of the position of the quasi-bound state level near which the structure is transparent. Such a shift can be registered by measuring the spectrum of ultracold neutrons transmitted through the interferometer. The corresponding experiment was carried out [25] and the shift of the filter transmission line as the lateral speed of neutrons changed was detected. Later, however, it became clear that in case of resonant tunneling such effect may occur due to huge increase in neutron scattering on optical inhomogeneities of the medium [26]. Interference between the transmitted and forward scattered waves leads to distortion of the transmission line with the strength of the effect depending on the total wave number. Thus the Fabry–Perot interferometer turns out to be a not entirely suitable tool for such experiments.

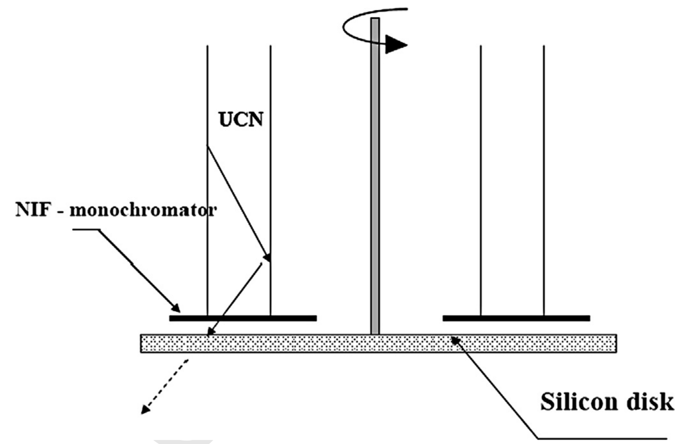

Fig. 1. The idea of the experiment.

However, a useful result can be obtained in a simpler experiment. The fact is that in the general case of a complex but potential dispersion law the transmission of a homogeneous sample should also be independent of the lateral speed of neutrons or movement of the sample parallel to its borders. This is demonstrated in [27] where there was used a thin film of natural gadolinium as a strongly absorbing sample. The fact that the complex potential is constant is due to that the law $1/v$ for the absorption cross section is valid in this case even for substances that have resonances in the thermal energy region [28] because of low UCN energy. The same approach is obviously possible in the case of relatively transparent samples. The idea is to check independence of the sample transmission of the neutron velocity component parallel to the surface without measuring an absolute value of the absorption cross section. The transmission being constant would indicate both invariance of the normal component of the wave number in medium determined by the real part V of the potential U and that the imaginary part of the effective potential W responsible for absorption is constant. It is just such an experiment that is described below.

3. Experimental setup, measuring procedure and main results

The experiment was carried on the UCN source of the Institute Laue–Langevin (Grenoble, France) [29] using the same as in [27] UCN spectrometer. A disk of silicon single crystal with a diameter of 150 mm and a thickness of 1.85 mm was used as a sample. It could be set in rotation by a motor. UCN got to the sample by passing through an annular gap and a monochromator (see Fig. 1). The latter was an interference filter [24] – the neutron Fabry–Perot interferometer. It transmitted neutrons with a narrow spectrum of vertical velocities ($\Delta v/v \approx 0.02$) (Fig. 2) with a maximum at 4.52 m/s corresponding to the energy $E_z = mv_z^2/2 = 107$ neV. The transmission of the sample was approximately 0.3. Having passed through the sample neutrons came into a vertical mirror neutron guide to be transported to the detector.

In the experiment the number of neutrons transmitted through the disc sample rotating with a frequency of 3 or 100 rot/s was measured. The frequency of rotation altered every 200 s, although the periodicity was not strict. For the two rotational speeds the linear velocity of the sample in the area of neutron transmission in the sample was ∼1.1 and 37.5 m/s, respectively. The dispersion of linear velocities determined by the width of the annular diaphragm was about ±10%. Note that the monochromator used in the experiment transmitted UCN with a specified vertical component of speed, while their horizontal velocity was not specified.

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