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Proposed Fundamental Investigations Using Neutron Interference Filters and Gravity Spectrometry

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The neutron interference filter, which is analogous to the Fabry-Perot interferometer for light, is a well-known optical device. Excellent resolution, sensitivity to only one component of neutron speed, and relative simplicity in fabrication make such devices very attractive for the measurement of fine effects which follow changes in UCN energy. A number of fundamental experiments may be performed using a special gravity UCN spectrometer with a couple of such filters located at different heights inside the neutron guide.

KEYOWRDS: UCN, interference filter, gravity spectrometer, dispersion law, quasi-energy, equivalence principle.

§.1 Introduction

The neutron interference filter, which is analogous to the Fabry-Perot interferometer for light, is a well-known optical device. It was proposed by A.Seregin[1)] and tested by A.Steyerl et al.[2)] Excellent resolution, sensitivity to only one component of neutron speed, and relative simplicity in fabrication make such devices very attractive for the measurement of fine effects which follow changes in UCN energy. Below, we shall discuss some possibilities for using such devices in fundamental neutron experiments.

§.2 Neutron interference filters

The interference filter is a three-layer structure coated on a substrate transparent to UCN. It is well known that long wavelength neutron scattering by matter may be described by the introduction of an effective potential, associated with the medium

$$U = \frac{2\pi \hbar^2}{m} \rho b \,, \qquad (1)$$

where m is the neutron mass, ρ is the density of nuclei and b is the coherent scattering length. The outer films are characterized by a greater value of ρb than the inner one. Consequently, the potential structure of the filter represents a two-humped barrier with a well in between (see Fig.1) and exhibits the essentially resonance character of neutron transmission in the vicinity of the quasi-bound state. The energy, E_r, of the resonance defined in the first approximation by the relation

$$k_r d = \pi p \,, \qquad k_r = \left[\frac{2m}{\hbar} (E - U_2) \right]^{1/2} \,, \quad (2)$$

where d is the well width, p is the integer value, and U_2 is the potential of the inner film matter. The energy width of the resonance depends on the time of life of the quasi-bound state and is determined by the width of the outer layers. The exact form of the transmitivity curve may be obtained by the quantum-mechanical calculations.

§.3 Experimental test of the dispersion law for slow neutrons

The dispersion relation of neutron waves in matter, corresponding to the potential (1), may be written with high accuracy in the form

$$k^2 = k_0^2 - 4\pi \rho b \,, \qquad (3)$$

where k_0 is the wave number of the initial wave and k is the wave number of the refracted wave. Relations (1) and (3) form the basis of a number of precise methods for measuring coherent scattering amplitudes, b, of different elements. Advanced experimental techniques[3)] permit us to achieve an accuracy of $\Delta b/b \approx 10^{-4}$ which is extremely important for such fundamental experiments as the investigation of neutron-electron scattering[4)] and verification of the equivalence principle.[5)]

Nevertheless, relation (3) is only an approximation, and corrections of the order of 10^{-4} , connected with multiple neutron scattering, should be taken into account.[6)] The theory of these phenomena is outlined in Refs. 6 and 7, however, no deviation from (3) has been experimentally observed so far. Relations (1) and (3) are routinely used for calculating optical phenomena in UCN optics.

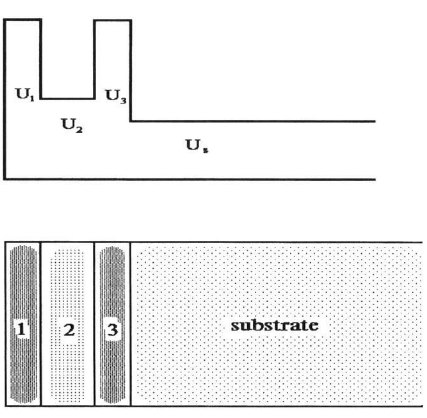

Fig. 1. Three-layered interference filter. The structure of the potential is shown at the top.

Nevertheless, the experimentally observed ultracold neutron losses during storage in vessels are systematically in excess of theoretical predictions. This so-called storage anomaly[8)] now remains the possibility to set the limit of accuracy in neutron life-time experiments. Some theoretical arguments for possible deviations from dispersion law (1) for extremely slow neutrons were presented recently.[9)] All the same, no experiments have been performed with UCN to test (1) and (3) precisely.

An experimental approach for a precise test of the validity of dispersion law (3) was proposed in Ref. 9. The idea of the proposed experiment is based on the specific properties of dispersion law (3). If some correction ε to it exists, (3) may be modified to read:

$$k^2 = k_0^2 - 4\pi\rho b + \varepsilon(k_0^2)\,. \qquad (4)$$

Equation (4) describes the change in the wave vector on refraction. Due to translation invariance along the interface of the media, the longitudinal component of k does not change at refraction and $k_{\parallel} = k_{0\parallel}$. After the cancellation of $k_{\parallel}$ and $k_{0\parallel}$ from both sides of eq.(4), one obtains

$$k_{\perp}^2 = k_{0\perp}^2 - 4\pi\rho b + \varepsilon(k_0^2)\,. \qquad (5)$$

It is easy to see, that if $\varepsilon \equiv 0$, the normal component of the wave vector in media depends only on the normal component of the initial wave vector $k_{0\perp}$ and not on k_0, or more specifically, not on $k_{0\parallel}$. In other words, a change in $k_{\perp}$ due to variation in $k_{0\parallel}$ means that some deviation from (3) must exist. Note that moving the refracting medium parallel to its surface is an experimental alternative to changing the neutron velocity. The validity of this approach has been tested experimentally.[10)] In Ref. 9 a new UCN spectrometer based on the use of interference filters was proposed for testing the dispersion law.

The essence of the proposal is to prepare an interference filter on the surface of a thin silicon disk, a material that is fairly transparent to UCN. The value of $k_{\parallel}$ in matter depends on the rotation speed of the disk. Consequently, in the case of a non-potential dispersion law (4), change in the rotation speed would lead to a shift in the position of the transmitting resonance. The energy of neutrons transmitted through the moving disk will be determined by a second filter. Energy scanning will be carried out by varying the height of the analyzing filter in the vertical neutron guide (Fig.2).

Estimated sensitivity to the possible change in the effective scattering amplitude b, which is proportional to the potential U, is $\Delta b/b \approx 10^{-5}$ if the experiments are performed at the ILL turbine source.[11)] Note, that as predicted in Ref.6, the effective field correction is about Jb, where $J \approx 10^{-4}$. This must change to a value of 5×10^{-5} when the relative velocity varies from $V \approx 6$m/s (the disk at rest) to the $V \approx 200$m/s when the disk is rotating.

At the moment, we have started an experimental test of the spectrometer with Cu-Al-Cu filters. In Fig.3 the reflectivity curve of such filters, measured at the REFLEX reflectometer,[12)] is represented.

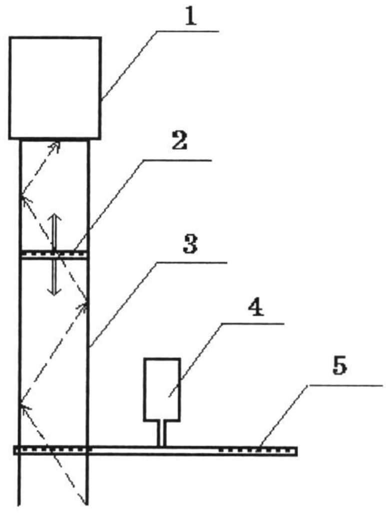

Fig. 2. Layout of the proposed experiment to test the neutron dispersion law: (1) detector, (2) interference filter-analyzer, (3) neutron guide, (4) motor / turbine, (5) disk with interference filter.

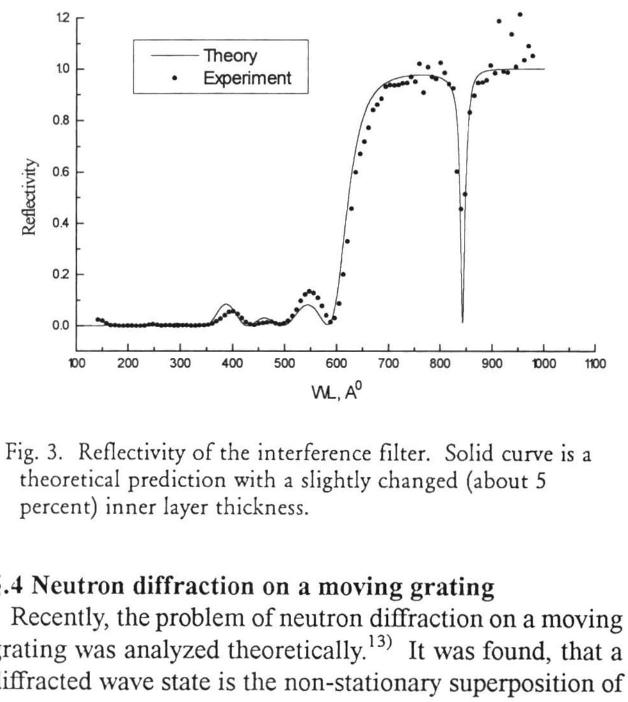

Fig. 3. Reflectivity of the interference filter. Solid curve is a theoretical prediction with a slightly changed (about 5 percent) inner layer thickness.

§.4 Neutron diffraction on a moving grating

Recently, the problem of neutron diffraction on a moving grating was analyzed theoretically.[13)] It was found, that a diffracted wave state is the non-stationary superposition of waves, each of them having an energy $\hbar\omega_s$ and corresponding wave number k_s, where

$$\omega_s = \omega + \frac{2\pi(2s-1)V}{d}\,, \quad k_s = \left(\frac{2m\omega_s}{\hbar}\right)^{1/2}\,, \qquad (6)$$

V is the grating velocity and d is the grating space period. The experiment to verify this result may be performed using the UCN gravity spectrometer discussed above. In this case, the grating will be formed on the surface of the disk located between the filter-monochromator, 2b, and filter-analyzer, 2a.

§.5 Validity tests of the equivalence principle for the neutron

The equivalence of inertial and gravitational masses is one of the fundamental principles of general relativity

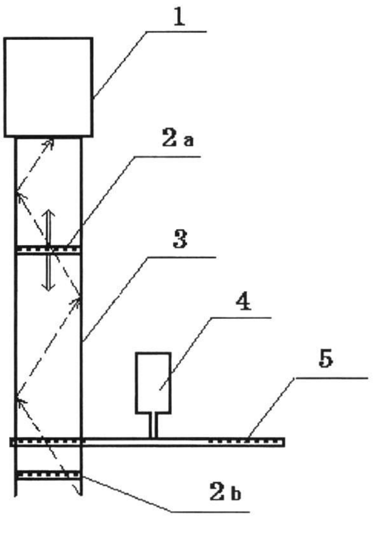

Fig. 4. Layout of the proposed experiment on neutron diffraction on a moving grating: (1) detector, (2a) and (2b) filters, (3) neutron guide, (4) motor/turbine, (5) diffraction grating.

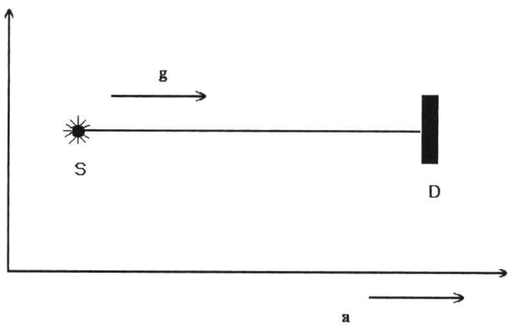

Fig. 5. The spectrometric experiment in a non-inertial system of reference in the presence of gravity (see the main text).

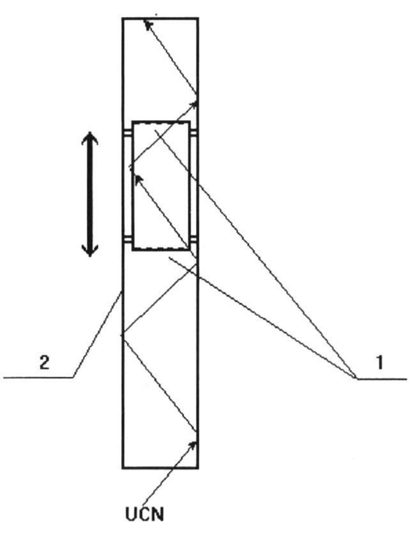

Fig. 6. Layout of the proposed experiment for the equivalence principle test.

theory. In the case of macroscopic bodies, this weak equivalence principle has been verified[14,15] with a precision on the order of 10^{-12}. In the case of elementary particles, however, the precision is significantly worse. Experiments carried out for many years with neutron interferometers[16] have resulted in the equality between the inertial and gravitational masses being established at a level on the order of 0.01.

A measurement of the local acceleration of free fall, performed for the neutron with a precision of 0.15%, is presented in Ref.17. The estimate at the level of 10^{-4} given in Ref. 5 results from a comparison of coherent neutron nucleus scattering lengths, obtained with the aid of a neutron gravity refractometer and by purely neutron optical methods.[18]

Our proposal is to perform the spectrometric experiment in the presence of gravity in a non-inertial system of reference (see Fig.5).

Let a source of monochromatic neutrons, S, and a detector, D, spaced out at a distance L apart be located in a non-inertial system of reference. In a laboratory system, neutrons are moving with an acceleration g. Reasoning from practical considerations, one can assume that the law for a moving device is the harmonic function $x = A\sin(\Omega t)$.

Suppose, that the detector has an ideal energy resolution and detects only those neutrons which have exactly the same energy they had when emitted. We set the difference between the velocities of the source at the moment of neutron emission and those of the detector at the moment of detection to be equal to the neutron velocity change caused by gravity. As a result, we obtain the detection condition

$$g\tau = A\Omega\cos(\Omega(t+\tau)) - A\Omega\cos(\Omega t), \qquad (7)$$

where τ is the neutron time of flight. If τ much less than the oscillation period, eq.(7) becomes trivial

$$g = -A\Omega^2\sin(\Omega t) = a(t); \quad \Omega\tau \ll 1. \qquad (8)$$

It is easy to see that the detector acts only at moments of an exact compensation of gravity acceleration, g, by the accelerated moving of the system in a full correspondence with the equivalence principle. Testing the validity of this relation is the aim of the proposed experiment.

The scheme of the proposed experiment is presented in Fig.6. Two identical filters (indicated by 1) are located inside a neutron guide (indicated by 2) and synchronously move by harmonic law.

The total transmission of such system represents, in a first approximation, two peaks on the time scale during a period. Their positions are defined by formula (8). Strictly speaking, the time of flight, τ, is a solution of the equation

$$A\sin(\Omega t) + (v - A\Omega\sin(\Omega t))\tau \pm \frac{g\tau^2}{2} = L + A\sin(\Omega(t+\tau)), \qquad (9)$$

where v is the neutron velocity in a reference system connected with the first filter.

If the amplitude of oscillation, A, is much less than the distance, L, between filters, and the gravity energy change, mgL, is much less than the neutron energy, then the solution of Eq.(9) is not much different from the value, $\tau_0 = L/v_m$ where v_m is the neutron velocity, corresponding to the maximum transmission of the filter at rest.

In Fig.7 the results of a computer simulation of the experiment are presented. Total transmission of the pair of filters was calculated as a function of the moving phase

$\phi = \Omega t$ under the following conditions. The filters were the Cu^{65}-Al-Cu^{65} type with thickness of 350-280-350Å, an energy resolution 2.5neV, L = 10cm, the amplitude of oscillation A = 1cm, and frequency f = 7.4Hz, which corresponds to a maximum acceleration of 2.21g.

By fitting the number of calculated transmission curves at the exact defined moving law, the gravity acceleration, g, was extracted. No data connected with the filter properties were used in this procedure. As a result, it was found that an accuracy of the experiment of about of 10^{-4} may be achieved if statistics on the order of 10^{-6} are collected. Estimations show that a time on the order of some days is enough for the experiment if it is performed at the ILL UCN source.[11)]

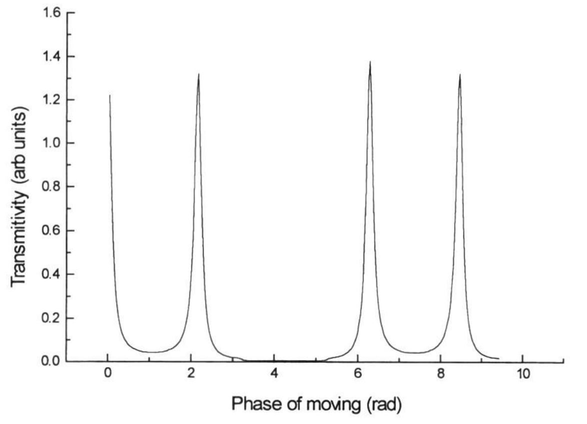

Fig. 7. Transmitivity of the pair of filters.

Acknowledgments

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