validity. At the same time, a work was done and the candidate thesis was successfully defended, and its starting point consisted of a check of results obtained earlier. Il'ya Mikhailovich praised the author: "You nicely criticized the Americans";

— sixth, the capability of comprehending the substantiated arguments of a colleague, independently of his/her age and position, as well as respect for the results of work done by colleagues and pupils. "It is better to do one's own work than to criticize the work of others." "Well, how's the work, of which I am not a patriot, going on?" He instilled the first into me when I was a young junior researcher. I heard the second from Il'ya Mikhailovich during our penultimate meeting in a room of the hospital of the Academy of Sciences;

— seventh, strict adherence to ethical principles in all, including business, relationships. As far as I understand, Il'ya Mikhailovich was quite selective in his contacts with the people surrounding him. Being extremely cultured and educated himself, he highly estimated this quality in others. However, while attaching much importance to the rules of 'good behavior', Il'ya Mikhailovich never extended automatically his estimate of the personal qualities of an individual to the results of their work.

Il'ya Mikhailovich wrote the following about his understanding of intelligence [6, p. 85]: "I was born into a cultured family that came from the so-called 'working intelligentsia'. Nearly all my life the word 'intelligentsia' was pronounced depreciatingly with the addition 'rotten' — abusively. My father, of whom I am very proud, and a number of my teachers were significantly more intelligent than I." And further: "I am far from considering all people working in administrative bodies to be bureaucrats. Among them there are many knowledgeable and competent people, but there also exist bureaucrats. And bureaucrats have always been and remain the main malevolent force for the intelligentsia. Scientists-bureaucrats are no less dangerous. A bureaucrat in science is no less dangerous than in management... . And intellectuals and bureaucrats have always been and will always be worst enemies" [6, p. 89].

As a mentor of the young staff, Il'ya Mikhailovich consistently adhered to the principle of 'better later, but better'. "The first to defend themselves are those who very much want to, followed by the most talented, then all the rest." "The exam in the professional subject is necessary (as Sergei Ivanovich Vavilov used to say) in order not to let those pass who shouldn't."

I will permit myself to conclude this article with Il'ya Mikhailovich's reflections about one's soul. I present these lines not from the text of the edited manuscript from the archive [6, p. 85], but the facsimile [6, pp. 170, 171 (photocopy)] in the same edition, since when I read the facsimile text I internally hear the voice of Il'ya Mikhailovich and his manner of speaking.

"People my age must take care of their soul. A human being not only has a soul, but it often hurts. But, nevertheless, and let believers forgive me, I do not believe it to be immortal. But each one of us must remain alone together with his or her conscience, and it will suggest whether to recite our prayers.

No one dies without leaving a trace. Something of us remains to live in those who surrounded us. Inside us something lives that was left by those whom we lost."

I am grateful to everyone who helped me in preparing this talk, in particular to M M Salokhina, researcher at the Laboratory of Atomic Nucleus at INR, RAS.

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I M Frank and the optics of ultracold neutrons

A I Frank

Il'ya Mikhailovich Frank first turned to the problems of neutron optics at the beginning of the 1970s, soon after F L Shapiro and his colleagues discovered ultracold neutrons (UCNs). This, naturally, did not happen by chance. The unusual wave properties of neutrons so vividly manifest themselves in experiments with UCNs that they could not but excite Il'ya Mikhailovich, to whom precisely the wave approach in physics was so close. In neutron optics he most probably recognized a field where his beloved optics and neutron physics, to which he devoted more than a decade, come closely together.

We recall that after the first brilliant studies in which UCNs were observed, there arose a problem that subsequently became more and more apparent. According to expectations, UCNs could indeed be stored in vessels for a long time, but the storage time turned out to be noticeably shorter than the time predicted by theory, which represented the so-called anomaly in UCN storage. This circumstance, doubtless, gave rise to a certain challenge for both experimenters and theorists.

Therefore, it is not surprising that most work on neutron optics [1 – 7] carried out by Il'ya Mikhailovich belongs to the period immediately following the discovery of UCNs in 1968. Here, I would like to briefly recall some of the results of these studies and to relate the further destiny of the ideas put forward in them.

The results of the first period of research with ultracold neutrons were summarized by F L Shapiro in his talk [8]* presented at a conference in Budapest in summer 1972. I M Frank [3] presented a supplement to this talk at the same conference.

* Since F L Shapiro was ill, this talk was presented by V I Lushchikov.

It is known that the interaction of long-wave neutrons with matter can be described by introducing a so-called effective potential

$$U_{\text{eff}} = \frac{\hbar^2}{2m}\frac{Nb}{\pi} \tag{1}$$

that is proportional to the density N of atomic nuclei in the matter and the coherent scattering length b of neutrons on the nuclei. Precisely this approach was adopted by F L Shapiro in his work. The effective potential U is the result of averaging of a pointlike Fermi quasipotential

$$u = \frac{2\pi\hbar^2}{m}\, b\delta(\mathbf{r} - \mathbf{r}_j) \tag{2}$$

describing, in the first Born approximation, the behavior of a wave scattered by a pointlike object at large distances from the latter. However, Il'ya Mikhailovich immediately applied the description that was more customary to him, which traces back to Fermi and describes the interaction of neutrons with a medium in terms of the refractive index $n = k/k_0$, where k and k_0 are the wave numbers in the medium and in a vacuum, respectively. In this case, the square of the refractive index was related to the dielectric constant ε for light:

$$n^2 = \varepsilon' + \mathrm{i}\varepsilon'' = 1 - \frac{4\pi N}{k_0^2}(b' - \mathrm{i}b'')\,. \tag{3}$$

Here, several circumstances must be pointed out. First, the scattering length b is a complex quantity. Consequently, the dielectric constant is also a complex quantity, which, by the way, is quite customary in optics. Its imaginary part is determined by the cross section of processes resulting in the disappearance of UCNs, namely, of radiative capture and of inelastic scattering. Second, the real part of b is positive for most substances. And third, the imaginary part of b is usually much smaller than the real part.

Thus, from formula (3) it is seen that, if the wave number k_0 of the incident wave becomes smaller than a certain threshold value $k_{\text{lim}} = \sqrt{4\pi N b'}$, then the real part of ε turns out to be negative. Recalling that the refractive index is also a complex quantity: $n = n' + \mathrm{i}n''$, we immediately see that a negative sign of ε' indicates that the imaginary part of the refractive index is greater than its real part:

$$\varepsilon = n^2 = (n'^2 - n''^2) + 2\mathrm{i}n'n''\,. \tag{4}$$

Such a situation is peculiar to the optics of metals. Thus, Il'ya Mikhailovich confronted total UCN reflection with the reflection of light from a metal, namely, from a metal with anomalously high conductivity. By analogy with what is done in metal optics, he determined the amplitude of the reflected wave via the Fresnel coefficient.

It must be said that the analogy between UCN reflection from the surface of a substance and the reflection of light from an ideal metal is still not quite universally accepted, because actually a totally different phenomenon is often unjustifiably termed the metal reflection of neutrons. The work [3] was essentially the first in UCN optics. Subsequently, I M Frank (hereinafter referred to as I M) developed these ideas [4, 5] and in 1974 he delivered a lecture, remembered by many, at the Second Neutron School in Alushta [6]. We shall now turn to this lecture.

As we saw, the square of the wave number of neutrons in a medium is a complex quantity:

$$k^2 = k_0^2 - 4\pi N(b' - \mathrm{i}b'')\,, \qquad k = k' + \mathrm{i}k''\,. \tag{5}$$

Substituting the square of the complex wave number into the left-hand part of the first of equations (5) and equating the imaginary and real parts of this equation, one readily obtains explicit expressions for the real and complex parts of the wave number, which was done by I M in Refs [5, 6]:

$$\begin{aligned} k' &= \sqrt{\frac{k_0^2 - 4\pi N b'}{2} + \sqrt{\frac{(k_0^2 - 4\pi N b')^2}{4} + (2\pi N b'')^2}}\,, \\ k'' &= \sqrt{\frac{4\pi N b' - k_0^2}{2} + \sqrt{\frac{(k_0^2 - 4\pi N b')^2}{4} + (2\pi N b'')^2}}\,. \end{aligned} \tag{6}$$

Formulae (6) are not applied often, because the smallness of the quantity b'' permits expanding the expression under the radical sign and obtaining simpler approximate formulae. There exists, however, an important, although not too often encountered, case of strongly absorbing media, in which the imaginary and real parts of the scattering length happen to be of the same order of magnitude. Then, in accordance with Eqn (6) both the real and the imaginary parts of the wave number depend strongly on the real and the imaginary parts of the scattering length.

It is here that an astonishing property of the optics of absorbing media is manifested. Suppose that the wave number k_0 of a wave incident upon the medium tends toward zero. It is readily demonstrated that the real part k' of the wave number inside the medium is limited by the quantity

$$k_{\text{min}}^2 = 2\pi\rho b'\left(\sqrt{1 + \left(\frac{b''}{b'}\right)^2} - 1\right). \tag{7}$$

This means that the velocity of a neutron in the medium remains finite, even when the velocity of the neutron incident on the medium turns to zero. Il'ya Mikhailovich explained the reason for this immediately. Indeed, the total neutron flux entering the medium is absorbed in it. Thus, absorption results in the appearance of a constant flow of neutrons crossing the boundary of the medium. The effective velocity related to this flow can, apparently, be attributed a physical meaning.

It is precisely to this effect that restriction in the cross section enhancement of neutron capture in media with significant absorption, predicted earlier by I I Gurevich and P E Nemirovskii [11], is related. As the neutron velocity decreases, the cross section continues to rise, according to the $1/v$ law, and by the velocity v in the medium must be understood the finite quantity

$$v' = \frac{h}{m}\,k'\,. \tag{8}$$

Direct experimental examination of the neutron velocity in a strongly absorbing medium has regretfully not been achieved, but on the whole the theory has been verified. The results of experiments [12], in which ultracold neutrons were transferred through films containing natural gadolinium, were in very good agreement with calculations by formulae (6). It must be said that the conditions of these experiments were in a certain sense unique. The cross section of UCN

capture amounted to the impressive value of 20 Mb, while the damping length of the wave was three times shorter than the wavelength itself.

It must be noted that I M in no way considered the issue of the physical meaning of neutron velocity in a medium to be trivial. In this connection, the following episode comes to mind. At the 1974 School in Neutron Physics in Alushta, a lecture on experiments with very cold neutrons was delivered by Albert Steyerl of the Münich Technical University [13]. Among other things, he spoke of the results of measurements done with very slow neutrons transmitted through thin films. The experiments seemed to reveal an apparent deviation from the $1/v$ law for the absorption cross section, if one understood the velocity to be the neutron velocity in a vacuum, v_0. This contradiction, however, was fully removed when, instead of v_0, one considered the neutron velocity (8) in the medium. In his comments on Steyerl's lecture, I M Frank highly estimated this result which fully corresponded with his own ideas. Many years later, A Steyerl wrote [14] the following in his reminiscences of Il'ya Mikhailovich: "Over the long period of almost 40 years of common research interests, starting from the early days of ultracold neutrons at Dubna and Garching, I remember just one incidence where I am afraid I did not understand Il'ya Mikhailovich. That is when he summarized our work at Garching as 'confirmation of the $1/v$ law'. This was surprising to us since we had never doubted that the $1/v$ law for neutron reaction processes should be valid even at the lowest energies, as long as a refractive correction to neutron velocity inside the medium is applied. It is a pity that I had not asked him what exactly he meant."

One can speculate why the issue of neutron velocity in a medium did not seem so simple to I M. Below follows what he wrote several years later concerning the propagation of light in a medium [15]: "A photon in a medium is obviously not a free particle. The propagation of a wave is realized owing to coherent superposition of the waves of individual atoms. Thus, the collective motion of the atoms of the medium is essential for the wave to appear. This represents a property that is peculiar not to a particle, but to a quasiparticle (for example, by analogy with phonons)." The above certainly holds true, also, for neutrons in a refractive medium. Therefore, Steyerl's result, which demonstrated not only the possibility of attributing physical meaning to the neutron velocity in a medium, but also the difference between this velocity and its vacuum value, seemed important to him.

Much later the difference between the neutron velocities in a medium and in a vacuum was measured in a straightforward experiment [16]. It was shown that a refractive sample, placed in the way of a neutron beam, altered the total neutron time of flight in accordance with

$$\Delta t = \frac{d}{v}\left(\frac{1}{n} - 1\right), \tag{9}$$

where n and d are the sample's refractive index and thickness, respectively. The actual time delay varied between 4×10^{-10} s and 10^{-7} s, while the total time of flight was on the order of 0.017 s. Precession of the neutron spin in a magnetic field was used as the clock, and the results of the experiment matched the results of calculations within several percent.

But let us return to the aforementioned lecture delivered by I M at the Alushta Neutron School. Turning once again to the problem of the dispersion law for neutron waves, he recalled, for instance, that the dispersion law (3) for neutrons is quite similar to the dispersion law for light in a rarefied medium:

$$k^2 = k_0^2 + 4\pi N \frac{\omega^2 \alpha}{c^2}, \qquad |n^2 - 1| \ll 1, \tag{10}$$

and that they are both described by the well-known Foldy formula [17]:

$$k^2 = k_0^2 + 4\pi N f_0 . \tag{11}$$

The latter relates the wave numbers in a vacuum and in a medium with a number density N of scatterers and amplitude f_0 of forward scattering on an elementary scattering center. Indeed, when light is scattered on an atom, the role of the scattering amplitude is assumed by the polarizability α with the corresponding multiplier ω^2/c^2, while the coherent neutron scattering length b is the limit value of the forward scattering amplitude taken with the opposite sign: $b = -\lim f_0$, when the wave number tends to zero.

However, the Foldy formula for light cannot be applied in the case of a dense medium. The refractive index in a dense medium is described by the known Lorentz–Lorenz formula

$$n^2 = 1 + \frac{4\pi N\alpha}{1 - (4\pi/3)N\alpha} . \tag{12}$$

The reason that formulas (10) and (12) differ from each other is well known. The point is that in a dense medium the electric field E', acting on an atom, differs from the field E impinging on the medium:

$$E' = \frac{E}{1 - (4\pi/3)N\alpha} . \tag{13}$$

If the ratio of these field strengths is denoted by C, the dispersion law for light can be written down in the form of the universal formula obtained by Lax [18]:

$$k^2 = k_0^2 + 4\pi N C f_0 . \tag{14}$$

Thus, the Lax formula describes in a unique manner the dispersion law for both light and neutrons, the difference consisting only in the different value of the coefficient C representing the ratio of the external field strength to the so-called coherent field strength in the medium. For light in a rarefied medium and for neutrons one conventionally assumes $C = 1$.

And here Il'ya Mikhailovich made a surprising assumption: what if we do not fully understand the scattering theory of neutrons in a dense medium and the Lax coefficient for neutrons is not precisely equal to unity? Then, if it acquires a small imaginary part C'' and is multiplied by the relatively large value of b', it will noticeably alter the imaginary part of ε and, at the same time, the probability of neutron capture in the medium:

$$\varepsilon = n^2 = 1 - \frac{4\pi N}{k_0^2}(C' - \mathrm{i}C'')(b' - \mathrm{i}b'') . \tag{15}$$

Thus, the coefficient C being complex may quite be the reason for the anomaly in UCN storage.

This assumption was surprising and, as far as I remember, did not receive any special attention at the time. However, when about 10 years had passed, other authors dealing with

the dispersion theory of neutron waves showed that the Foldy formula is indeed not quite correct and corrections for the coherent field should exist and that the corresponding coefficient C is actually complex. The nature of these corrections is related to scatterers-nuclei being not quite arbitrarily distributed in the medium, since all substances, even liquids and amorphous bodies, exhibit, at least, short-range order. A certain correlation occurs even in the model in which scatterers are hard spheres. In this case, the point is simply that the distance between their centers cannot be smaller than their diameter. By the way, it is precisely in this model that it is easiest to perform calculations if the radius of the sphere is set equal to the radius of the atom a. In this connection, we shall present the results obtained by Sears [9]:

$$C = 1 + J' + \mathrm{i}J'' ,$$

$$J' = J_0 \left(\frac{\sin k_0 a}{k_0 a} \right)^2 , \qquad J'' = \frac{J_0}{2(k_0 a)^2} (2k_0 a - \sin 2k_0 a) , \quad (16)$$

$$J_0 = 2\pi N b a^2 .$$

It is readily seen that if $k_0 a \to 0$, then we arrive at

$$C' \approx 1 + 2\pi N b' a^2 , \qquad C'' \approx \frac{4}{3} \pi N b' k_0 a^3 . \quad (17)$$

Similar results were obtained in the work [10]. From (17) it is seen that in the case of UCNs, when n^2 is close to zero and $k_0^2 \approx 4\pi N b'$, one has

$$C' \approx 1 + k_0^2 a^2 , \qquad C'' \approx k_0^3 a^3 , \quad (18)$$

where the characteristic parameter $k_0 a \approx 10^{-2}$. Consequently, if it is correct to extrapolate the results of Refs [9, 10] to the UCN region, then for the latter the value of C'' may be on the order of $10^{-5} - 10^{-6}$.

The situation became even more complicated after the publication of Ref. [19], in which it was indicated that the applicability region of the theory based on the application of the pointlike Fermi quasipotential (2) is limited by the condition $k_0 \gg 4\pi N b d$, where $d \approx N^{-1/3}$ is the interatomic distance. Although in the case of UCNs this condition is quite well satisfied, one cannot totally exclude that even in this case the universally adopted theory may not be quite precise.

Thus, the theory definitely predicts the existence of small deviations from the Foldy dispersion law which is often termed 'potential', since it relies on the model of the effective potential (1). However, there exist no experimental data that could either confirm or disprove this conclusion, while the precision with which the dispersion law for neutron waves in matter has been established experimentally does not exceed several percent. Nevertheless, the approaches to experimental tests of the validity of the potential dispersion law had already been indicated in the I M Frank's work [4, 6].

He showed that if dispersion law (5) holds valid, then the same dispersion law is also valid for the component of the wave number normal to the surface, viz.

$$k_\perp^2 = k_{0\perp}^2 - 4\pi N b . \quad (19)$$

Hence, it follows that in the case of a potential dispersion law the normal component $k_\perp$ of the wave number in a medium depends only on the normal component $k_{0\perp}$ of the wave number in a vacuum. For a dispersion law of any other form this is not correct.

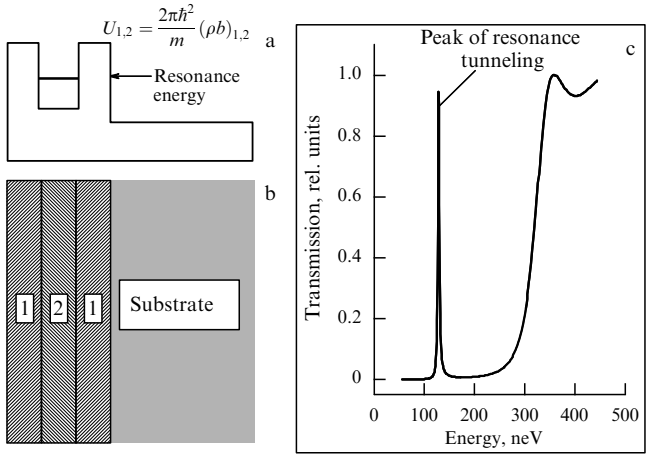

Figure 1. Fabry–Perot interferometer (FPI) for neutrons. (a) FPI potential structure. (b) Layout of the interferometer: three films of two kinds of substances are deposited on the substrate. (c) FPI transmission dependence on energy in the case of normal incidence of neutrons on it.

Thus, if the value of $k_{0\perp}$ does not vary and in the experiment a dependence is found of the normal component of the wave number in the medium on the component $k_{0\parallel}$ parallel to the boundary of the substance, this should point to a deviation from dispersion law (5). A different formulation of the statement was given in Ref. [20].

In principle, such a dependence could be revealed in experiments with neutron interferometers. Thus, for example, in the experiment of Ref. [21] a rotating quartz disk was placed in one of the arms of a neutron interferometer operating with thermal neutrons at a wavelength $\lambda = 1.27$ Å. The axis of rotation of the disk was parallel to the wave vector of the incident wave. Clearly, the wave number k_0 of the neutrons scattered on nuclei of the sample depends in this case on the rotation velocity of the disk, while the boundaries of the disk are fixed. When the disk was set into rotation, the phase of the wave that traversed the disk remained the same with a precision on the order of 10^{-4}, which demonstrated the independence of $k_\perp$ from k_0. However, the change in k_0 was extremely small, since the linear velocity of the sample at the point where the neutrons entered was two orders of magnitude smaller than the velocity of the neutrons. Therefore, as was pointed out in Ref. [22], the accuracy of the experiment was clearly insufficient for detecting the corrections to the dispersion law predicted in Refs [9, 10].

A somewhat different experimental approach, applicable in the case of UCNs, was presented in Ref. [23] in which it was proposed to use a neutron Fabry–Perot interferometer, which represents a structure consisting of three films characterized by different magnitudes of the effective potential (1). The potential structure of such an interferometer represents two barriers and a well in between them (Fig. 1). When the well width d is not too small, in the well there may form levels of quasistable states, the position of which is determined with a certain approximation by the relationship

$$k_{2\perp} d \approx p\pi , \qquad p = 1, 2, 3, \ldots , \quad (20)$$

where $k_{2\perp}$ is the normal component of the wave number in the substance of the middle film forming the potential well. Such a structure exhibits a pronounced resonance character in neutron transmission, which was well confirmed by experiments [24] that had been performed by that time.

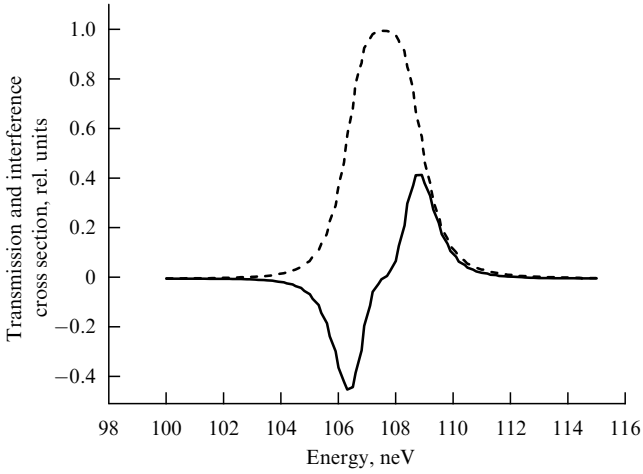

Figure 2. The interference cross section characterizing deformation of the neutron transmission line through the real FPI. The dashed line shows the position of the unperturbed transmission curve. The scale is arbitrary. The behavior of the cross section showing alternating signs corresponds to the asymmetric deformation of the line.

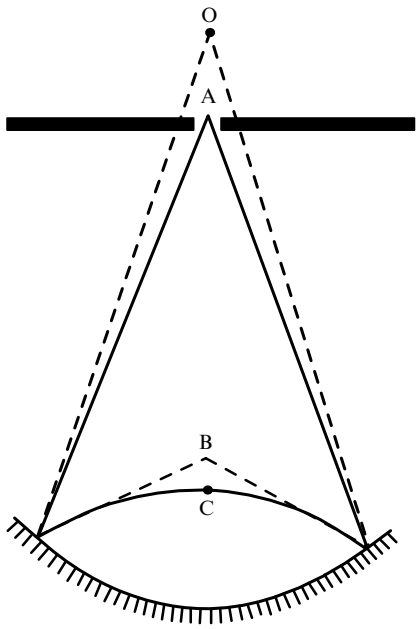

Figure 3. Sketch from an article by I M Frank in the journal *Priroda* (1972).

It has been suggested that such an interferometer be prepared on the surface of a disk transparent to neutrons, and, as in Ref. [21], neutrons be directed perpendicularly to its surface. In the absence of corrections to the potential dispersion law, the component of the wave number in the medium, $k_{2\perp}$, is not sensitive to whether the disk is at rest or rotates in its plane. In the opposite case, it should depend on the rotation velocity, which in accordance with relation (20) would lead to a shift in the position of the resonance and, correspondingly, in the spectrum of neutrons transmitted by the interferometer.

Such an experiment was carried out in Ref. [25], and its results testified that, when the disk with the interferometer rotated, the UCN transmission spectrum was noticeably shifted. Subsequently, however, it became apparent that there exists one more physical reason for the revelation of this effect. It turned out to be that in the case of UCNs the shape of the interferometer's transmission spectrum may differ from its shape predicted by the solution of the one-dimensional quantum problem [26]. The point is that in conditions of resonance tunneling, a colossal enhancement takes place of the cross sections of all neutron scattering and capture processes, including the cross section of neutron scattering from optical inhomogeneities. It was shown that interference of an unperturbed wave traversing the structure by tunneling and of a wave scattered through a zero angle on an inhomogeneity leads to a nonsymmetric distortion of the shape of the transmission line. Here, the corresponding interference cross section turns out to be inversely proportional to the total wave number:

$$\sigma_{\rm ts} = -\frac{4\pi}{k}\,\mathrm{Im}\left\{T^{*}f(k_{\rm t},k_{\rm t})\right\}, \qquad (21)$$

where T is the amplitude of the unperturbed wave, and $f(k_{\rm t},k_{\rm t})$ is the forward scattering amplitude. Thus, in the case of UCNs the shape of the transmission spectrum turns out to be distorted (Fig. 2). When the disk with the interferometer rotates, the wave number k in the disk coordinate system increases, the interference cross section (21) decreases, and the transmission spectrum is restored. The existence of this additional effect has not permitted judging the degree of validity of the potential dispersion law, and so the issue remains open.

I would like now to turn to one more work by I M Frank, devoted to neutron optics [2]. In this work, the issue was first raised of the possibility of creating a neutron microscope. I shall quote the entire relevant passage to make the idea of this problem, characteristic of those times, most clear:

"Subsequently, when it becomes possible, we shall also have to carry out the simplest optical experiments. For example, one can imagine the following experiment. Ultracold neutrons pass through a small aperture, impinge on a concave mirror, and upon being reflected assemble at the focus (Fig. 3). Here, owing to gravity, they will acquire additional vertical velocity in moving downward. As a result, their motion in the vicinity of the mirror will be such as if they had left point O, which is somewhat higher than the aperture A, and they will assemble at focus C, below the geometrical focus B. In optical devices for ultracold neutrons such a peculiar chromatic aberration, dependent on velocity, must be taken into account. I believe that to obtain an optical image with the aid of the reflection and refraction of very slow neutrons represents an experiment of such importance that it just must be performed. One can even dream of a distant future when the optics of very slow neutrons will permit creating a neutron microscope."

At the time this proposal was very audacious. The state of affairs with UCN sources was such that it was very difficult even to think about such a microscope seriously, and the proposal seemed quite hopeless. However, the highlighted problem of gravitational chromatism did represent a certain challenge, and it seemed desirable to find some kinds of approaches, even if only theoretical, to its resolution.

The scheme of the experiment proposed by I M permitted discussion in quite a classical, i.e., corpuscular, language. Within this approach it was clear that a neutron traveling toward the focus along different trajectories would take diverse time intervals. It was not quite easy to understand which consequences this would result in if the problem was considered from a wave standpoint. I spoke several times

about this with Il'ya Mikhailovich. The result of our conversations was the idea that one can take into account gravity applying purely optical concepts, namely, one can introduce the concept of a 'gravitational refractive index' [27]:

$$n(z) = \left(1 - \frac{2gz}{v_0^2}\right)^{1/2}, \qquad v_0 = v\big|_{z=0}. \tag{22}$$

Thus, the space in which the force of gravity acts can be considered an optically inhomogeneous medium in which one of the fundamental principles of optics, Fermat's principle, holds valid without any restrictions. From the validity of Fermat's principle followed the possibility itself of forming an image with the aid of neutron waves in a potential field. The notion of an optically inhomogeneous medium made it possible to apply a number of ready conclusions that were well known in optics [28]. However, the correct answer to the question concerning the role of the nonisochronicity of classical trajectories was not found immediately. At the same time, it became more and more clear that this was an important question. In the case of concrete optical calculations, the classical time of flight appeared in a quite straightforward way in the expressions for the main parameters of optical devices, such as the focal distance and magnification [29, 30]. Further studies clarified the situation, and the role of the classical propagation time of a particle became more comprehensible. It turned out that the requirement of isochronicity of classical trajectories in an optical system coincides with the condition of its achromatization [31].

In succeeding years much has been done in the field of practical UCN optics. Thus, for example, significant progress has been achieved in the compensation for gravitational aberrations. A number of devices have been created that are prototypes of the neutron microscope. However, creation of a full-fledged microscope is still hindered by the important problem of UCN sources exhibiting insufficient intensity. Therefore, the issue of the possibility and expedience of practical applicability of the neutron microscope remains open. I shall not deal with this issue in detail, while the interested reader is referred to reviews [31, 32].

I shall recall one more, not so well known, work by I M Frank. While thinking about the reason for the anomaly in UCN storage, he admitted the possibility of the existence, in addition to the hypothesis for an inaccurate theory, of a certain universal mechanism leading to inelastic neutron scattering in the case of reflection from a surface. Here, a neutron may acquire such an additional energy that its velocity will exceed the limit value. Then, when undergoing a subsequent collision with the wall of the vessel, it may enter the substance and perish there.

In the search for a possible reason for such UCN 'heating', Il'ya Mikhailovich turned to neutron diffraction by a running surface wave of a medium [7]. The propagation velocity of such waves is close to the speed of sound in the medium, i.e., amounts to several kilometers per second, while the velocity of UCNs is about a thousand times less. For a qualitative analysis of the problem, I M considered the reflection of a neutron from the surface of a medium in a frame of reference moving with the velocity V of a surface wave. In this reference system, the surface of the medium represents a diffraction grating at rest with a period equal to the length Λ of the surface wave, the longitudinal velocity of the neutron $v'_x = V$, while its normal component v'_y is precisely the same as in the laboratory system. Since $v'_x \gg v'_y$, the total velocity v' is close in absolute value to V. The neutron's de Broglie wavelength $\lambda \approx h/mv'$ is small here, and to an order of magnitude it is close to the period of the grating.

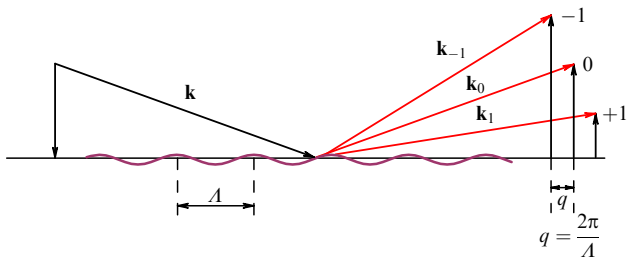

Figure 4. Neutron diffraction by a surface wave in a moving frame of reference. The wave vectors of all the waves are identical in absolute value. The normal components of waves of nonzero orders of diffraction differ from the normal component of the incident wave.

When neutrons are reflected from a surface with such a profile, diffraction maxima will inevitably be observed (Fig. 4), and the directions of the diffracted waves can be readily calculated just as is done in conventional optics. Thus, in a moving reference system the neutron may be scattered with the same velocity v', but at a different angle to the surface. The normal velocity component will change, with the change depending on the order of diffraction. Let us recall that the normal velocity component is the same in both reference systems.

One can say that the effect predicted by I M Frank was in a certain sense astonishing. It is well known that in the case of light diffraction by a (supersonic) density wave running in a medium there appear in the spectrum of scattered waves satellites with frequencies differing from the frequency of the initial wave. The frequency split in this so-called Mandelstam–Brillouin doublet is determined by the relationship

$$\pm\frac{\Delta v}{v} = \pm 2\,\frac{v}{c}\,\sin\frac{\theta}{2}\,, \tag{23}$$

where v is the wave velocity in the medium, c is the speed of light in vacuum, and θ is the Bragg angle determined by the relation $2\Lambda \sin(\theta/2) = \lambda$. Here, Λ and λ are the ultrasonic and light wavelengths, respectively. Clearly, the magnitude of this Doppler shift in frequency is relatively small, owing to the smallness of the factor v/c. Moreover, if the light and acoustic waves propagate in orthogonal directions, then the relative frequency shift turns out to be on the order of magnitude of $(v/c)^2$, and the effect becomes really small. Such a transverse Doppler effect is of a purely relativistic nature.

A totally different situation occurs in the case of UCN diffraction by a surface wave. First, the velocities of both the neutron and the running wave are much smaller than the speed of light, and the problem can be dealt with classically. Second, the velocity of the wave is much greater than the velocity of the neutron, and precisely for this reason the change in frequency in the case of normal incidence of the neutron on the medium turns out to be significant. Third, since we are dealing with a massive particle, a change in the frequency of the neutron wave directly signifies a change in the energy and classical velocity of the neutron.

Twelve years after the publication of Ref. [7], neutron diffraction by a running surface wave was indeed examined experimentally [33]. True, the experiment was not arranged

with ultracold, but with so-called cold neutrons, the velocity of which amounts to several hundred meters per second. But in this case also, it was significantly smaller than the velocity of the ultrasonic wave artificially excited on the surface of a quartz crystal. The authors carried out quite a detailed theoretical analysis of the problem from which, for instance, it followed that the energy of neutrons corresponding to an order of diffraction equal to ± 1 actually does differ from the initial energy by the quantity $\Delta E = \pm\hbar\Delta\omega$, $\omega = 2\pi f$, where f is the frequency of the ultrasonic wave. The value of ΔE here was on the order of 10^{-7} eV, close to the typical UCN energy. True, the change in energy of such cold neutrons turned out to be three orders of magnitude lower than the energy itself. It could hardly be registered, and the authors did not really intend to do so, being concentrated on measuring the direction and intensity of the diffraction maxima. They naturally knew nothing of the work performed by Frank, which had been published in Russian in the form of a preprint.

The effect of a change in the neutron energy in the case of neutron diffraction by a moving wave was actually newly discovered nearly two decades after I M Frank's work. The problem of UCN diffraction by a moving periodic structure (diffraction grating) was dealt with in Ref. [34]. As in I M Frank's work, the solution was found in a moving frame of reference, where the grating was at rest, with subsequent transition to the laboratory system of coordinates.

In the case of normal incidence of the wave on the grating and when the wavelength is much larger than its period, this solution has the form

$$\Psi(x,y,t) = \sum_j a_j \exp\left[\mathrm{i}(k_j x + q_j y - \omega_j t)\right],$$
$$k_j = k_0\left(1 + j\frac{\Omega}{\omega}\right)^{1/2}, \qquad \omega_j = \omega + j\Omega, \tag{24}$$
$$\Omega = \frac{2\pi V}{L}, \qquad q_j = j\frac{2\pi}{L}, \qquad Lk_0 \ll 1,$$

where k_0 is the wave number of the incident wave, L is the period of the grating, V is its velocity, j is the order of diffraction, and a_j are the amplitudes determined by the Fourier transform of the transmission (reflection) function of the grating.

With an accuracy up to the term $q_j y$, which is of a purely diffractive nature, this expression coincides with the expression for the wave function of neutrons having passed through a fast (quantum) modulator, periodically acting on the wave with a frequency $f = \Omega/(2\pi)$ [35]. As can be seen from Eqn (24), in the case of a moving grating the role of the modulation frequency is assumed by the ratio of the grating's velocity of motion to the space period: $f = V/L$. Qualitatively, this result is readily explainable. Indeed, in moving across the direction of propagation of the wave, the grating modulates the transmitted wave at each point of the neutron beam. Such modulation should result in the occurrence of satellites, the frequencies of which differ from the initial one by a multiple of Ω.

Thus, it turned out that a moving grating can act as a quantum modulator, giving rise to neutron waves with energies differing from the initial energy by multiples of $\hbar\Omega$. In Ref. [35], it was proposed to observe this phenomenon with the aid of an ultracold neutron spectrometer.

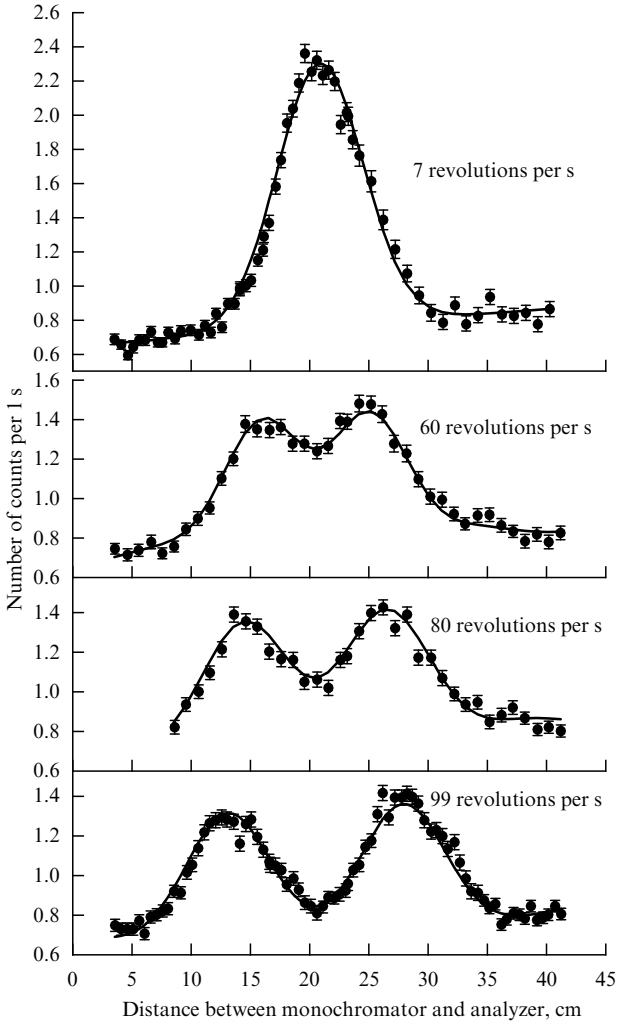

Figure 5. Spectrum of neutrons transmitted through a rotating grating. The grating rotation frequency is indicated in the figure. A change in distance between the analyzer and the monochromator of 1 cm corresponds to a change in energy of 1 neV. A grating rotation velocity of 100 revolutions per s corresponds to a modulation frequency of the neutron wave of 1.89 MHz.

Such an experiment was arranged several years later, when experimenters had at their disposal a UCN spectrometer with the aforementioned Fabry–Perot interferometers. Instead of making use of the translational motion of the grating, it happened to be more convenient to make it rotate. Therefore, the grating represented a silicon disk with radial grooves at its periphery.

The experiment of Ref. [36] demonstrated quite clearly that when the grating rotated, in full agreement with theory there indeed arose in the spectrum of transmitted neutrons satellites with an energy differing from the initial value by the quantity $\hbar\Omega$ (Fig. 5). The intensity of neutrons corresponding to the ± 1st order of diffraction was also in agreement with the results of calculations and amounted to nearly 40% of the incident wave intensity. Thus, a quarter of a century after the work done by I M Frank, the effect he predicted was examined experimentally.

At the same time, still another important circumstance was realized. Since the transfer of energy from the grating to the neutron is quantized, it turns out to be possible not only to accelerate and decelerate neutrons, but also to transfer to

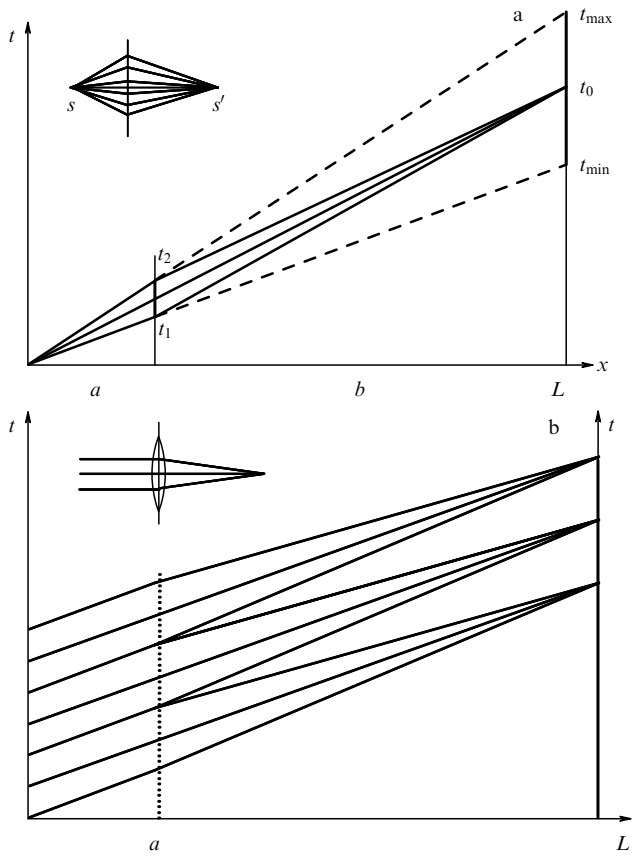

Figure 6. (a) Focusing of neutrons from a pulsed source in time. (b) Schematic of the demonstration experiment. Monochromatic neutrons of identical velocities enter the device at arbitrary instants of time. The neutron lens of periodic action alters their velocities. As a result, neutrons assemble (group) at the observation point L (time focusing).

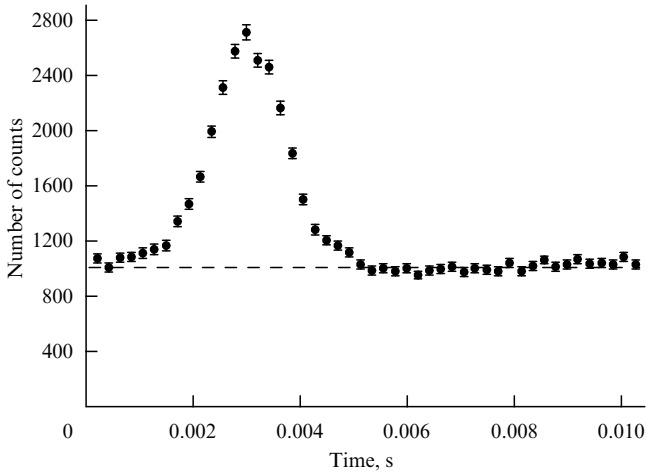

Figure 7. Demonstration of the possibility of time focusing. Monochromatic neutrons entering the device at arbitrary instants of time traverse the time lens operating periodically. The dependence of the counting rate on time clearly reveals a peak of neutrons focused in time. The time scale is equal to the revolution time of the grating.

them an exactly known quantum of energy, which is very attractive for the implementation of a whole series of new experiments. Thus, for instance, the possibility arose of creating a so-called neutron time lens, with the aid of which it would be possible to focus neutrons in time [37]. The principle of time focusing is explained in Fig. 6a.

In ordinary optics, a focusing lens transforms the angular distribution of rays, as a result of which they intersect at the focal point. A time lens transforms the velocity distribution of neutrons, as a result of which neutrons emitted by a pulsed source within a certain range of velocities arrive at the point of observation at the same time. Figure 6a illustrates neutron trajectories in path–time coordinates. The straight lines (rays) correspond to neutrons moving with a constant velocity. In the absence of focusing, the neutrons would arrive at the point of observation at different instants of time within the interval between t_{min} and t_{max}.

Naturally, the pulse length τ of any real source cannot be infinitesimal. Correspondingly, the pulse length Θ at the point of registration is also finite. By analogy with geometrical optics, one can introduce the concept of time magnification M. It turns out that in the case of a relatively small energy transfer $\Delta E \ll E$, the following formula for a thin lens, known from geometrical optics, is also valid for time magnification:

$$M = \frac{\Theta}{\tau} = \frac{b}{a}\,, \tag{25}$$

where a and b are the respective distances from the source to the lens and from the lens to the observation point.

The role of a time lens can well be assumed by a moving grating, which was demonstrated in Ref. [38]. The version chosen for the demonstration experiment involved focusing rays from an infinitely distant source, when parallel rays incident on the time lens are collected by it at the focus. The trajectories of monochromatic neutrons departing from a certain stationary source (Fig. 6b) correspond to this experimental scheme. Here, the lens operates in a cyclic mode and focuses neutrons arriving at the device during a certain period T_{cycl}.

As in the experiment of Ref. [36], the grating was a silicon disk with radial grooves. However, the distance L between the grooves of the diffraction grating was no longer constant, but depended in a certain manner on the azimuthal angle at the surface of the disk. At each moment of time the neutrons could only traverse a small sector of the grating. Thus, when the grating rotated, the neutrons only 'saw' a small fragment of it, which moved with a constant angular velocity but with a space period depending on time. In accordance with Eqn (24), the variable in the time value of L did provide the necessary time dependence of the frequency $\Omega(t)$. Time focusing of ultracold neutrons was observed quite confidently in the experiment, true, with an efficiency somewhat smaller than calculated (Fig. 7). Thus, the possibility of creating a time lens based on the effect of acceleration and deceleration of neutrons during their diffraction by a moving grating was demonstrated.

Before long, still another application was found for the diffraction energy quantization effect, precisely on which a new method was based for testing the equivalence principle for the neutron. In a recent experiment [39], the energy mgH acquired by a neutron falling in the gravitational field of the Earth through a height H was compensated for by a quantum of energy $\hbar\Omega$ transferred to it by diffraction to the -1st order by the moving grating. The gravitational force $m_n g_n$ acting on the neutron, measured in this way, turned out to be equal to mg_{loc}, with an accuracy on the order of 2×10^{-3}. Here, m is the tabulated neutron mass, and g_{loc} is the acceleration of free fall of macroscopic bodies at the site of the experiment.

Already after the publication of Ref. [39] it was understood that the quantum nature of the experiment permits overcoming a difficulty consisting in the fact that for interpretation of the experiment, instead of using the tabulated neutron mass m, its inertial mass $m_{\rm i}$ should have been used, although strictly speaking its value is not really known [40]. However, the ratio $\hbar/m_{\rm i}$ is known [41] and determined from experiments in which the neutron wavelength $\lambda = \hbar/(m_{\rm i}v)$ and its velocity v are measured simultaneously. This is sufficient for the correct interpretation of the data obtained in experiment [39]. Further work is planned on precision testing of the equivalence principle for the neutron.

I shall briefly dwell upon yet another optical effect in which the analogy between neutron and usual optics is manifested strikingly. It is well known that in a homogeneous medium the frequency of a wave and its wave number are conserved, although the latter differs from its vacuum value. For a long time it was tacitly implied that as soon as the wave traverses the sample and enters the vacuum again, its wave number acquires its initial vacuum value. However, this is true only in the case of a sample at rest or moving uniformly.

For a long time, the case of a sample moving arbitrarily was not studied, either in conventional or in neutron optics. An exception was the work by V I Mikerov [42]. Analyzing the possibility of filling a UCN trap without its dehermetization, V I Mikerov proposed using a membrane, the motion of which followed a harmonic law in the direction of and opposite to the UCN motion. Mikerov found that the UCN energy should change after passing through the oscillating film. Since this result was not published, it remained unknown for a long time.

Several years later, theoretical investigation started of the interaction of an electromagnetic wave with a dielectric moving with acceleration. In 1982, K Tanaka considered the problem of a wave being reflected from and traversing a plane-parallel dielectric layer moving with a constant linear acceleration, and he found that the frequency of an electromagnetic wave traversing a sample being accelerated changes [43]. The expression for the change in frequency of the transmitted electromagnetic wave, if multiple reflection from the boundaries of the sample are neglected, is of the form

$$\Delta\omega = \frac{\omega_0}{c^2}\, wd(n-1)\,, \qquad \frac{wd}{c^2} \ll 1\,, \tag{26}$$

where w is the acceleration of the sample, and d is its thickness. Formula (26) does not contain the velocity of the sample, while the only characteristic of the medium is its refractive index.

The magnitude of the effect, which we shall term the effect of a medium being accelerated, is very small. Taking the sample to have a thickness $d \approx 1$ m, and setting the refractive index to $n \approx 1.5$, we obtain from formula (26) that in the case of an acceleration $w \approx 100$ m s^{-2} the relative change in frequency is $\Delta\omega/\omega \approx 5 \times 10^{-16}$. The possibility of its experimental determination was discussed in Ref. [44]. However, as far as is known, the effect of a medium being accelerated has not yet been observed in optics. Tanaka's work was not noticed by the neutron community.

In 1993, F V Kowalski published a work [45] in which he proposed testing the equivalence principle in a new type of neutron experiment. Kowalski considered the issue of the passage of neutrons through a material layer moving with acceleration. Essentially, on the basis of the propagation time of neutrons from the source to the detector he concluded that when the neutrons left the plate their energy should differ from the initial one. He obtained a formula for the energy change, which is very similar to expression (26):

$$\Delta E \cong mwd\left(\frac{1}{n} - 1\right). \tag{27}$$

The same result was later obtained in Ref. [46] by calculating successively the change in the neutron wave number for refraction by the entrance and exit surfaces of a sample moving with acceleration. The difference in velocities of these surfaces, when traversed by a neutron, gave rise to the effect.

In a recent work [47], formulae (26) and (27) were obtained in a unique manner from the equivalence principle. It was shown that the kinematic reason leading to the effect manifestation consists in the delay in time of the wave propagation due to the presence of the refracting sample. The respective time delays for an electromagnetic and a neutron wave are given by

$$\Delta\tau_{\rm em} \cong \frac{d}{c}(n-1)\,, \qquad \Delta\tau_{\rm n} = \frac{d}{v}\left(\frac{1}{n} - 1\right). \tag{28}$$

The effect of a medium being accelerated was recently exposed in experiments with ultracold neutrons [47]. Using UCNs in experiments of this type gives a certain advantage, since the refractive index for them may be noticeably smaller than unity. True, owing to the $1/v$ law the low velocities of UCNs result in rigorous restrictions on the thickness d of the sample.

The sample used in the experiment of Ref. [47] was a silicon plate with a thickness on the order of 1 mm, which underwent harmonic motion with a frequency of several dozen hertzes. The maximum acceleration of the sample amounted to 75 m s^{-2}, while the change in the neutron energy was several units of dimensionality [10^{-10} eV]. The results of the experiment were in agreement with the results of calculations with an accuracy superior to 10%.

Although in the conditions of a laboratory experiment the effect of a medium being accelerated is very small, one must not consider studying it to be only of academic interest. The point is that in the Universe there exist objects exhibiting dimensions exceeding 'laboratory' dimensions by many orders of magnitude and often moving with significant accelerations. The question of the significance of the effect of a medium being accelerated in astrophysical phenomena apparently deserves the most careful analysis.

Here, one must bear in mind that, owing to its kinematical nature, the effect may be due not only to the acceleration of a limited volume of matter containing scattering centers, but also to a region of space characterized by a force field. For manifestation of the effect it is only important for the wave number to change inside a volume moving with acceleration. Owing to the universality of this effect, it may involve waves (and particles) of any nature. This issue was also discussed in Ref. [47].

Let us also note one more circumstance. The theory leading to formula (27) in the first approximation is based on the assumption of the 'potential' dispersion law being valid for neutron waves in a medium moving with acceleration. However, this assumption is not quite evident. Turning to the microscopic picture of the phenomenon of dispersion, we recall that the wave number in a medium differing from its

vacuum value is a result of the interference of a wave incident on the medium and the waves scattered by all the elementary scatterers. In the case of neutron waves, such scatterers are atomic nuclei. In a noninertial frame of reference related to the medium undergoing acceleration or in the equivalent case of a force acting on a particle, all the waves in the medium stop being spherical, and the conditions for interference should change. The significance of this circumstance has not yet been studied, and the appearance of new experimental data may shed light on this problem.

In this talk I wanted to show that many of the ideas advanced by Il'ya Mikhailovich Frank nearly forty years ago still retain their importance, while many of them have undergone essential and sometimes unexpected development. Concerning the author's own results dealt with above and in quoted works, most of them were obtained in collaboration with numerous colleagues. The author expresses his sincere gratitude to all of them.

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Pulsed nuclear reactors in neutron physics

V L Aksenov

1. Introduction

The first pulsed nuclear reactor IBR was put into operation at the Joint Institute for Nuclear Research (JINR) in Dubna in 1960. By the end of the 1960s, outstanding scientific results had already been obtained, and the advantages of this type of neutron source, as well as ways of further developing, had also been understood. In 1971, a group of authors, which included I M Frank, was awarded a State Prize for work on the creation of a fast pulsed reactor (IBR in *Russ. abbr.*) for research and an IBR with an injector. At the same time, construction of the new pulsed reactor IBR-2 had already started.

In 1971, an article by I M Frank, "Issues of the development of neutron optics" [1], was published in the journal *Dokl. Akad. Nauk SSSR* (*Sov. Phys. Dokl.*), in which a comprehensive formulation is given of the fundamentals of pulsed reactors, of experimental methods, and of lines of research. I M Frank stressed that the utilization of neutrons in scattering experiments is governed by the laws of optics and that the optics of thermal and cold neutrons in many aspects resembles the optics of electromagnetic radiation (light), especially in the X-ray range. There exist, however, differences, related, first, to the difference in their interaction with matter and, second, to the neutron having a finite mass. The latter circumstance provides for the possibility of developing the time-of-flight method in neutron optics, and this method is most effectively applied to pulsed neutron sources. In this talk we shall consider development of the time-of-flight method and the role which pulsed reactors have played in neutron physics.

2. The time-of-flight method

The time-of-flight method in neutron physics consists in neutrons being registered at a given distance L from the