Ultracold neutrons—discovery and research

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A review is given of progress in the physics of ultracold neutrons (UCN), beginning with the first experiments. The problems that the author had to investigate under the immediate direction of Fedor L'vovich Shapiro are described in detail. It is shown how a solution to the problems took shape, and how unexpectedly their connection with questions from completely different fields of physics was discovered. An account is given of the main problem of ultracold neutrons, which is as yet unresolved—their anomalous losses in bottles, and of the attempts to find an explanation for this problem. Results are given for the measurement of the neutron lifetime and for the searches for an electric dipole moment. Some directions of academic and applied research into ultracold neutrons are pointed out, and the possibilities for increasing the intensity of the ultracold neutron sources also are considered.

1. LYRICAL FOREWORD

My acquaintance with Fedor L'vovich did not at all come about in connection with ultracold neutrons, but was in connection with work on quantum electrodynamics, which I was carrying out with V. Pashkevich under the direction of D. I. Blokhintsev, as a visiting student at the Laboratory of Theoretical Physics. The problem concerned the determination of the minimum charge of an atomic nucleus, at which the atom loses stability. I do not remember the details any more, but I remember that this problem was causing me much torment with the formulation of complicated equations and the search for admissible approximations and suitable solutions. I do not remember either how Vitaliĭ Pashkevich and I found ourselves in Fedor L'vovich's study or why we turned precisely to him, but I remember very well how we explained our results to him by means of equations, and how he suddenly understood everything all at once and explained to us himself what we had done. The result was not very interesting, but after his explanation it was even obvious. It became clear that there was no point in letting loose such powerful mathematical machinery, and I obviously looked depressed and disheartened, because Fedor L'vovich suddenly said that we could publish it all anyway. I replied that I wasn't worried about it, and it seems that I gained his favor.

I loved to go to the seminars on neutron physics; I would often not understand anything, but I would always wait until the end, because Fedor L'vovich would always quickly explain the basic results in an accessible form. I would feel enriched.

One day, Fedor L'vovich even gave me a task. He sat me down in a room, put Landau's *Quantum Mechanics* in front of me and asked me to prove one of the claims made by him (Shapiro) in connection with the results of the experiment on the polarization of neutrons during transmission through a polarized target; and then he left the room. I do not remember the task now, but I remember that after about an hour or two I had become convinced of the improbability of Fedor L'vovich's assertion and was able to prove this to him.

This won his approval, and, when my time as a visiting student at the Laboratory of Theoretical Physics was over, he suggested that I transfer to his laboratory. It was only later that I realized the extent of my idiocy, but, in response to his offer, I answered that I would like to stay on at the Laboratory of Theoretical Physics and simultaneously study neutron physics. It seemed to me then that it was extremely prestigious to be a researcher at the Laboratory of Theoretical Physics and to investigate elementary particles and field theory, and I was very keen not to lose that feeling of being one of the elite.

Fedor L'vovich tried to talk Blokhintsev round. I did not have a very good relationship with him, but, having said that I was not very bright, he still agreed that I could stay on for another year. This year was enough to make me realize the extent of my stupidity. It is true that my research into neutron physics was becoming more and more focused—I was starting the calculations for an experiment that I had proposed to determine the electron electric dipole moment—but my calculations were going so terribly slowly, as my qualification was so basic, that I, it appeared, had lost all my authority in the eyes of Fedor L'vovich. Therefore, I was awaiting his decision with great trepidation when I dared to tell him that my time as a visiting student was over and that I deeply regretted not having taken up his invitation straightaway. "Well, come to us then, Volodya," he said. That was to become the most important event in my life. I transferred to the Neutron Laboratory, and my relationship with Fedor L'vovich became so close that I felt like a court theoretician. I could always visit him at home, and we sometimes went to a café together or to the cinema at the House of Scientists. I could borrow money off him, and, one day, when I was due to pay him back, he said: "Keep it, Volodya. The distribution of income is so inadequate that it is not worth talking about." To this day, I am ashamed that, instead of pleasing him, I brought about unpleasantness by my arrogance and by refusing such indulgences. I grew up without a father in the terrifying Stalin era, and my acquaintance with Fedor L'vovich was a great piece of luck for me. The days I spent with him were some of the best in my life, and his death was a real loss.

On the one hand, it was wonderful to feel like a court theoretician, but, on the other hand, I became so dependent on his attention and approval (without realizing it) that I often lost my confidence if I could not obtain the results that he needed.

2. THE BEGINNING OF THE EXPERIMENTS WITH ULTRACOLD NEUTRONS

Now is the time to come to the story of the beginning of experiments with ultracold neutrons.1) I did not take part in their discovery myself; that honor belongs to Shapiro, and also to V. I. Lushchikov, Yu. N. Pokotilovskiĭ, and A. V. Strelkov.[1]

2.1. Neutrons between crystals

Even before the experiment, the success of which seemed rather doubtful because of the expected low number of ultracold neutrons,2) Fedor L'vovich gave me the task of considering how long it was possible to confine a thermal neutron3) between ideal crystals.4)

It was proposed to set up two single crystals opposite each other or four single crystals in the corners of a right-angled region, so that a neutron, repeatedly undergoing Bragg reflection, would pass from one crystal to the other, winding a long trajectory inside the limited space of the region. Fedor L'vovich wanted me to solve this question in time for the jubilee conference for the tenth anniversary of the Pulsed Fast Reactor (IBR).

I occupied myself with this problem, and after long reflection and calculations, I only achieved a result of which I was convinced when the conference was already under way. Fedor L'vovich had gathered together a small collective of physicists in the organizing committee, among whom I remember Yu. G. Abov. Fedor L'vovich asked me to give a talk. I was a little embarrassed, and I said that I didn't know how to begin. "Begin with the end," advised Fedor L'vovich, and that helped me a great deal to present the rather pessimistic result in a short and, as it seemed to me, clear way. The essence of the result lay in the fact that the beam expands linearly with time at right angles to the plane of the trajectory wound between the crystals. In order to decrease this expansion, it is necessary to collimate the beam strongly. But then the number of neutrons in it falls catastrophically to a level which is equivalent to the number of ultracold neutrons.

Today, I see that it would have been easy to reduce the loss due to the expansion if bent focusing crystals had been used, but at that time the question of reflection from such crystals had not been discussed in the literature, and this idea did not occur to me.

Fedor L'vovich decided not to use such a system of neutron confinement and returned to ultracold neutrons. It has to be said that, after 22 years, this idea has nevertheless been realized.[3,4]

The arrangement of the experiment is shown in Fig. 1. To combat the expansion, the neutron beam is confined by the walls of a glass neutron guide. But in order for the glass neutron guide to reflect the neutrons completely, their speed at right angles to the walls must be less than the limiting

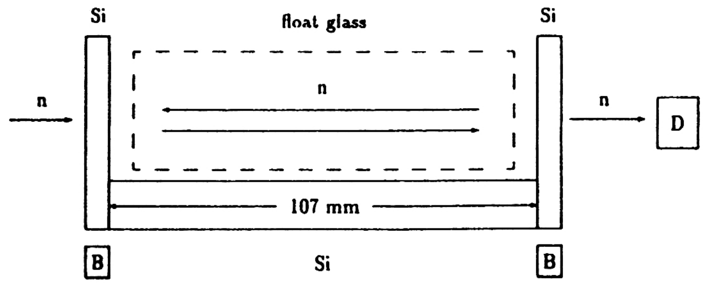

FIG. 1. Neutrons with a speed of 650.8 m/s were passed between two Si crystalline plates, placed at a distance of 107 mm from each other, which, together with the base between them, were cut out from a single monolith. To prevent the expanding beam from going beyond the limits of the system (the end crystals measured 52×30×3.9 mm), a portion of neutron guide with perfectly smooth glass walls was placed between the crystals. The neutrons were introduced into the system and then extracted from it by means of a short (1.2 ms) switching on of a magnetic field of 1.25 T near one of the crystals. The experiments were carried out[3,4] on a powerful pulsed proton source of neutrons at the Rutherford–Appleton Laboratory in England. The bursts from the source lasted 120 μs. Neutrons with the above velocity formed a little cloud of diameter 10 cm, and their time of flight between the crystals was 1.7 ms. In each filling, approximately 0.5 neutrons were accumulated between the crystals. The total number of neutrons counted after 12 reflections from the crystals (six flights there and back, exposure time $t_{\rm exp}$=20.2 ms) was 438 neutrons for 1000 fillings; after 96 reflections ($t_{\rm exp}$=161.9 ms), there were 154 neutrons; and after 156 reflections ($t_{\rm exp}$=263.1 ms), there were approximately 80 neutrons. The mean coefficient of reflection from the single crystal was 0.9978.

velocity of the walls.5) These conditions determine the total fraction Φ of the neutron flux that can be confined in this way. If the primary spectrum is Maxwellian, then the fraction of confined neutrons differs little from the fraction of ultracold neutrons in this spectrum.

In fact, the spectral density of the flux of neutrons that leave the surface of the moderator in the direction, for example, of the z axis can be expressed by the Maxwellian expression

$$d\Phi = 2v_z d^3v\,\frac{\Phi_0}{\pi v_T^4}\exp(-v^2/v_T^2)$$
$$= dv_z^2 d^2v_\perp \rho\,\exp(-v^2/v_T^2), \tag{1}$$

where Φ_0 is the total density of the thermal neutron flux, ρ is the differential flux density, $\rho=\Phi_0/(\pi v_T^4)$, which is constant in the complete velocity interval, $v_T = \sqrt{2mk_BT}$ is the thermal velocity of the neutrons at the temperature T, v_z is the velocity component along the chosen z axis, and $v_\perp$ are the velocity components at right angles to the z axis. The differential $dv_z^2 d^2v_\perp$ determines the interval of velocities of the confined neutrons. For ultracold neutrons, for which $v<v_l \ll v_T$, this interval is equal to v_l^4, and the flux density of the confined neutrons is $\int d\Phi = \rho v_l^4$.

In the experiment,[3,4] the interval dv_z^2 was determined by the width of the Darwin interval6) and was $2v_l^2$. Because the neutrons are confined at right angles to the crystals on account of the total reflection from the walls of the neutron guide, $d^2v_\perp$ can be set equal to v_l^2.

In this way, the number of neutrons confined on account of the Bragg reflection between the crystals can exceed the fraction of ultracold neutrons by an amount determined by the factor

$$2\exp(-v_B^2/v_T^2)<2$$

and for experiments to find an electric dipole moment of the neutron this gain by no means compensates the loss associated with the confinement time. This shows the correctness of the conclusions that I came to at that time. It is true that the experiment is very beautiful in itself, and it opens up many opportunities for fundamental research.[4]

An aside about mechanical generators of ultracold neutrons

The previous arguments concerning the spectral volume of the neutrons confined by the crystals also apply to mechanical generators of ultracold neutrons. In mechanical generators, a neutron beam with velocity v is directed at a mirror, which is moving away with a velocity u. The neutrons reflected by the mirror have a velocity $v'=v-2u$. If $|v'|<v_l$, the reflected neutrons are ultracold. For a long time, it was generally accepted that considerably more ultracold neutrons could be obtained in this way than in a Maxwellian spectrum. According to the argument, the neutron flux is proportional to $v\Delta v$, and that is why, for a fixed interval of reflection Δv, the flux is greater, the greater is v. Since no neutrons are lost in the case of specular reflection, all neutrons from a faster flux are changed into ultracold neutrons. As a result, the flux of the ultracold neutrons[7)] is apparently greater by a factor v/v_l than in the case of direct extraction of ultracold neutrons from a Maxwellian spectrum.

In fact, there is no gain because it is not a fixed velocity interval Δv that is reflected but a fixed energy interval,

$$\Delta E \propto \Delta v^2 = 2v\Delta v = v_l^2,$$

and the greater the velocity v, the smaller the interval $\Delta v = v_l^2/2v$.

Of course, this does not mean that mechanical generators are useless. They can possess technological advantages in comparison to converters[8)] if the experimentalist only has a given extracted beam at his disposal, or if the losses during the transportation of the ultracold neutrons from the converter along the long neutron guide are too great. Incidentally, one of the most intensive sources of ultracold neutrons at present is precisely the mechanical generator set up at Grenoble, which is known as the Steyerl turbine.[7]

Magnetic barriers

The system of neutron input and extraction in the experiments of Refs. 3 and 4 is also interesting. It works in the following way. Since the neutrons have a magnetic moment μ, they interact with the magnetic field B: $U=\pm\mu B$, as a result of which the neutrons with one spin projection are accelerated when they enter the magnetic field, while those with the other projection are decelerated and lose the ability to be totally reflected by the crystal because their velocity exceeds the limits of the Darwin interval $(v_B, v_B+v_l^2/v_B)$.

This method was suggested earlier for the pulsed accumulation of ultracold neutrons,[8] for example, using a beryllium converter. If a magnetic-field pulse is applied to the beryllium converter during the time of the burst from the reactor, then the total energy of the interaction in the converter is reduced very considerably for one of the spin directions (like the water level in a lock), and the neutrons are not accelerated as they come out of the converter. After the pulse, the magnetic field is switched off, and the Be potential barrier is restored, preventing a leak of ultracold neutrons back through the converter. The difficulty lies in the fact that, for ultracold neutrons, the field must be completely concentrated entirely within the beryllium (just as a change in water level in a lock can only take place between the gates). In the experiment of Ref. 4, this was completely unnecessary.

2.2. The first experiment with ultracold neutrons

The actual discovery of ultracold neutrons (it was so prestigious for us to use the word *discovery*, instead of the word *observation*) could best be described by A. V. Strelkov, who worked directly on this project and can remember literally everything. I only know from what he has said that, at first, an attempt was made to detect ultracold neutrons directly in the reactor hall. The idea was to observe neutrons with a certain time delay after the burst of the reactor. However, the background in the reactor hall was so great that it was completely impossible to separate the signal coming directly from the ultracold neutron. Therefore, it was decided to construct a long bent copper neutron guide (a pipe 10.5 m long and 96 mm in diameter), along which the ultracold neutrons were taken from the moderator to the experiment hall, filtered from the direct beam of fast neutrons and gamma rays, and detected by two scintillation detectors, alternately covered by a reflecting copper screen.[1] The mean counting rate[9)] of ultracold neutrons in the first experiment, in which the reactor gave one pulse every 5 s with an average power of 6 kW, was just 1 neutron in 200 s, but the background was still lower, 0.001 neutrons/s, and the intensity was sufficient to obtain a picture of the properties of ultracold neutrons and to conduct various experiments with them, for example, experiments to study the transmission of the neutron guide when it was filled with helium. But more about that later.

2.3. The dramatic moment

It is true that the first attempt to observe ultracold neutrons was unsuccessful for a purely technical reason. A good vacuum just could not be created in the neutron guide, although it was hermetically sealed at both ends. In a poor vacuum, the ultracold neutrons heat up through collision with the gas molecules and do not reach the detectors. The question arose: Why could the gas not be evacuated with a pump? There could be two reasons for this: The first was very simple—a leak through which the air from the atmosphere got into the neutron guide. The second reason was more serious and was associated with a possible radiation-induced decomposition of the actual source of the ultracold neutrons. The fact is that ultracold neutrons could not penetrate the tube from the outside for the very reason that they could not get out of it; therefore, it was necessary to put into the neutron guide an additional substance in which faster neutrons, which could freely penetrate the walls, were scattered inelastically, lost energy, and were transformed into ultracold neutrons. Such a substance is a source of ultracold neutrons and is called a converter.

In the first experiment, the role of the converter was played by a thick[10)] piece of polyethylene, which was situated at the end of the neutron guide, positioned closer to the reactor. The suspicion arose that the radiation from the reactor was knocking protons out of the polyethylene. In this case, hydrogen would be accumulating inside the neutron guide, and it would have been impossible in principle to achieve a vacuum without changing the construction of the converter.

Events developed dramatically. The overwhelming desire to conduct the experiment hit a serious obstacle. Moreover, the previously planned time for the shutdown of the reactor, in order to reconstruct it, had arrived. The reactor was already practically shut down, and Fedor L'vovich, as deputy director, had to make incredible efforts to put off the start of reconstruction. At the directors' meeting, the director of the Laboratory, I. M. Frank, raised doubts about the expediency of holding up work for the sake of ultracold neutrons. His arguments were incontrovertible: A blitzkrieg would not be successful, and it was necessary to study the reasons for failure in peaceful circumstances and carefully prepare for the following experiments, for which it might be necessary to change completely the construction of the converter if the reason for the poor vacuum turned out to be the decomposition of the polyethylene under the effects of radiation from the reactor.

It was only possible to overcome these doubts in one way—to become convinced and show everyone that the poor vacuum was linked not to decomposition of the converter but to penetration into the neutron guide of air from the atmosphere. Fedor L'vovich left the directors' meeting and asked Sasha Strelkov to complete the corresponding check in half an hour. To go into detail, it is necessary to describe how Sasha leapt onto his bicycle, grabbed an empty retort, got hold of sensitive scales, broke them (because the retort could not fit on them at all), rearranged the scales with the retort suspended on the outside, pumped the air out of the retort, and weighed it. He then removed from the neutron guide the gas, which could not be pumped out, and which had disturbed the experiment, and put it in the retort. Then he weighed the retort with the gas, made sure that its molecular weight exactly corresponded to air, raced back on his bicycle and slipped a note under the door of the director's study (because the secretary would not allow him to go in himself). Written on the note in capital letters was one word—AIR. I do not undertake to describe this in detail, because only those who were directly involved in all the events can do so. But importantly, as a result, the doubts were stilled, the experiments continued, the leak in the neutron guide was found and mended, and the ultracold neutrons were discovered anyway.

It was not fear of competition that lay behind the experiments being conducted quickly but the passion that usually grips the experimentalist—to see as quickly as possible what the outcome will be. Therefore, it was a surprise for Fedor L'vovich, when, literally two months after the publication in Pis'ma Zh. Éksp. Teor. Fiz., I brought him an article, published in Physics Letters, which announced[9] that A. Steyerl in Germany had also observed very slow neutrons, whose spectrum bordered on the region of ultracold neutrons. This news confirmed the opportuneness of the experiments and laid the foundations for close collaboration with Steyerl, who was to become one of the major researchers of ultracold neutrons.[10]

2.4. The first fiasco

Meanwhile, Fedor L'vovich was concentrating on the preparations for an experiment to store ultracold neutrons, and the main question here was: How could the neutron density be raised in the bottle (trap)? He had the idea of raising the density of the neutrons in the trap by means of a worm—a mechanism similar to the screw in a mincing machine. He asked me to think of the best way to achieve this. I willingly, but unsuccessfully, mulled this problem over, when one day, after a seminar at the Lebedev Physics Institute, he came to me and, grief-stricken, said: "Yes, Volodya, we really slipped up here." He had been shown at the seminar that such a mechanism could not work in principle, because raising the density of neutrons is equivalent to compression of an ideal gas, which means that it is heated up. We could not heat up the neutrons at all, because that would bring about a leak of ultracold neutrons from the vessel.[11)] I was, of course, very ashamed. I realized that the Green's functions and the problems of renormalization, which I constantly had to deal with, had completely atrophied my understanding of physics, and that it was necessary to fill the gap in my knowledge immediately. I blamed this on my feeling of dependence and decided to be more independent from then on. This merely led to one fiasco after another. One of them was to do with the experiments on transmission in neutron guides, which had started at the Kurchatov Institute.

2.5. The episode with roughness and the question of the lost rouble

When experiments were performed with different neutron guides, it was assumed that reflection from the walls takes place diffusely; therefore, the flux J along the neutron guide is described by the diffusion formula $J=-D\ \mathrm{grad}\ n$, where $D=2rv/3$ is the diffusion coefficient, r is the radius of the neutron guide, v is the neutron velocity, and $n=n(z)$ is the neutron density as a function of z, the coordinate along the axis of the neutron guide. Applying the equation of continuity

$$\mathrm{div}\ J=-n/\tau, \tag{2}$$

where $\tau=2r/\mu v$ is the lifetime of a neutron in the tube, and μ is the probability of loss when the neutron strikes the walls once, and substituting here the expression for J, we obtain the diffusion equation

$$d^2n/dz^2=n/L_D^2, \tag{3}$$

whose solution without allowance for boundary conditions has the form $n=n_0\exp(-z/L_D)$. It follows from this that the flux $J(L)$ at the exit from a neutron guide of length L is

$$J(L)=J(0)\exp(-L/L_D), \qquad (4)$$

where $L_D=\sqrt{D\tau}$, and n_0 and $J(0)$ are the neutron density and flux at the entrance opening.

The expressions are absolutely transparent and do not give cause for any doubts. Measuring the dependence of $J(L)$ on L, we find L_D, from which it is still impossible to determine the lifetime and diffusion coefficient separately.

To determine them separately, a method was used which was tested in the first experiment.[11] This method was to fill the neutron guide with the gas ^{4}He, which scatters the neutrons inelastically, and to measure the dependence of the counting rate of the ultracold neutrons on the pressure of the gas.

The lifetime of the neutrons in the tube was determined from this dependence in the following way: Because the neutron velocity $v_{\rm UCN}$ is significantly lower than the velocity of the atoms ($v_{\rm He}$), it was assumed that a neutron in the tube is motionless and is bombarded from all sides by helium atoms. The number of atoms interacting with the neutron per unit time is

$$\nu=N_{\rm He}v_{\rm He}\sigma(v_{\rm He})=p_{\rm He}v_{\rm He}\sigma(v_{\rm He})/k_BT,$$

where the subscript He relates to the helium atoms, $k_{\rm B}$ is Boltzmann's constant, and N is the number of atoms per unit volume with the temperature T and pressure p. Accordingly, the lifetime of a neutron before collision with a gas atom is

$$\tau_{\rm He}=1/\nu=k_BT/p_{\rm He}v_{\rm He}\sigma(v_{\rm He})=[250/p_{\rm He}]\ \text{s}, \qquad (5)$$

where the pressure $p_{\rm He}$ is measured in millimeters of mercury. The very first experiment[1] showed that on an increase of the pressure from 0 to 1.25 mm Hg the count of the detectors at the exit of the channel was reduced by a factor 2, leading to the conclusion that the lifetime of a neutron in the channel was 200 s.

The results of the following experiments were rather paradoxical: Neutron guides with approximately the same L_D gave different τ, and since $L_D = \sqrt{D\tau}$, the greater τ (that is, the smaller the loss), the smaller D, which means the greater the roughness[12)] must be. In connection with this, Fedor L'vovich gave me the task of determining whether the roughness can decrease the loss coefficient, i.e., decrease the probability of loss in one collision with the wall.

No matter how hard I tried, I could not get this result. However, if it is borne in mind that the question of scattering on roughness to this date generates several studies a year,[13)] that my acquaintance with Green's functions under the conditions of total reflection was not at all close, and that roughness can be of all different sizes, ruling out, at times, the application of perturbation theory, my conviction grew from day to day that it was impossible to obtain the desired result (provide an explanation of the result of this experiment). In the end, I waved good-bye to the possibility of obtaining the result by an exact calculation and descended into all kinds of speculations. (Do we not all do that in difficult cases?) I began to think up all kinds of reflection indicatrices for which the incident and reflected waves cancel each other on the roughness and, in this way, decrease the interaction of the neutrons with the matter and with it the losses.

A digression on detailed balance

This is where Fedor L'vovich taught me a good lesson. Having glanced at one of my indicatrices of reflection,[14)] Fedor L'vovich said that it was no good for anything. I was astounded: Surely I was free to choose whatever I wanted?[15)] If what I chose described the experiment well, then surely my courage and resourcefulness made me worthy to take up a position befitting me on a pedestal, alongside such titans as Planck and Einstein? When I said this, Fedor L'vovich smiled and explained that my indicatrix violated the principle of detailed balance, i.e., the number of neutrons reflected from the direction θ_0 to the direction θ, was not equal to the number reflected back again. I agreed that he was right, but I did not agree with the necessity for such equality. Fedor L'vovich explained that if the neutrons in my tube were distributed isotropically, then the reflection from the walls should not destroy the isotropy. I replied that I agreed, but that our distribution was nonisotropic. He said that I was right, but what would happen if it became isotropic? I was not beaten yet, and I said to him that in that case there would be no flux at all in the tube, because $J=-\text{grad}\, n$ would be equal to zero. He remarked that we were not talking about that, but about the indicatrix of reflection and that it should not make an isotropic distribution nonisotropic and decrease the entropy. I decided to fight to the last ditch, and told him that our distribution was nonisotropic! Fedor L'vovich said that we were constantly going round in circles and that we should think about it in our spare time.

I thought about it. Once again, like many times before, I was ashamed of my dimwittedness and accepted his simple method, which I was to use many times in the future. In fact, if the neutron guide is filled with an isotropic gas of ultracold neutrons with a density of n neutrons per unit volume, and if the neutrons experience only elastic reflection from the wall, then the flux of neutrons with velocity v flowing onto an element ds of the surface of the wall from the direction Ω_0 is equal to $dJ=dsnv\cos\theta_0 d\Omega_0$, where θ_0 is the angle of incidence. If the indicatrix of reflection from the roughness of the surface from the direction Ω_0 in the direction Ω is described by the function $W(\Omega_0, \Omega)$, then the complete flux reflected from the direction Ω_0 to the direction Ω is

$$d^2J(\Omega_0\to\Omega)=dsnv\cos\theta_0 d\Omega_0 W(\Omega_0,\Omega)d\Omega.$$

The condition of detailed balance states that

$$d^2J(\Omega_0\to\Omega)=d^2J(\Omega\to\Omega_0)$$

or

$$\cos\theta_0 d\Omega_0 W(\Omega_0,\Omega)d\Omega=\cos\theta d\Omega W(\Omega,\Omega_0)d\Omega_0,$$

from which it follows that

$$W(\Omega,\Omega_0)=\frac{S(\Omega,\Omega_0)}{\cos\theta},$$

where S is a symmetric function of its argument.

It is interesting to note that symmetry, in general, can be hidden. An example is $S(\Omega,\Omega_0)=|f(\theta)|^2|f(\theta_0)|^2$. This function is clearly symmetric. Now we take $f(\theta)$

$= \exp(\sqrt{\theta-a})$, where a is some parameter. When $\theta<a$, we have $|f|=1$, and when $\theta_0<a<\theta$ we obtain the apparently asymmetric expression

$$S(x,x_0)=\exp(2\sqrt{x-a}).$$

The solution to the problem

In the end, I became convinced that an increase in the roughness would never decrease the loss,[16] and it was necessary to change the way the experiment was conducted.

In fact, we were actually interested in the lifetime of a neutron in the neutron guide until its destruction on the walls, and not in the time during which it was subject to the effect of the helium atoms. The time τ_{He} given by (5) characterizes the total time of interaction of the ultracold neutrons with the helium atoms, i.e., not only the lifetime until destruction on the walls, τ, but also the travel time in the neutron guide.

If τ_{He} increases, i.e., the flux at the end of the neutron guide falls by a factor 2 at a lower He pressure, then that can only mean that the neutron is in the neutron guide for a longer time, for example, as a result of its extension. It by no means follows from this that the loss at the walls decreases. Thus, we are concerned with a situation like the one in the famous riddle:

Three travellers paid ten roubles each to stay at a hotel, but when they had left the owner saw that they had only needed to pay 25 roubles. He sent a boy after them to give them back five roubles. Each of them took back a rouble, and gave the remaining two roubles to the boy. As a result, they paid in all 27 roubles and gave two to the boy. Where is the other rouble? The rouble has obviously disappeared, but what type of rouble was it? It was exactly this type of situation that arose as well concerning the determination of (5).

The correct analysis is to replace $1/\tau$ in Eq. (2) by $1/\tau+1/\tau_{\text{He}}$. Accordingly, L_D in Eq. (3) and the solution (4) is

$$L_D(p)=\sqrt{D\frac{\tau\tau_{\text{He}}}{\tau+\tau_{\text{He}}}}=L_D(0)\sqrt{\frac{\tau_{\text{He}}}{\tau+\tau_{\text{He}}}},$$

where $L_D(0) = \sqrt{D\tau}$ is the diffusion length in the absence of helium. From these expressions, it immediately follows that a change in the pressure of the helium in the neutron guide changes the diffusion length itself, and if at some pressure p the count at the exit of the neutron guide is reduced by a factor e, then this means that $L/L_D(p)=L/L_D(0)+1$, i.e.,

$$\frac{L}{L_D(0)}\left(\sqrt{\frac{\tau+\tau_{\text{He}}}{\tau_{\text{He}}}}-1\right)=1. \tag{6}$$

Equation (6) is easy to solve, and we obtain

$$\tau=\tau_{\text{He}}\left[\left(\frac{L_D(0)}{L}+1\right)^2-1\right]=\tau_{\text{He}}\left(\frac{L_D^2(0)}{L^2}+2\frac{L_D(0)}{L}\right). \tag{7}$$

Thus, knowing $L_D(0)$ and τ_{He}, we can easily find τ and then D. After this, the time during which a neutron is in the neutron guide can also be found. For this, it is necessary to use the fact that, according to the laws of random walks, a neutron travels in a time T a distance s determined by the relation $s^2=2DT$. In particular, the time that the neutron needs to travel from the start of the neutron guide to its end ($s=L$) is $T=L^2/2D$. Using this relation, we can rewrite Eq. (7) in the form

$$\tau_{\text{He}}=\frac{2T}{1+2\sqrt{2\tau/T}}. \tag{8}$$

This equation shows clearly how τ_{He}, τ, and T are related to each other.

Thus, although τ can be determined from τ_{He}, the connection is nevertheless not completely straightforward. In fact, if we substitute in (7) the expression for $L_D(0)$, we obtain

$$\tau=\tau_{\text{He}}\frac{4D\tau_{\text{He}}L^2}{(L^2-D\tau_{\text{He}})^2}. \tag{9}$$

However, this is not the whole story. For the transmission in the neutron guide, we used the very simple expression (4), which, in general, is insufficient, for it does not take into account the boundary conditions at the entrance and exit openings. If we assume that none of the neutrons that escape from the neutron guide can return back into it, then the transmission of the neutron guide $T(L)=J(L)/J(0)$ and its reflection (defined as $R(L)=J_L(0)/J(0)$, where $J_L(0)$ is the flux of neutrons escaping through the entrance opening of the neutron guide) are equal to[17]

$$T(L)=e\frac{1-r^2}{1-r^2e^2},\quad R(L)=r\frac{1-e^2}{1-r^2e^2}, \tag{10}$$

where

$$e\equiv\exp(-L/L_D),\quad r=\frac{1-q}{1+q},\quad q=2D/vL_D \tag{11}$$

is the reflection from the entrance opening of a semi-infinite neutron guide.

Taking into account that the helium pressure occurs in L_D, we see that the relationship between τ and τ_{He} is even more complicated than what follows from (9). However, it is fully amenable to analysis with the help of the simplest computer facilities.

Using the given expressions, we can establish whether the flow of the gas of the ultracold neutrons is described by a constant diffusion coefficient D, or whether D depends on the length of the neutron guide. But if it becomes clear that D changes when L changes, then the question arises of the processes that regulate the flow of the rarefied neutron gas. We will go into this a little later.

However, that is still not the whole story. The helium curves can also give information about the time that a neutron spends in the neutron guide even when it is impossible to apply the simplest expressions (8), and in order to extract this information it is necessary to measure the derivative of the transmission $dT(L)/dp_{\text{He}}$ when $p_{\text{He}}\to 0$. In this connection, it will be useful to make a small digression into modern studies on fundamental physics, in which the same theme of the losses described by the expression (5) is continued.

A modest proposal concerning tunneling times

That is precisely the title of Ref. 14, the content of which is related to our theme. In that paper, a prescription is suggested for determination of the time that a quantum particle spends in the region of a scattering potential. In general, there are many such prescriptions (see, for example, the review of Ref. 15), but we will consider only one—the one that is referred to in Ref. 14—so that we do not get confused.

Thus, we imagine that we have a right-angled purely real potential step of height U (for example, an infinitely thick layer of a nonabsorbing monoatomic[18] substance with a perfectly ordered arrangement of atoms[19] and at zero temperature,[20] and that we measure the coefficient of reflection $R=|r|^2$ of ultracold neutrons.[21] How can we find out how long a particle spends inside the potential?

The following device is suggested: We add to the potential a small imaginary part

$$-iW \ll U.$$

For example, this could be a uniform solution of absorbing atoms with a low concentration (to be precise, like helium in the neutron guide)

$$W=\frac{\hbar}{2} N_a v \sigma_a(v)=\frac{\hbar}{2\tau_a},$$

where N_a is the concentration of the atoms, $\sigma_a(v)$ is the cross section for absorption of a neutron with velocity v, and τ_a is the characteristic time of absorption determined by the second equation [see (5)]: $\tau_a=1/N_a v \sigma_a(v)$.

We consider total reflection of ultracold neutrons from the infinitely wide potential step. It can be expected beforehand that the time that a neutron spends inside the step is characterized by a distribution, and not by one single time. We denote the density of the distribution with respect to the times that the neutron spends inside the step by $f(\tau)$; then in the case of total reflection

$$\int_0^\infty f(\tau)d\tau=1.$$

When absorbing atoms that do not influence the law of reflection but absorb neutrons with a characteristic time τ_a are added, the number of reflected neutrons is

$$R=\int_0^\infty e^{-\tau/\tau_a} f(\tau)d\tau<1. \tag{12}$$

From this expression, it is easy to find the mean value $\langle\tau\rangle$:

$$\langle\tau\rangle=\int_0^\infty \tau f(\tau)d\tau=\lim_{\tau_a\to\infty}\tau_a^2\frac{d}{d\tau_a}\int_0^\infty e^{-\tau/\tau_a}f(\tau)d\tau.$$

Since the final integral is related to the coefficient of reflection,

$$\langle\tau\rangle=\lim_{\tau_a\to\infty}\tau_a^2\frac{d}{d\tau_a}R=\lim_{W\to 0}\frac{\hbar}{2}\frac{d}{dW}R. \tag{13}$$

It is precisely this time which is defined in Ref. 14 as the time that the neutron spends inside the potential.[22]

To get a feel for the physical meaning of the result, it is useful to look at a similar case in diffusion. The analogy with the reflection of ultracold neutrons will be almost complete if one considers a semi-infinite neutron guide with nonabsorbing walls, and then, in order to determine the time during which a neutron is present, helium is put into the neutron guide.

The limit of $R(L)$ in (10) as $L\to\infty$ is $R=r(L_D)$, where the dependence on L_D is indicated explicitly. In the absence of helium, the diffusion length is $L_D=\infty$, and $r(L_D)=1$.

For a low helium pressure, we use the first equation in (13):

$$\langle\tau\rangle=\lim_{\tau_{\mathrm{He}}\to\infty}\tau_{\mathrm{He}}^2\frac{d}{d\tau_{\mathrm{He}}}r=\lim_{\tau_{\mathrm{He}}\to\infty}\tau_{\mathrm{He}}^2\frac{dL_D}{d\tau_{\mathrm{He}}}\frac{dq}{dL_D}\frac{d}{dq}r\propto\frac{\tau_{\mathrm{He}}^2}{\tau_{\mathrm{He}}^{3/2}}\to\infty. \tag{14}$$

Thus, we have obtained a completely natural result—the time that the neutron spends in the infinitely long neutron guide until it escapes is equal to infinity.

So far, the time during which the neutron remains in the potential has only been considered for semi-infinite systems, but the same arguments can be made for finite neutron guides and for finite potentials without restriction to below-barrier energies.

Such rather basic problems from the study of ultracold neutrons lead to interesting results in the field of fundamental physics. Now we will pass to another episode, concerning roughness, which was also linked to great poetry.

Another episode concerning roughness

Meanwhile, the question of roughness acquired a new complexion. For quite a long time, Fedor L'vovich and I were convinced of the existence of diffusion propagation of a neutron through a neutron guide. But in 1971, at the First School of Neutron Physics, a discussion arose in which Jacrot convinced us that this was not so. The concept of diffusion propagation was undermined by results from the dynamics of rarefied gases. It was known from vacuum physics that the flow of molecules along tubes is accompanied by their almost completely diffuse reflection from the walls. However, physicists who had already worked with neutron guides for thermal neutrons knew well that there is a high probability for neutrons to be reflected specularly from a surface. It was necessary to learn how to calculate the coefficient of diffusion D for the most varied indicatrices of reflection from the walls. For this, one can consider an infinitely long neutron guide, select in one's mind a neutron at an arbitrary point a, and follow the time dependence of the square of its separation $\langle(z-a)^2\rangle$ from this point in a random walk. At large times, this dependence must become linear: $\langle(z-a)^2\rangle=At$, and, equating it to $2Dt$, we readily obtain the diffusion coefficient $D=A/2$.

If in each collision with the wall the reflection is completely diffuse, then $D=2rv/3$, but if diffuse reflection occurs only with probability $g<1$, while pure specular reflection occurs with probability $1-g$, with g independent of the angle of incidence, then the diffusion coefficient becomes $D=(2rv/3)(2-g)/g$, i.e., with decreasing g it increases, as one would expect, since, using specular reflection, the particle can travel further from the point a during a time t.

However, such a law of reflection is in general unrealistic. In practice, everyone knows that if one looks at a surface, then it appears to be a better mirror, the closer one looks at a glancing angle. This means that the coefficient g must be assumed to depend on the angle. In fact, what is wrong with this? If a method of calculation is known, then, if you please, we can feed any reflection law through the mathematical formalism and obtain the diffusion coefficient. However, I did not obtain anything.

It was Friday evening. The following morning, Fedor L'vovich traveled to Moscow, and, since at that time I also regularly went to Moscow for weekends, he usually gave me a lift. During the complete journey to Moscow, I discussed with him the most varied subjects, which concerned not only ultracold neutrons. However, on this occasion he expected from me a result, and this I did not at all have to hand. I was angry with myself, could not sleep, and work also went terribly badly. I gave up and went out onto the street; it was summer, and I stormed along just in order to get rid of my anger; suddenly I understood everything. A result could not be obtained at all. The diffusion coefficient must be infinite. The reason is as follows: If it is reflected even once in a direction that makes a small angle with the axis of the neutron guide, the neutron will subsequently move between the next two collisions with the wall over a huge distance, comparable with the total length of the neutron guide. With overwhelming probability, it will be reflected purely specularly. In no way can such propagation be called a random walk, and therefore it cannot be described by diffusion equations.

I could no longer go to sleep. It was not only on account of the delight that captures one after such illumination and for the sake of which we all study science, but also because tomorrow I would have something to share with Fedor L'vovich.

Of course, we are not afraid of infinities; they can always be truncated—this is what the majority of field theoreticians do. I had also some experience in this matter. Therefore, I finally finished the problem. The diffusion coefficient acquired a very different form, and after my cutoff (which itself depended on the length L) the diffusion coefficient also had to depend on L, a fact that should be reflected, for example, in the value of τ extracted from the helium curves for different lengths in accordance with the expression (9). Subsequently, allowance was made for the fact that because of the presence of the gravitational force the neutron mean free path along the horizontal axis of a neutron guide of radius r cannot be greater than $L_g = v\sqrt{4r/g}$, where g is the acceleration of free fall; in fact, it was this quantity that was taken as the cutoff parameter. Here one could stop. Of course, it would also be interesting to consider the propagation in vertical or inclined neutron guides with allowance for gravity, and this was done, but this will be the subject of later discussion. The main thing was that the problem could be regarded as solved.

However, as things later turned out, I had turned away from the problem to no purpose. Subsequently, I realized that this down-to-earth problem of the propagation of a particle in a neutron guide is a close neighbor of high poetry—the problem of the foundation of statistics, the classical St. Petersburg[16] paradox in games of chance, dynamical chaos, self-similar processes, Levi statistics, and fractals. The lines of Edward Lear come naturally to mind:

Far and few, far and few,
Are the lands where the Jumblies live;
Their heads are green, and their hands are blue,
And they went to sea in a Sieve.

The only consolation is that this entire beautiful physics and mathematics is already before one's eyes and, as Edward Lear again said:

And they drank their health, and gave them a feast
Of dumplings made of beautiful yeast;
And every one said, 'If we only live,
We too will go to sea in a Sieve.'

Postscript to diffusion and neutron guides

At the present time, no experiments are being made on the transmission of neutron guides. In calculations, Monte Carlo methods are mainly used. The latest study devoted to this problem was made by Pokotilovskiĭ's group,[17] to which, with its references, we refer the interested reader.

It should be said that Monte Carlo calculations sometimes help one to understand the physics of processes. For example, it would seem to be obvious that in the case of isotropic reflection of neutrons from walls and for isotropic distribution of neutrons entering the neutron guide the angular distribution at the exit from the neutron guide should be isotropic. However, when Berceanu[18] obtained a result that revealed an angular distribution drawn out in the forward direction, the first impression was that one must look for a mistake in the program. However, it then became clear that this is how it must be. The point is that the neutrons that propagate at small angles to the axis are those that were reflected from the walls closer to the beginning of the neutron guide, and there the particle density is greater and the wall reflects (or, in other words, emits) more neutrons.

Having understood this, one could have predicted the results of the calculation. For example, if the indicatrix of reflection from the walls is such that a neutron incident on the wall at a glancing angle is reflected specularly with high probability, then the angular distribution will be even more elongated. The results of calculations confirmed this prediction.

A second surprise was the results of calculations in the case of completely specular reflection from the walls, which showed that the transmission of a neutron guide could be 100% even if it has bends. It had seemed earlier that any bend must decrease the transmission. In fact, the bends can be arranged in such a way that in the case of specular reflection a neutron can never reverse the direction of its motion,[17] and even a bend through 180° need not increase the resistance of the neutron guide.

3. THE PRESENT STATUS OF THE PHYSICS OF ULTRACOLD NEUTRONS

Because of lack of space, only a few aspects will be mentioned briefly in this section. A more detailed survey of the present status of the physics of ultracold neutrons will be given in Ref. 19.

3.1. The main problem of ultracold neutrons

We now note briefly the present status of the physics of ultracold neutrons. The main puzzle—the anomalously large neutron losses in bottles—is still unresolved. The problem arose at the very beginning of the experiments with ultracold neutrons, but it always appeared that the problem was due to the lack of experience of the experimentalists rather than a need to reexamine the concepts. Time passed, and the experience of the experimentalists and the reliability of the experiments increased, but the problem did not admit to solution.

The most important result is the one recently obtained by Serebrov's group,[20] in accordance with which the probability of loss in one collision for the bottles that are best in this respect is a quantity of order 3×10^{-5}, which, although small, is nevertheless greater by two orders of magnitude than the theoretical value.

The losses are due both to absorption of neutrons by nuclei and to inelastic scattering with heating of the neutrons (heated neutrons have an energy higher than U and escape freely through the walls of the bottle). However, the cross section σ_{ie} depends on the temperature and can be eliminated by cooling of the matter, and this can be tested experimentally.

The experiments of Ref. 20 indicate that the ratio $\sigma_l^{\mathrm{obs}}/\sigma_l^{\mathrm{th}}$ of the observed and theoretical cross sections now reaches a value of the order 100. At the same time, however, the part of the observed cross section that depends on the temperature, $\sigma_{ie}^{\mathrm{obs}}$, agrees well with the theoretical cross section $\sigma_{ie}^{\mathrm{th}}$ of inelastic scattering in both magnitude and the nature of the temperature dependence.

Attempts to solve the problem

The lack of success in the search for simple solutions forces us to seek the cause in fundamental notions.[21] On the one hand, this is always desirable, but, on the other, it is rather dangerous.[23)] Here we mention only one such attempt.

It should said[24)] that the first such excursion into the fundamental domain, in fact into the domain of reexamination of quantum mechanics, was made by Fedor L'vovich himself. He put forward the suggestion that the neutron is a wave packet in which some components have an energy greater than the barrier, so that by virtue of these components the neutron can pass through the walls with a definite probability. However, this proposal was radically refuted by one of the greatest authorities on quantum mechanics in our city, M. I. Podgoretskiĭ, who noted with perfect reason that quantum mechanics is a linear theory; therefore, in the first collision with the wall, the high-energy components will escape, while the low-energy components are reflected, and it is the latter that will then represent the wave function of the ultracold neutrons.

Knowing nothing about this but being comparatively young and absolutely ignorant, I also made such a proposal already at the First Neutron School in 1971. Indeed, my packet was not, in general, a solution of the homogeneous Schrödinger equation. This raised fierce opposition on the part of M. V. Kazarnovskiĭ and subsequently all but destroyed my candidate's dissertation.[25)] Later, through Steyerl, I found that de Broglie had used these packets.

The result is as follows. If the neutron wave function is represented in the form

$$\psi(s,\mathbf{v},\mathbf{r},t)=c\,\exp(i\mathbf{v}\mathbf{r}-i\omega t)\,\frac{\exp(-s|\mathbf{r}-\mathbf{v}t|)}{|\mathbf{r}-\mathbf{v}t|},\tag{15}$$

then the results of the experiment can be explained[21] if $s\approx5\times10^{-5}mv/\hbar$.

Now what can be the answer to Podgoretskiĭ's objection? The answer could be as follows: Quantum mechanics gives a prescription for how to calculate scattering of a particle by a potential but does not give any explanation of how the particle is in only one of the directions. Therefore, we may assume that the wave packet is an immanent property of the particle (just as the Coulomb field is a property of a charged particle), and the particle is scattered together with its packet. Then all the scattering probabilities are calculated as is assumed in quantum mechanics, but quantum mechanics cannot tell us how it is that the scattered particle is nevertheless there with its undeformed packet any more than quantum mechanics can tell us in which direction the particle will be scattered.

A neutron that has made an above-barrier entry into matter has no other channels for disappearing than absorption, inelastic scattering, and unhindered escape from the matter through the other interface. It is easy to estimate the cross section for loss of the neutron within the medium and to predict the experimental consequences, but we shall not do this here; rather, we refer the interested reader to Ref. 21.

3.2. The neutron lifetime

Three groups in the world are occupied with measuring the neutron lifetime in experiments in which ultracold neutrons are kept in solid-state traps. In the experiments of Ref. 22, the value $\tau_\beta=887.6\pm3$ s was obtained. The main uncertainty was associated with the need to take into account the effect of the gravitational field on the storage time.[23,24]

In Ref. 25, the result $\tau_\beta=888.4\pm2.9$ s was obtained. This result was refined in the detailed paper of Ref. 26 and is now $\tau_\beta=88.4\pm3.3$ s; the systematic error is of order 1 s, and the main uncertainty is due to the statistical error.

Finally, in Ref. 27 the result $\tau_\beta=882.56\pm2.7$ s was obtained. The reliability of this last result is in doubt on account of a variety of reasons that are indicated in Ref. 28. In particular, in Ref. 27 the sign of the correction for the escape of the ultracold neutrons from the slit during the storage time was incorrectly chosen. After correction, the result agrees with the result of Ref. 22 and agrees better with the currently adopted value $\tau_\beta=889.1\pm2.1$ s; however, the spread of the experimental data exceeds by almost two orders of magnitude the estimated systematic error, and therefore gives rise to doubt about the reliability of the result.

3.3. Electric dipole moment of the neutron

During the last five years, no particular progress has been made in this direction. As reviews on this question, we can recommend Ref. 29. Here, we only mention the results of recent experiments made at Grenoble and at Gatchina. With allowance for the earlier measurements, the latest results of the Grenoble group[30] can be given as

$$d_n=(-3.3\pm 4.3)\times 10^{-26}\ e\ \text{cm},$$

or, at the confidence level 90%,

$$d_n<12\times 10^{-26}\ e\ \text{cm}.$$

The result of the Gatchina group[31] is

$$d_n=(2.6\pm 4.0\pm 1.6)\times 10^{-26}\ e\ \text{cm},$$

or, at the same confidence level,

$$d_n<1.1\times 10^{-25}\ e\ \text{cm}.$$

A good review of the development of methods for searching for an electric dipole moment of the neutron is given in Ref. 29. Here we consider the possibilities of increasing the sensitivity of the searches for an electric dipole moment by three orders of magnitude by means of the generation and storage of ultracold neutrons in liquid helium with dissolved polarized ^{3}He. In this arrangement, ^{3}He plays the role of polarizer, polarization analyzer, magnetometer, and neutron detector. We refer the interested reader to this review for more detailed information. We merely point out that the reader will find there a clear exposition of issues such as the "dressing of a neutron" by means of an external alternating field, in the presence of which the magnetic moment of the particle is, as it were, effectively decreased.

3.4. Neutron–antineutron oscillations

As yet, no experiments have been made in this direction, but projects are being discussed quite intensively, and we refer the interested reader to Refs. 32–35.

3.5. Berry phase

In recent years, there has been a great deal of talk about the Berry phase. It has become fashionable and, from the point of view of obtaining a grant for fundamental research even helpful, to find the Berry phase in simple, long-known phenomena. An example of this is neutron physics. With regard to the interaction of the neutron with a magnetic field, everything has long been rather well known, and therefore the neutron is convenient for illustrating what the Berry phase is. We shall not do this here, but refer to the study of Ref. 36 of the Berry phase, the conclusion of which can be formulated as follows: The concept of the Berry phase gives nothing new as compared with what has long been known for neutrons.

3.6. Applied and academic investigations

Applied and academic investigations are combined here in a single subsection because in the field of ultracold neutrons it is sometimes difficult to draw a dividing line between them.

The studies that are *most nearly applied* are those of a group at the Moscow Institute of Nuclear Research, which publishes its results mainly in Kratk. Soobshch. Fiz. (Refs. 37–40). The studies are in the field of inhomogeneities in condensed media. Essentially, these studies are similar to small-angle scattering, but instead of measurement of the angular distributions of the scattered neutrons one measures, since the neutron wavelength is large, the total scattering as a function of the energy of the incident neutrons. At the same time, part of the neutron spectrum somewhat above the part that directly corresponds to ultracold neutrons is used. The nature of the specific investigations can be best judged from the titles of the corresponding publications, and for lack of space we refer the reader directly to the original sources.

In the investigation of surfaces, one studies the dependence of the reflection coefficient on the energy (all possible impurities and inhomogeneities modify the reflection coefficient most strongly just above the limiting energy) and the reflection indicatrix in the presence of roughness.[41]

One should probably regard as *academic* the studies devoted to superultracold neutrons, i.e., neutrons that form a two-dimensional quantum gas over a flat surface in a gravitational field or a one-dimensional gas in narrow channels.[42,43] The energy of these neutrons is quantized in the direction of the normal to the plane, and the ground level is 1.4×10^{-12} eV. Accordingly, the height to which such neutrons rise is about 10 μm, and the velocity is about 1 cm/s. If the motion along the plane is characterized by appreciably greater velocities, then as a result of scattering by roughness the neutron can acquire a high velocity and cease to be two-dimensional. If this is to be avoided, the neutron velocity in all directions should not significantly exceed a value of the order of 1 cm/s.

The importance of this work can be judged from the fact that it was published in Pis'ma Zh. Éksp. Teor. Fiz.,[42] which accepts only material requiring prompt publication. Speed was here indeed necessary, since because of the delay associated with publication in Yad. Fiz., the pair increased from 1–10 m (Ref. 42) to 6–20 km (Ref. 43).

One could also regard as *applied* the neutron microscope,[44–47] but as yet it is very far from the stage in which it could be used in practice. The calculation of its properties associated with magnification and aberrations is made on the basis of the ballistic, and not wave, principle. Here experiments are rare and mainly in the nature of demonstration. As is noted in Ref. 45, the resolution is 17 μm and more than three times greater than the calculated 5 μm. However, as the authors themselves say: "It would evidently be premature to draw any conclusions from the fact of discrepancy between the observed and the calculated resolution."

3.7. Optimistic prospects

The fate of all experiments with ultracold neutrons depends on the power of their source. The maximum density that it has hitherto proved possible to achieve has not exceeded 100 neutrons/cm^3 (see the reviews of Refs. 48 and 49), and it appears that a limit has been reached. Three approaches for raising the output of sources of ultracold neutrons can presently be identified. One of them is to use superfluid helium.[50–52] Calculations show that the intensity of ultracold-neutron production should be rather high. However, the experiments that have been performed[53] have not yet confirmed these predictions (in this connection, see the discussion in Refs. 54 and 55).

Another approach is to attempt to capture a cloud of ultracold neutrons formed around a moderator during a burst of a powerful pulsed reactor directly within a hermetically sealed container.[56,57] This means that the container is accelerated to a high velocity $v \gg v_l$ and directed onto the cloud of ultracold neutrons. Because of the high relative velocity, the cloud readily passes through the walls, and, when the cloud is entirely inside the container, the container is rapidly decelerated. As a result, the cloud of ultracold neutrons is in a trap. In order to release the neutrons from the trap, it is sufficient to accelerate the container abruptly, as a result of which the neutrons are, as it were, shaken out of it. It is expected that in the experiment the density of stored ultracold neutrons will reach 10^5 neutrons/cm^3.

Finally, the third apporach is associated with obtaining ultracold neutrons from a stationary[58] or pulsed[59] reactor from solid deuterium at a low temperature $\leqslant 10$ K. The hopes of obtaining here a high intensity of ultracold neutrons are based on earlier experiments at Gatchina, which showed that the rate of generation of ultracold neutrons in deuterium at 10 K begins to exceed the rate of generation in liquid hydrogen. The first such experiments showed that solid deuterium does indeed give a gain of the order of 1000. If it proves to be possible to build such sources of ultracold neutrons at powerful compact reactors like TRIGA, then experiments with ultracold neutrons will enter a qualitatively new phase.

The investigations whose results have been given in this paper were made possible by Grant J6P100 by the International Science Foundation and by the Government of Russia. I thank I. Carron for his interest and support.

[1)]For those who are not very well acquainted with them, we recall that neutrons are called ultracold if they have an energy of the order of 10^{-7} eV. They can be totally reflected from the majority of substances at all angles of incidence, and can thus be conserved in hermetically sealed containers.

[2)]In relation to this, it is useful to quote from the well-known book by I. I. Gurevich and A. V. Tarasov,[2] where it is literally stated that even if it were possible to separate the ultracold neutrons from the Maxwell spectrum "the intensities of the beams of such neutrons will be so small that it would hardly allow them to be used in experiments."

[3)]A neutron with energy $\approx 2.5 \times 10^{-2}$ eV.

[4)]This question interested him in relation to his intention of setting up an experiment to look for an electric dipole moment (EDM). If the neutron has an EDM **d**, then it should interact with an external electric field **E**: $U = \mathbf{dE}$, and the longer the time t during which the neutron is in the field, the smaller the value of $|\mathbf{d}|$ which can be discovered during one measurement cycle.

[5)]The limiting velocity v_l is defined as $v_l = \sqrt{2mU}$, where U is the potential of the walls, and m is the neutron mass. For glass, this is 4.26 m/s (Refs. 5 and 6).

[6)]The Bragg reflection is total in the velocity interval $v_B \leqslant v_\perp \leqslant v_B + \Delta$, where v_B is the Bragg velocity, and Δ determines the width of the interval of a total reflection and is called the Darwin interval, because it was first calculated by Darwin. For each substance, Δ is equal to v_l^2/v_B, where v_l is the limiting velocity for ultracold neutrons.

[7)]It is assumed that $\Delta v = v_l$.

[8)]Inside the sealed volume, which the ultracold neutrons cannot penetrate from the outside, an additional moderator, called a converter, is set up for the generation of ultracold neutrons. More details will be given on this later.

[9)]The difference between the counts of open and closed detectors between bursts of the reactor.

[10)]It became understood later that for the generation of ultracold neutrons thin layers of matter are sufficient.

[11)]Neutrons are confined in the vessel until their kinetic energy E exceeds the potential barrier created by the wall: $U \approx 10^{-7}$ eV.

[12)]More is said about the connection between roughness and the diffusion coefficient a little later.

[13)]An example of this is the Conference on Neutron Interaction with Surfaces, which took place at Dubna in 1993 [see Physica (Utrecht) B **188**, 1 (1994)], where two talks were given on this subject.

[14)]The indicatrix of reflection $W(\theta_0, \theta)$ specifies how many neutrons are reflected in the direction θ relative to the normal to the surface in the case of incidence on the surface at the angle θ_0.

[15)]An example of a careless attitude toward the principle of detailed balance is Ref. 12, which is criticized in Ref. 13.

[16)]It is only possible to decrease the loss in a special case, when nonabsorbing roughness is created on a strongly absorbing flat surface. Then scattering by the roughness decreases the interaction with the substrate and thus decreases the absorption, i.e., an effective screening of the surface by means of the roughness arises.

[17)]We here assume the expressions (10) without derivation (we note only that they have wide application in the most varied fields of physics), since their derivation will be given below in the investigation of the reasons for total reflection of ultracold neutrons from the walls.

[18)]To avoid elastic incoherent scattering.

[19)]To avoid diffusive elastic scattering.

[20)]To rule out inelastic scattering.

[21)]It is obvious that under these conditions $|R|^2 = 1$.

[22)]We note that although $|r|^2 = 1$ the derivative dR/dW in (13) is not zero, because when the coefficient of reflection leaves the real axis (Im $U = 0$) it decreases.

[23)]For example, try to obtain a grant for such investigations if you have no connections.

[24)]To admit the truth, I myself did not know this, but A. Strelkov says so, and he has perfect memory and is a respected person.

[25)]Here I must recall with gratitude I. M. Frank, who chaired the council and after the two-hour defense addressed encouraging words to me.

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