CONFERENCES AND SYMPOSIA

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Commemoration of the centenary of the birth of Academician I M Frank
(Scientific session of the Physical Sciences Division of the Russian Academy of Sciences, 22 October 2008)

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To commemorate the centenary of the birth of the Nobel Prize Laureate in Physics 1958 Academician I M Frank, a scientific session of the Physical Sciences Division of the Russian Academy of Sciences (RAS) took place on October 22, 2008 in the Conference Hall of the P N Lebedev Physical Institute. The following reports were presented at the session:

(1) **Mesyats G A** (P N Lebedev Physical Institute, RAS, Moscow) "Il'ya Mikhailovich Frank (opening address)";

(2) **Krokhin O N** (P N Lebedev Physical Institute, RAS, Moscow) "I M Frank and research in optics";

(3) **Bolotovskii B M** (P N Lebedev Physical Institute, RAS, Moscow) "I M Frank's papers on the radiation of sources moving in refractive media (the 'optics of moving sources')";

(4) **Sissakian A N, Itkis M G** (Joint Institute for Nuclear Research, Dubna, Moscow region) "I M Frank and the development of the Joint Institute for Nuclear Research";

(5) **Benetskii B A** (Institute for Nuclear Research, RAS, Moscow) "I M Frank: founder and leader of FIAN's Laboratory of Atomic Nucleus";

(6) **Frank A I** (Joint Institute for Nuclear Research, Dubna, Moscow region) "I M Frank and the optics of ultracold neutrons";

(7) **Aksenov V L** (Joint Institute for Nuclear Research, Dubna, Moscow region) "Pulsed nuclear reactors in neutron physics".

An abridge version of the opening address and reports 3–7 is given below.

Il'ya Mikhailovich Frank
(23.10.1908 – 22.06.1990)

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Il'ya Mikhailovich Frank
(opening address)

G A Mesyats

On October 23, 2008, Il'ya Mikhailovich Frank — an outstanding physicist, Full Member of the Academy, Nobel Prize Laureate — would have celebrated his 100th anniversary of the birth. Il'ya Mikhailovich was born in Saint Petersburg into a family of intelligentsia. His father, a talented mathematician and teacher of mathematics, greatly influenced the futures of his sons (Il'ya Mikhailovich's brother Gleb became a well-known specialist in biophysics). At the beginning of the 1920s, the Franks moved to the Crimea. Il'ya attended secondary school in Yalta, then attended lectures at the Crimea University in Simferopol', without enrolling as a student; his father was a professor there. Il'ya Mikhailovich worked in the physics laboratory and attended a mathematics hobby group. In 1926, he enrolled in the Physics and Mathematics Department of Moscow State University (MGU) and graduated from there

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in 1930, having majored in two subjects: physics (at the Chair of Theoretical Physics under L I Mandel'shtam) and mathematics. In his sophomore year he began working in S I Vavilov's laboratory; they published a joint paper on luminescence in 1931. In 1930–1934, he studied photochemical processes at the State Optical Institute in which S I Vavilov was deputy director for research; in 1932, Vavilov became head of the Physics Department of the Physicomathematical Institute. The Physics Department was the place where work had started on studying the properties of the newly discovered neutrons, luminescence of liquids under ionizing radiation, the coloring of crystals, the microstructure of liquids, electric breakdown in gases, and the catalysts of chemical reactions.

This was the period when, together with I M Frank, a number of brilliant scientists were working under S I Vavilov's guidance: G A Gamow, L V Mysovskii, N A Dobrotin, P A Cherenkov, L V Groshev, and some others. More laboratory equipment was acquired, various seminars opened up. The department grew familiar with new physics and was rapidly opening a new efficacious phase in its life. Even though S I Vavilov's specialty per se was physical optics, the range of his interests in science was much broader. At that particular moment, Vavilov's goal was to create a new 'polyphysics' institute that would combine the main avenues of research in the present-day physics, dictated by the logic of progress in science; each field was to be headed by a first-class specialist. S I Vavilov discussed the future structure of the Physical Institute with his colleagues. He clearly recognized the importance of the physics of the atomic nucleus that was just emerging then and understood the compelling need to support the 'new physics' born at the start of the 20th century — the theory of relativity and quantum mechanics. He also understood very clearly that theory is just as important for modern physics as experimentation is and that these two components of physics as a science are inseparably tied together.

The general meeting of the USSR Academy of Sciences on 28 April 1934 decided to split the Physicomathematical Institute in two: the Mathematical Institute, and the Physical Institute. Soon after, in summer 1934, the USSR Government decreed that both institutes and the Academy of Sciences itself should move to Moscow into the building on 3rd Miusskaya Street, already built in 1912; the money for the building was donations for the laboratory of Petr Nikolaevich Lebedev. This step completed a more than 200 years' evolution of a small department of the Kunstkamera, followed by the transformation (started by A N Krylov and accomplished by S I Vavilov) of the Physicomathematical Institute to the Physical Institute of the Academy of Sciences (FIAN in *Russ. abbr*., or the Lebedev Physical Institute). This event also symbolized the merger of the older Petersburg academic physics with the younger Moscow university physics. This is the right place to mention the friendship between B B Golitsyn and P N Lebedev, which began in their student days at Strasbourg University and continued until the death of P N Lebedev. The new Physical Institute thus combined the traditions of the Golitsyn and Lebedev scientific schools. The first head of the Physical Institute was, incidentally, a student of P P Lazarev, Academician S I Vavilov (Lazarev was an assistant professor and P N Lebedev's closest assistant).

When S I Vavilov looked for coworkers, he invariably tried to identify the most talented researchers and thus laid the foundation for the growth of strong scientific schools in the future. Academician A N Krylov is known to have quipped that Sergei Ivanovich tried to hire only people stronger than himself.

In fact, 1934 was the year when the new history of FIAN began. Soon to appear here were the Laboratory of Atomic Nucleus headed by D V Skobel'tsyn, whose staff included V I Veksler, S N Vernov, L V Groshev, N A Dobrotin, I M Frank, P A Cherenkov, and others; the Laboratory of the Physics of Oscillations headed by N D Papaleksi (A A Andronov, B A Vvedenskii, L I Mandel'shtam, G S Gorelik, S M Rytov, P A Ryazin, E Ya Shchegolev, and others); the Laboratory of Physical Optics led by G S Landsberg; the Laboratory of Luminescence headed by S I Vavilov (V V Antonov-Romanovskii, V L Levshin, M A Konstantinova, L A Tumerman, and others); the Laboratory of Spectral Analysis led by S L Mandel'shtam; the Laboratory of the Physics of Dielectrics under B M Vul; the Laboratory of Theoretical Physics headed by I E Tamm (D I Blokhintsev, V L Ginzburg, M A Markov, K V Nikol'skii, E L Feinberg, V A Fock, and others), and the Laboratory of Acoustics headed by A A Andreev (S N Rzhevkin, L D Rozenberg, Yu M Sukharevskii, and others). From 1934 till 1937 the Institute also included the Laboratory of Surface Phenomena headed by P A Rebinder. In the pre-WWII period, FIAN organized annually an expedition to Mount Elbrus to record cosmic rays and observe certain atmospheric optics phenomena. I M Frank went on two Elbrus expeditions, where he used the Wilson chamber to study cosmic rays.

I M Frank worked at FIAN from 1934 to 1970. In 1935 (at 26 years of age!), Il'ya Mikhailovich submitted and viva voce defended his DSc thesis. In 1940, he became a professor at Moscow State University, and between 1946 and 1956 headed the Laboratory of Radioactive Radiation at the Research Institute of Nuclear Physics at Moscow State University. In 1957, I M Frank became Director of the Laboratory of Neutron Physics at the Joint Institute for Nuclear Research (JINR) at Dubna, and in 1971 headed a laboratory at the Institute for Nuclear Research of the USSR Academy of Sciences. I M Frank's main publications were devoted to physical optics, neutron physics, and low-energy nuclear physics.

Vavilov insisted that, having transferred to FIAN, Frank should switch to nuclear physics. From 1937 to 1940 Frank (together with L V Groshev) published a series of papers concerning the creation of electron–positron pairs in a Wilson chamber filled with krypton and irradiated by gamma quanta.

At about this time, Pavel Cherenkov, one of Vavilov's postgraduates at the Lebedev Physical Institute, began studying blue-color glow (later named Cherenkov or Vavilov–Cherenkov radiation) which was caused by gamma rays in refracting media. Cherenkov was able to show that this radiation was not just another form of luminescence, but he was unable to explain it in theoretical terms. In 1937, I M Frank and I E Tamm succeeded in calculating the properties of an electron moving uniformly through a medium with a velocity exceeding the speed of light in this medium. They disclosed that energy must be emitted in this situation, with the angle at which the generated wave propagates expressed in a simple way in terms of the speed of the electron and the speed of light in a given medium and in a vacuum. One of the first results of the new theory was the explanation of the polarization of Cherenkov radiation. The theory proved to be so successful that Frank, Tamm, and

Cherenkov were able to check some of its predictions experimentally, such as the presence of energy threshold for the incident gamma radiation, the dependence of this threshold on the refractive index of the medium, and the characteristic geometric shape of the emerging radiation (a hollow cone with the axis along the direction of the incident radiation).

In 1946, I M Frank was elected Corresponding Member of the USSR Academy of Sciences, and the team-work by Tamm, Frank, Cherenkov, and Vavilov was awarded the USSR State Prize. In 1958, Cherenkov, Frank, and Tamm won the Nobel Prize in Physics "for the discovery and the interpretation of the Cherenkov effect." In his Nobel lecture Frank said that the "Cherenkov effect had found numerous applications in the physics of high-energy particles. A connection between this phenomenon and many other problems has also been found, as for example, the physics of plasma, astrophysics, the problem of radio wave generation, the problem of acceleration of particles, etc." The discovery of Vavilov–Cherenkov radiation resulted in the development of a new method of detection and measurement of the velocity of high-energy nuclear particles. This method plays an enormously important role in current experimental nuclear physics.

This particular work started the whole series of I M Frank's theoretical publications treating light sources moving in a refracting medium. He developed the theory of the so-called complex Doppler effect — that is, the Doppler effect in a refracting medium, and of the anomalous Doppler effect for a source moving with superluminal speed (in 1947, together with V L Ginzburg). In 1946, Frank and Ginzburg predicted the transition radiation emitted when a moving charge crosses a planar interface between two media. This type of radiation is emitted due to the restructuring of the electric field of a uniformly moving particle when it crosses the interface between two media possessing different optical properties. Even though this theory was later experimentally verified, some of its important implications continued to resist laboratory tests for more than a decade.

In the mid-1940s, I M Frank conducted theoretical and experimental studies of neutron multiplication in heterogeneous uranium–graphite systems. This work helped in understanding the laws of neutron transfer in nuclear reactors; for example, it was possible to determine with high accuracy the critical dimensions and the neutron multiplication factor in an infinitely large system and to study how these parameters depend on the properties of the uranium–graphite lattice. Il'ya Mikhailovich suggested and developed a pulse technique for studying the diffusion of thermal neutrons, and discovered in 1954 how the mean diffusion coefficient depends on the geometric parameter (the diffusion cooling effect). He also developed a new method of neutron spectrometry — by the time of neutron slowing-down in lead.

I M Frank supervised a series of experimental studies of reactions involving light nuclei in which neutrons are emitted, the interaction between fast neutrons and the nuclei of tritium, lithium, and uranium, and the process of fission in the nucleus; he launched studies of short-lived quasistationary states and the fission of nuclei bombarded by mesons and high-energy particles. In 1957, I M Frank supervised the establishment of the Laboratory of Neutron Physics at JINR. Here he was one of the leaders of the program of developing fast periodic pulse reactors for spectroscopic neutron studies: IBR-1 (1960) and IBR-2 (1981). From 1970, Frank worked exclusively for JINR.

In 1954 and 1971, I M Frank's work was rewarded by USSR State Prizes, and in 1968 he was elected Full Member of the USSR Academy of Sciences.

I M Frank was convinced that a scientist absolutely must be widely educated and a person of the intelligentsia. His scientific papers are perfectly designed and written in clear style. Colleagues always appreciated his exceptional intuition in the arrangement of experiments and in searching for solutions to theoretical problems. All his life I M Frank deeply respected his beloved teacher — S I Vavilov. He prepared a volume of collected reminiscences about Sergei Ivanovich, which went through two editions. Il'ya Mikhailovich died (in Moscow on 22 June 1990) several days after he had completed work on the third edition. Until the very end, Il'ya Mikhailovich was unflinchingly faithful to his optimistic attitude to creative work and to life in general, most of all because fate gave him the possibility of always being able to do the job he loved.

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I M Frank's papers on the radiation of sources moving in refractive media (the 'optics of moving sources')

B M Bolotovskii

A charged particle which travels through a refractive medium, i.e., a medium whose properties are defined by specifying its permittivity and permeability, becomes a source of electromagnetic waves. At the present time, the radiation of moving sources in different kinds of refractive media has become a rather vast field of physics. Extensive experimental and theoretical data have been accumulated in this field, and the results of investigators have led to significant application in physics.

This branch appeared in the 1930s, when the Vavilov–Cherenkov effect was discovered and interpreted. In this case, the emergence and progress of the electrodynamics of moving sources (or the optics of moving sources) are intimately related to I M Frank's name. He deserves the credit for the underlying contributions to this field of physics, which define the level of achievements and the present state of the problem. By the way, the term 'optics of moving sources' owes its origin to I M Frank and implies precisely the same meaning as the 'electrodynamics of moving sources'.

I M Frank studied at the Physics Department of Moscow State University (MGU in *Russ. abbr.*). When it was time to choose a specialty, he opted for optics. The supervisor of his degree research was Professor Sergei Ivanovich Vavilov, the founder-to-be of the P N Lebedev Physical Institute and the president-to-be of the USSR Academy of Sciences. S I Vavilov made a substantial contribution to several branches of optics, to the nature of luminescence in particular. During the student years of I M Frank, optics at the Physics Department of MGU was embodied in world-famous physicists like G S Landsberg and L I Mandel'shtam. They were outstanding scientists and wonderful teachers.

The lectures on electromagnetic theory were delivered by Igor' Evgen'evich Tamm. At that time, he was writing the course *Osnovy Teorii Elektrichestva* (Foundations of Electric

Theory), which later became a textbook for many generations of physicists. I M Frank attended G S Landsberg's lectures on optics and the famous seminars of L I Mandel'shtam, and did not miss I E Tamm's lectures on electrodynamics. I M Frank, whose future interests in physics had already taken shape, studied the theory of electricity as an optics expert. In many respects, optics is the electrodynamics of wave processes. I M Frank perceived the corresponding electrodynamic laws as the optical ones.

Many years later, in December 1958, in Stockholm I M Frank was presented with a Nobel Prize in Physics for the theory of Vavilov–Cherenkov radiation. This theory had been developed eleven years earlier in the joint work by I M Frank and I E Tamm. The prize was awarded to three physicists: P A Cherenkov, I E Tamm, and I M Frank. By that time, S I Vavilov had passed away. Each of the recipients had to deliver a Nobel Lecture. I M Frank's lecture was entitled "Optics of light sources moving in refractive media". More recently, in 1969, I M Frank wrote a preprint entitled "Optics and nuclear physics", which was published by the Publishing Department of the Joint Institute for Nuclear Research (JINR) in Dubna. The preprint was concerned with what the wave processes in optics (electrodynamics) and quantum mechanics have in common. Yet more recently, in 1974, I M Frank published a revised version of that paper in the collection entitled *Sovremennye Problemy Optiki i Yadernoi Fiziki* (*Modern Problems of Optics and Nuclear Physics*) (Kiev: Naukova Dumka, 1974). An optics expert is accustomed to the wave aspect of quantum mechanics.

It should not be supposed that I M Frank was an expert in optics in a narrow sense. Rather, he saw the association of different branches of the physical science.

Upon graduation from Moscow State University, I M Frank worked for several years at the State Optical Institute (SOI) in Leningrad. Upon S I Vavilov's recommendation, I M Frank was employed in A N Terenin's laboratory, where he dealt with photochemical reactions research under Terenin's supervision. The Institute was directed by D S Rozhdestvensky, an outstanding physicist known for his remarkable investigations in optical spectroscopy. I M Frank had familiarized himself with this institute even in his student years. Much later he reminisced: "When I first found myself in Leningrad in 1929 to undergo student practice, I happened to familiarize myself with a wonderful scientific institute, where D S Rozhdestvenskii had immense prestige and where research was pursued in a quite creative atmosphere, which any of our institutes might envy."

In those years, S I Vavilov worked in Leningrad. He was D S Rozhdestvensky's deputy at the SOI and was also the head of the Physics Department of the V A Steklov Physico-mathematical Institute of the USSR Academy of Sciences.

In April 1934, a general meeting of the Academy of Sciences passed a resolution about dividing the V A Steklov Institute into two institutes: the Physical Institute, and the Mathematical Institute. At the same time, it was decided that these two institutes — the physical and mathematical — should be transferred to Moscow. S I Vavilov became Director of the Physical Institute.

At the inception of the Physical Institute of the USSR Academy of Sciences (FIAN in *Russ. abbr.*), I M Frank became a staff member and moved to Moscow together with the institute. He joined the group involved in the physics of the atomic nucleus and cosmic rays.

A wonderful atmosphere of cooperation and scientific quest reigned at the new institute. Many years later, I M Frank reminisced:

"In my youth I had the good fortune of finding myself, even during my student years, in an environment in which the influence of science was perceived in an especially intensive and versatile way. I mean the scientific school of L I Mandel'shtam, which comprised my direct teachers and the outstanding physicists S I Vavilov, G S Landsberg, and I E Tamm — scientists so unalike in their individuality. However, there was a feature common to all of them — permanent scientific communication. Theoretical problems and experimental findings were invariably and constantly discussed, and no one considered these talks (they occurred outside the scientific seminars as well), which were frequent and lengthy, to be a loss of time. At first it seemed strange to me that these outstanding people spent hours of their precious time, during which they could be doing something remarkable, for talks, in which much space was devoted to things that produced no outcome or turned out to be rubbish. Nor did I understand at that time that these conversations quite often saw the emergence of new ideas, long before their publication and, of course, without the fear that they would be published by someone else. In addition, no one spared any effort to promote new understanding or gave a second thought to co-authorship. In the moral atmosphere inherent in L I Mandel'shtam's school, that was only natural" [I M Frank, in *Vospominaniya o I.E. Tamme* (Reminiscences of I.E. Tamm) 3rd enlarged ed. (Moscow: IZDAT, 1995) p. 347].

At the Physical Institute, even before its transfer to Moscow, a new phenomenon was discovered, which came to be known as the 'Vavilov–Cherenkov effect' (or the Vavilov–Cherenkov glow). S I Vavilov charged his postgraduate student Pavel Andreevich Cherenkov with investigating the luminescence of some solutions under irradiation by hard gamma-ray photons emitted by radioactive samples. In the course of measurements, P A Cherenkov discovered that the hard gamma-ray radiation was responsible for the glow of not only the solutions, but also of pure solvents. Both kinds of glow — of the solutions and of the pure solvents — were quite weak; it was almost impossible to identify them separately, and the experimental observations were close to the detection limit. That is why P A Cherenkov initially considered the glow of pure solvents he had discovered as being a mishap. However, S I Vavilov became interested in the unusual glow. A standard set of measurements developed in Vavilov's laboratory for luminescence studies was carried out. Based on the data of these measurements, S I Vavilov draw the conclusion that the discovered glow of pure liquids under gamma-ray irradiation was not due to luminescence. Concerning the nature of this glow, S I Vavilov hypothesized that gamma-rays knock out electrons from the atoms as they traverse through a liquid. The knocked-out electrons travel through the liquid and are the source of the observed radiation. S I Vavilov also proposed that the observed radiation was due to the deceleration of electrons passing through the liquid, i.e., is electron bremsstrahlung — a phenomenon known by that time.

S I Vavilov's hypothesis that the observed glow arose from bremsstrahlung was not subsequently borne out. But his statement that the source of radiation was due to the electrons knocked out of atoms proved to be quite correct.

After FIAN moved to Moscow, the investigations related to the new kind of glow were continued.

The state of investigations regarding the new kind of glow was constantly discussed at the seminar of Sergei Ivanovich Vavilov and also during meetings outside the seminar. It is pertinent to note that not all physicists who were familiar with these investigations treated them seriously. Some of them doubted the purity of the experiments and distrusted the data measured at the threshold of vision. However, all of Sergei Ivanovich's closest colleagues were certain that a new kind of glow had been discovered and attentively followed the progress of research. In particular, Igor' Evgen'evich Tamm and Il'ya Mikhailovich Frank discussed the possible cause of the new glow several times.

At one of the seminar sessions conducted by S I Vavilov, it was proposed that a glass with the glowing liquid be placed in a magnetic field. The electrons knocked out of the atoms in the liquid were to change their propagation direction under the action of the magnetic field. Since the electrons were assumed to be the source of the glow, the properties of the light observed were bound to change.

Experiments involving the magnetic field were carried out and they revealed a new property of the radiation under investigation — it turned out to be directional. The electrons emitted radiation in the forward direction.

When Il'ya Mikhailovich Frank told this to Tamm, Igor' Evgen'evich made a significant remark. He said that directional radiation had to be emitted from a relatively long path comparable to the wavelength of the wave radiated. This remark relied on the laws of wave optics. According to these laws, when a radiator of size L emits waves with a wavelength λ, these emitted waves propagate in the vicinity of some preferred direction, so that the angular spread $\Delta\theta$ in propagation directions is equal by an order of magnitude to the ratio between the wavelength λ and the radiating system dimension L:

$$\Delta\theta \approx \frac{\lambda}{L} .$$

When the dimension L of the system is much longer than the radiated wavelength λ, the angular spread $\Delta\theta$ is small and the radiation is said to be sharply directed.

Il'ya Mikhailovich Frank attached significance to this important remark. By that time S I Vavilov's proposition that the source of observed glow was the electrons knocked out from atoms by the radium gamma rays ('Compton electrons') had become a firmly established fact. The electrons travelled through the liquid under study in about the same direction as the gamma rays that had knocked them out. If it were assumed that the electrons radiated throughout their path in the liquid, then the path length was equal to the size of the radiator. I M Frank set himself the task of considering the superposition of electromagnetic waves emitted by the moving electron at every point of its path. To do this he actually took advantage of the same method which the great Dutch physicist Christian Huygens had applied when considering the reflection and refraction of light in his *Treatise on Light* (1690). According to Huygens, every point located on the wave front is a source of radiation of a secondary wave and the envelope of all these secondary waves makes up a new front which defines the properties of the wave and, in particular, its direction of propagation. In agreement with I E Tamm's remark, I M Frank assumed that a spherical wave was radiated from each point in the path of electron motion through the medium and that the addition of these waves made up the resultant field. This simple approach enabled elucidating the qualitative aspect of the phenomenon and interpreting some of the properties of Vavilov–Cherenkov radiation, radiation directivity in particular. It turned out that when the charged-particle velocity in a medium was lower than the phase velocity of light in the medium, the waves emitted from different points of the trajectory had no common envelope. When the particle velocity exceeded the phase velocity of light, the waves radiated in the entire path had a common envelope, i.e., there existed a radiated wave whose front coincided with the envelope. This envelope made a certain angle with the line of particle motion, which defined the radiation directivity. The radiated wave propagated at an angle θ to the electron velocity, the angle θ being defined by the relation

$$\cos\theta = \frac{1}{n\beta} ,$$

where $\beta = v/c$ is the ratio between the charge velocity and the speed of light, and n is the refractive index of the medium traversed by the electron. Simple estimates made by I M Frank showed that this picture yielded values of the radiation angle which were consistent with observations. However, in the picture obtained by I M Frank there was much that seemed, on the face of it, quite strange. It was well known that a uniformly moving charge did not emit electromagnetic waves. At variance with this well-known fact, I M Frank proceeded from the assumption that the charge radiated at every point of its path. I E Tamm's remark implied that he also adhered to this viewpoint. Nor was it clear, at first glance, how the velocity of a charged particle could exceed the speed of light. According to the relativity theory, no material body could have a velocity higher than the speed of light.

Il'ya Mikhailovich, in turn, informed several physicists about the resultant data, including M A Markov and M A Leontovich. They listened to Frank's story, but did not express keen interest in it. Later on, when it came to discussing I M Frank's statement, Mikhail Aleksandrovich Leontovich would say: "Il'ya is a serious man, he should be listened to attentively. In due time I did not, and missed the Nobel Prize."

I M Frank turned to Igor' Evgen'evich Tamm with his results (and his doubts). All that was close to Igor' Evgen'evich, because his discussions with S I Vavilov and I M Frank had made him fall to thinking about the nature of the new glow. He listened to I M Frank with genuine vivid interest and set himself the task of calculating this phenomenon by invoking a rigorous theory — Maxwell–Lorentz electrodynamics. Some time later, I E Tamm called up I M Frank and asked him to urgently come to his home. I M Frank wrote in his memoirs: "I found I E Tamm at the desk, deep at work, with many sheets of paper already covered with formulas. Straight away he started telling me of what he had done prior to my arrival. Today I can no longer recall what precisely we discussed during that night. I believe we discussed the development of the solution proposed by I E Tamm, the validity of calculations, and the physical foundations of the theory in which much still remained unclear. I only remember that we sat for a long time. I returned home on foot at daybreak, because the urban transport had finished (or had not resumed) working. I had a feeling that an important event had taken place in my life, doubtlessly largely because for the first time I was participating in theoretical work, and work jointly with I E Tamm to boot."

The article written jointly by I E Tamm and I M Frank was submitted to the journal *Doklady Akademii Nauk SSSR* (*Sov. Phys. Doklady*) on January 2, 1937. It was entitled "Kogerentnoe izluchenie bystrogo elektrona v srede" ("Coherent radiation of a fast electron in a medium"), and it provided a theoretical interpretation of Vavilov–Cherenkov radiation. By that time, the issues in doubt had been successfully resolved. In particular, the questions of whether a uniformly moving charged particle can radiate at every point in its path and whether this contradicts the proposition that a uniformly moving charge does not radiate were elucidated. It turned out that these two statements agree with each other. It may indeed be assumed that any moving charge, including a uniformly moving one, radiates at every point in its path. However, for a uniform motion the radiated waves cancel out when the particle velocity is lower than the phase velocity of light in the medium traversed by the particle. In this case, the absence of radiation is due to the mutual cancellation of all radiated waves. When the particle velocity exceeds the velocity of the waves radiated, these waves add up coherently and do not cancel each other.

It also became clear that particle motion with a velocity exceeding the phase velocity of light in a medium is inconsistent with the relativity theory. The relativity theory does indeed prohibit the motion of material particles with a velocity exceeding the speed of light in empty space. And the speed of light in the medium is, as a rule, lower than the speed of light in empty space. A transparent plastic, for instance, possesses a refractive index $n = 1.5$. The speed of light in such a medium is about 200,000 km s^{-1}. Meanwhile, the speed of light in vacuum is equal to 300,000 km s^{-1}, i.e., one and a half times more. That is why a particle may outrun a light wave in the medium and at the same time have a velocity lower than the speed of light in empty space.

The theory constructed by I E Tamm and I M Frank explained all previously obtained experimental data. But the theory also came up with predictions which had to be verified. The theory yielded numerical expressions regarding the radiation spectrum and the intensity, and exactly defined the polarization. Additional experiments carried out by P A Cherenkov in 1937 confirmed the quantitative implications of the theory. It is noteworthy that the measurements conducted by P A Cherenkov were distinguished by exceptional reliability from the very commencement of investigations. Working in arduous conditions, at the threshold of vision, he would repeatedly verify the data obtained, so that they could not be doubted.

Vavilov–Cherenkov radiation is widely used in high-energy physics, where it is possible to detect fast charged particles using the bursts of Vavilov–Cherenkov radiation. However, the first years following the discovery saw no proposals regarding the employment of Vavilov–Cherenkov radiation. The radiation was so weak that its use was out of the question. The situation reversed after the development of high-sensitivity radiation detectors — photomultipliers — during the Second World War. In 1947, an American physicist, I A Getting, proposed the employment of photomultipliers for recording Vavilov–Cherenkov radiation. The first Cherenkov counters thus made their appearance. Nowadays they are found in every laboratory involved in high-energy particle studies. With the aid of Cherenkov counters it is possible to measure diverse characteristics of fast charged particles: the direction of propagation, the magnitude of charge, the velocity, and the energy. The progress in high-energy physics, associated with the application of Cherenkov counters, underlay the conferring of the Nobel Prize in Physics 1958 to Cherenkov, Frank, and Tamm.

Subsequently, Il'ya Mikhailovich Frank would repeatedly return to different problems related to the theory of Vavilov–Cherenkov radiation. His joint work with Vitaly Lazarevich Ginzburg was concerned with the Vavilov–Cherenkov radiation arising in the motion of a charged particle, not in a continuous uniform medium, but through a channel made in this medium. The results of this work made it possible to judge what regions of the medium — remote from the charge trajectory or close to it — participate in the generation of radiation. He also investigated the duration of a Vavilov–Cherenkov radiation burst. This issue was important for determining the operation efficiency of Cherenkov counters.

Vavilov–Cherenkov radiation emerges when the velocity of a charged particle exceeds the phase velocity of electromagnetic waves. Seemingly, Vavilov–Cherenkov radiation cannot therefore occur in empty space: the velocity of a material body cannot exceed the speed of light in empty space. However, there are objects which can travel with a superluminal speed. An example is provided by a sunspot — a light spot on a wall produced by a solar beam reflected from a mirror; such a spot may travel with a velocity exceeding the speed of light in vacuum. This is by no means at variance with special relativity, because the sunspot's motion does not involve any energy transfer in the direction of motion. However, the light spot induces surface charges and currents at the interface. These charges and currents can move over the separation surface with an arbitrary velocity and, in particular, may become the source of Vavilov–Cherenkov radiation if the spot's velocity exceeds the speed of light in empty space. Examples of superluminal sources have been considered in works by V L Ginzburg and other authors.

The first example, a highly instructive one, of a superluminal source comes from I M Frank. Consider two media with different refractive indices separated by a flat interface. For definiteness, they will be referred to as 'the first medium' and 'the second medium'. The refractive index is equal to n_1 in the first medium, and to n_2 in the second one. Let a plane electromagnetic wave in the first medium be incident on the interface. It is easily shown that this wave excites charges and currents on the interface, which travel along the interface with a velocity $v = c/n_1 \sin\vartheta_1$, where ϑ_1 is the angle of incidence. It is evident that the velocity of travel of these surface formations always exceeds the speed of light in a first medium. Vavilov–Cherenkov radiation is therefore bound to occur in the first medium. It is easy to verify that this radiation yields precisely the reflected wave. The same surface currents and charges may also be the source of radiation in the second medium when their velocity exceeds the speed of light in the second medium, i.e., when $v = c/n_1 \sin\vartheta_1 > c/n_2$. In this case, Vavilov–Cherenkov radiation in the second medium yields precisely the refracted wave. When the velocity of surface charges and currents turns out to be lower than the speed of light in the second medium, i.e., when $v = c/n_1 \sin\vartheta_1 < c/n_2$, there is no Vavilov–Cherenkov radiation in the second medium — the refracted wave is not formed. The latter inequality coincides with the condition for total internal reflection.

Therefore, the reflected and refracted waves may be represented as Vavilov–Cherenkov radiation from the sources produced by the incident wave at the interface.

In the postwar years, I M Frank spared no time or effort to investigate the physics of neutrons. However, the classical theory of charged particle penetration through a substance would remain to be of concern to him. During the last years of his life he wrote a book, which may be regarded as the result of his research devoted to Vavilov–Cherenkov radiation [I M Frank *Izluchenie Vavilova–Cherenkova. Voprosy Teorii* (*Vavilov–Cherenkov Radiation. Theoretical Problems*) (Moscow: Nauka, 1988)].

* * *

The theory developed by Frank and Tamm had historical predecessors. In 1904, the famous German mathematician and physicist Arnold Sommerfeld calculated the field of an electron moving through empty space with a velocity exceeding that of light. Sommerfeld found that the electron emits electromagnetic waves in this case. However, in the next year the relativity theory was finally formulated, according to which superluminal motion in empty space was impossible. Sommerfeld's work was forgotten. Tamm and Frank did not know about this work when developing their theory. They learned about Sommerfeld's paper when they discussed the final results of their work with Abram Fedorovich Ioffe. He remembered Sommerfeld's paper and informed Tamm and Frank of it. That was how a reference to Sommerfeld's forgotten paper appeared in the aforementioned paper by Tamm and Frank, "Coherent radiation of a fast electron in a medium". A reprint of this paper was sent to A Sommerfeld. Sommerfeld responded with a letter of gratitude, and included a section entitled "Cherenkov radiation" in his textbook *Optics*. However, neither in his letter nor in his textbook did Sommerfeld mention the fact that even late in the 19th century the English scientist Oliver Heaviside had considered the motion of a point electric charge in a medium (in a medium, not in empty space!), including the case when the charge velocity was higher than the speed of light in the medium. He showed that in this case the emission of electromagnetic waves occurred, the radiation being directional, and determined some properties of this radiation. Heaviside's treatment was not as comprehensive as that by Frank and Tamm; in particular, he ignored dispersion, i.e., the dependence of the refractive index on the frequency of the light wave. He also assumed that the electron velocity may be arbitrarily high. He was unaware of the limitations on particle's velocity imposed by the relativity theory, because the relativity theory had not yet come into being. It is nevertheless valid to say that Heaviside had come closer than anybody else to the modern theory of Vavilov–Cherenkov radiation. But his work did not attract attention and was quickly forgotten. The reason lay in the fact that Heaviside was far ahead of his time, when the proponents of the atomistic structure of matter were few and far between, while the atom of electricity — the electron — had not even been discovered. And at that time it was hard to imagine that there might exist a particle whose velocity exceeded the speed of light in a medium. The opportunity of obtaining such particles emerged much later, in the first decade of the 20th century, after the discovery of radioactivity. Few people read Heaviside's papers and books, and those who did would believe that his treatment of the field of a superluminal charge was far from reality. By contrast, Tamm and Frank were facing the task of explaining a real, already discovered radiation emitted by real fast charged particles. Heaviside's works were recalled in the first half of the 1970s, approximately 90 years after they were carried out. At that time, Il'ya Mikhailovich Frank was recovering in the Uzkoe academic sanatorium. I went there to see him. On his request I brought the third volume of Heaviside's monograph *Electromagnetic Theory*. In that volume Heaviside considered the superluminal motion of a point charge in a refractive medium. Il'ya Mikhailovich read the book section of interest, and during my next visit, when the conversation turned to Heaviside, he said: "It is a great honor to have such a predecessor."

* * *

In 1942, I M Frank published his paper entitled "Effekt Doplera v prelomlyayushchei srede" (The Doppler effect in a refractive medium) in the journal *Izvestiya Akademii Nauk SSSR, Seriya Fizicheskaya* (*Sov. Phys. Izv., Ser. Phys.*). This work still defines the level of understanding in the field it was dedicated to. Let there be a transmitter which emits a wave of a certain wavelength. The function of the transmitter may be fulfilled by an atom, which radiates a light wave, or a laser, or a radio station. And let these signals be recorded by a person equipped with a receiver. When the reception and the transmission take place in empty space and both devices — the transmitter and the receiver — are stationary with respect to each other, the receiver should be tuned to the same frequency as the transmitter; otherwise, the signal will not be recorded. When the transmitter and the receiver move relative to each other, it turns out that the transmitter frequency and the frequency at which the signal is received do not coincide. This effect, by the example of light emanating from binary stars, was first investigated by the Austrian physicist Christian Doppler in the middle of the 19th century, and it came to be known as the Doppler effect.

Let the transmitter radiate at a frequency Ω. For simplicity sake assume that the transmitter is in motion, and the observer (the receiver) is at rest. The transmitter velocity will be denoted by v.

When the transmitter and the receiver are located in empty space, the transmitter frequency Ω and the frequency ω at which the transmitted signal is received are related as

$$\omega = \frac{\Omega}{1 - (v/c)\cos\theta} \,.$$

Here, v is the transmitter velocity, c is the speed of light in vacuum, and θ is the angle between the transmitter velocity and the direction of radiation propagation. It is significant that the frequency ω of the received signal has a single value for given values of v, Ω, and θ.

I M Frank considered the Doppler effect not in empty space, but in a refractive medium where dispersion occurs, i.e., waves with various frequencies travel with different velocities. It turned out that the Doppler effect in a refractive medium exhibits many interesting features. In particular, it may be that the transmitter operates at a single specific frequency, and the reception proceeds at several discreet frequencies. The signal splits in frequency. Indeed, in a medium with dispersion, the refractive index n depends on the frequency ω: $n = n(\omega)$. Accordingly, the phase velocity of light in this medium is $c/n(\omega)$. To obtain the formula for the Doppler effect in a dispersive medium, it would suffice to substitute the ratio $c/n(\omega)$ for c in the previous formula for the Doppler effect in empty space. This yields

$$\omega = \frac{\Omega}{1 - \beta n(\omega)\cos\theta} \,.$$

Here, β denotes the ratio between the transmitter velocity v and the speed of light c in empty space: $\beta = v/c$. Given the transmitter operation frequency Ω, the transmitter velocity v, and the angle θ of radiation emission, the latter relationship is an equation in frequency ω at which the signal is received. This equation may have several solutions, which is an indication that the signal splits in frequency. I M Frank called this phenomenon the complex Doppler effect.

In a refractive medium there is one more possibility: the radiator velocity may exceed the speed of light (for a radiator, one may consider, for instance, an atom traveling with a superluminal velocity in the medium). I M Frank's paper "The Doppler effect in a refractive medium" marked the beginning of investigations into the Doppler effect also in superluminal motion. More recently, in their joint paper V L Ginzburg and I M Frank elucidated a remarkable feature of the Doppler effect in the superluminal motion of the radiator. As is commonly known, an atom, being initially in an excited state, under ordinary conditions emits light and passes to its normal state. When the atom travels with a superluminal velocity, the radiation may be attended with a transition not to its normal state but to an even higher excited state, as shown by V L Ginzburg and I M Frank. This phenomenon has come to be known as the anomalous Doppler effect.

* * *

In his paper "The Doppler effect in a refractive medium", I M Frank introduced a very important quantity which determines the radiation emission by moving sources. Initially, he named this quantity 'the Fresnel zone' by analogy with the theory of diffraction, but later he began to use the term 'path of radiation formation'. Nowadays this quantity is more often referred to as 'coherence length'. It characterizes the motion of a charged particle in the field of an electromagnetic wave. Coherence length is the distance traversed by the charge in the wave field, so that the phase of the wave at the point where the charge is located changes by no more than one-half wavelength. To state it in different terms, the coherence length is the distance in which the charged particle either lags behind the wave or is ahead of it by one-half wavelength, i.e., shifts in phase (falls behind or leads) by $\pi/2$.

Consider a transparent medium with a refractive index n. Let a charged particle be moving with a constant velocity v in this medium. The particle emits electromagnetic waves from every point of its path. It is valid to say that the waves emanate in all directions from every point traversed by the particle, much like waves diverge on the water surface in all directions from a cruising ship.

Let the charge trajectory coincide with the z-axis of some coordinate system. Let us assume that the charge emits a wave

$$\exp\left[\mathrm{i}(\mathbf{kr} - \omega t)\right] \tag{1}$$

from a point $z = 0$. Here, ω is the radiated wave frequency, $\mathbf{k}$ is the wave vector, and $\mathbf{r}$ is the point of observation. The magnitude of the wave vector is defined by the relation $k = (\omega/c)n$.

Now consider a point $z = l$. When going through this point, the charge radiates, among other waves, a wave with the same values of the frequency and the wave vector as for the wave (1). However, the wave emitted from the point $z = l$ has a different phase. Indeed, the points $z = 0$ and $z = l$ are separated in space and, furthermore, the radiation emission from the point $z = l$ is shifted in time relative to the radiation emission from the point $z = 0$ by a value of $\Delta t = l/v$. That is why the wave emitted from the point $z = l$ is of the form

$$\exp\left\{\mathrm{i}\left[\mathbf{k}(\mathbf{r} - \mathbf{l}) - \omega\left(t - \frac{l}{v}\right)\right]\right\}, \tag{2}$$

where $\mathbf{l}$ is the vector directed from the point $z = 0$ to the point $z = l$ and equal to l in magnitude.

Let ϕ_1 designate the phase of the wave emitted by the moving charge at the point $l = 0$ [see expression (1)]:

$$\phi_1 = \mathbf{kr} - \omega t\,.$$

Accordingly, by ϕ_2 we denote the phase of the wave emitted by the charge at the point $z = l$ [see expression (2)]:

$$\phi_2 = \mathbf{k}(\mathbf{r} - \mathbf{l}) - \omega\left(t - \frac{l}{v}\right).$$

As is obvious from the expressions for ϕ_1 and ϕ_2, the waves emitted by the moving charge at the beginning and at the end of the path of length l are different in phase. The phase difference $\phi_2 - \phi_1$ is readily determined as

$$\phi_2 - \phi_1 = l\,\frac{\omega}{v}\left(1 - \frac{v}{c}\,n\cos\theta\right), \tag{3}$$

where θ is the angle between the direction of motion of a radiating particle (the z-axis) and the direction of wave propagation (i.e., the direction of the wave vector $\mathbf{k}$).

Initially, we assume that the path l is sufficiently short, so that the phase difference $\phi_2 - \phi_1$ is much smaller than unity. Clearly, in this case the waves emitted from any point of the path are close in phase, and therefore the fields of these waves add up and the resultant radiation amplitude is proportional to l. Then, with a further increase in path l, the phase difference $\phi_2 - \phi_1$ rises to become equal to π for some value of l. Then, the wave emitted at the beginning of the path and the wave emitted at the end of the path are in antiphase. The fields of these waves no longer add up but are subtracted. The resultant field is no longer strengthened with increasing path l.

When the waves emitted at the beginning and at the end of a path are shifted in phase by π, the fields of the waves emitted from any point between the beginning and the end of the path possess the same sign. It is valid to say that the waves are emitted in phase throughout the segment l.

The value of the path $l = l_{\mathrm{f}}$ from which the radiation is gathered in phase may be determined by putting the phase difference $\phi_2 - \phi_1 = \pi$ into formula (3). Then we obtain

$$l_{\mathrm{f}} = \frac{\pi v}{\omega}\,\frac{1}{1 - \beta n\cos\theta}\,, \tag{4}$$

where $\beta = v/c$.

This expression was first devised by I M Frank. Initially, he termed the quantity l_{f} the Fresnel zone for radiation by analogy with that in the theory of diffraction, where the Fresnel zone is the region from which radiation reaches the observer in phase. Later on, for l_{f} I M Frank employed the name 'path of radiation formation'. Nowadays, this quantity is not infrequently referred to as coherence length. In classical (nonquantum) physics this quantity defines the path length from which radiation is accumulated.

Interestingly, in quantum theory there is a quantity which has the same physical meaning as the formation path introduced by I M Frank. In the early 1930s, two theoretical physicists, Hans Bethe and Walter Heitler, calculated the electron bremsstrahlung in the field of a massive Coulomb center (atomic nucleus) in the framework of quantum electrodynamics.

Bethe and Heitler did not invoke the concept of a trajectory in their calculations. They described the electron by a plane wave. Therefore, they could not pose the question which I M Frank later formulated in the framework of the classical theory: what is the path length from which radiation is gathered in phase? However, in the framework of the quantum theory they raised an equivalent question: what are the dimensions of the domain located near the nucleus in which the electron produces the bulk of radiation? In other words, they estimated the dimension of the spatial domain which makes the main contribution to the matrix element. They arrived at the following estimate for the dimensions of this domain. Let us assume that the initial electron energy equals E_1, and the electron energy upon being radiated (when the electron has flown a long distance away from the nucleus) is E_2. Furthermore, let the electron emit a photon of frequency ω when flying by the nucleus. Under these assumptions, Bethe and Heitler concluded that the dimensions of the domain significant from the standpoint of emitting radiation are by an order of magnitude defined by the relationship

$$l_0 = \frac{2\pi c}{\omega} \frac{E_1}{mc^2} \frac{E_2}{mc^2} \,.$$

Here, c is the speed of light in vacuum, and m is the electron mass.

When the electron energy is sufficiently high, the length l_0 is measured in the direction of its initial momentum (however, when the energy is sufficiently high, the directions of the initial and final electron momenta as well as the bremsstrahlung photon momentum direction are all close: the photon is emitted forward, along the direction of the electron motion).

When the energy $h\omega$ of the bremsstrahlung photon amounts to only a small fraction of the incident electron energy E_1, one may put $E_1 \approx E_2 \approx E$ in the formula for l_0, and the quantity l_0 may then be written out as

$$l_0 = \frac{2\pi c}{\omega} \left(\frac{E}{mc^2}\right)^2 = \frac{2\pi c}{\omega} \frac{1}{1-\beta^2} \,.$$

We will assume that the electron velocity v in Frank's formula (4) for the formation path l_f is close to the speed of light c. Furthermore, we put $\theta = 0$ (forward radiation) and $n = 1$ (vacuum) in this formula. In this case, formula (4) goes over into the expression for l_0 derived by Bethe and Heitler.

For a relativistic electron and the forward radiation, the classical and quantum approaches therefore yield approximately the same estimates for the path from which the radiation is gathered. It is significant that the length of this path increases rapidly with energy (proportionally to the square of the energy).

There is a widespread belief that physical processes at high energies are characterized by intense short-range interaction, unfold in small spatial domains, and should be described with the aid of the quantum theory. I M Frank showed that even at high energies there is a class of processes which proceed over a long path and that the higher the particle energy, the longer this path is. Among these processes is, in particular, emission of Vavilov–Cherenkov radiation. This radiation is gathered from the entire path, no matter how long it may be. Indeed, when the value of $\cos\theta$ for Vavilov–Cherenkov radiation is substituted in expression (4) for l_f, the denominator vanishes and the expression for l_f becomes divergent. In this case, a particle moves arbitrarily long in phase with the radiated wave and the coherence length may therefore be arbitrarily long. However, when the radiation is gathered from a long path, it is the properties of the medium as a whole that come into play and not the individual properties of the atoms that constitute the medium. In a sense it is valid to say that the longer the formation path, the firmer the ground is to treat the process as a classical one. Among these processes are emission of Vavilov–Cherenkov radiation and the transition radiation, the latter being discussed below.

* * *

Vavilov–Cherenkov radiation appears in the motion of a charged particle in the uniform medium. In the mid-1940s, I M Frank became interested in the problem of the radiation emission by a particle traveling through a nonuniform medium. The simplest example of the emission by a charged particle moving in a nonuniform medium was considered jointly by I M Frank and V L Ginzburg. Their collaboration commenced back during the Great Patriotic War and its findings were reported in the *Zhurnal Eksperimental'noi i Teoreticheskoi Fiziki* (*Journal of Experimental and Theoretical Physics*) in 1946. The paper was entitled "Izluchenie ravnomerno dvizhushchegosya elektrona, voznikayushchee pri ego perekhode iz odnoi sredy v druguyu" ("Radiation of a uniformly moving electron, which emerges in its going from one medium to another"). Considered in that work were two different media (with different values of dielectric constant) separated by a flat interface. A charged particle was assumed to move uniformly in one of the media towards the interface and having intersected the interface along the normal to travel further in the second medium. It turned out that this intersection of the interface between two media is accompanied by the emission of electromagnetic waves. The authors called this radiation the transition radiation. They determined the fields on either side of the interface and calculated the energy loss by backward radiation, i.e., the radiation emitted into the medium in which the electron was initially moving.

Several years later, G M Garibyan calculated the total charged-particle energy loss by transition radiation. The energy loss was defined as the work done by the electric field over the entire particle path. It turned out that the total loss for relativistic electrons increased linearly with particle energy. Later on, it was determined that the forward radiation accounted for the bulk of the losses. It is the forward radiation that increases proportionally to the particle energy. High frequencies, up to those of X-rays, enter into the spectral composition of transition radiation. The backward radiation increases with charged-particle energy much more slowly (logarithmically).

As noted above, Vavilov–Cherenkov radiation awaited theoretical interpretation for several years after its discovery. By contrast, transition radiation was theoretically predicted first, and discovered in experiment twelve years later. Subsequently, not only did the transition radiation theory promote further the development of our theoretical notions about the passage of charged particles through a matter, but it also enabled realizing important applications in high-energy physics. Detecting fast charged particles by their transition radiation was made possible. Transition radiation detectors are now in use in all high-energy physics centers. A substantial contribution to the theory of transition radiation and the development of its applications was made by the scientists of the Yerevan Physical Institute. Prior to the disintegration of the Soviet Union, this institute was in the lead in the development of transition X-radiation theory and the making of transition radiation detectors.

Several international symposia dedicated to the theory and applications of this phenomenon were held in Yerevan. In recent years, international symposia on the interaction of fast particles with matter were regularly conducted on the initiative of the Tomsk Polytechnical Institute. Reports and discussions concerned with transition radiation have a significant place at these symposia.

Research on different aspects of transition radiation is also underway at Moscow State University, Belgorod University, FIAN, and JINR. Furthermore, transition radiation is employed for the generation of high-power electromagnetic radiation by intense charged-particle beams.

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Emphasized in the foregoing was Sergei Ivanovich Vavilov's role in the discovery of the effect which bears his name, along with the name of Pavel Alekseevich Cherenkov. S I Vavilov also played an important part in the regular discussions which fostered the understanding of the effect and eventually resulted in the creation of the Tamm–Frank theory. No less important was the part which S I Vavilov played at all stages of the scientific life of I M Frank. The student of Moscow State University Il'ya Mikhailovich Frank carried out his degree research under the scientific supervision of Sergei Ivanovich Vavilov. Upon graduation from the university, I M Frank was a researcher at the SOI, where S I Vavilov was Deputy Director for scientific research. When Sergei Ivanovich Vavilov was appointed Director of FIAN, he invited I M Frank to become a staff member in the Laboratory of Atomic Nucleus. This fact also deserves special consideration. At that time, few could estimate the prospects for the development of nuclear physics, which was at the onset of its rapid progress. And Vavilov foresaw the rapid strides it would make. His specialty was physical optics, but at that time he suggested to his pupils subjects that were adjacent to nuclear physics. Here is the subject of an investigation carried out by his postgraduate student P A Cherenkov: "Glow of uranyl salts solutions under the gamma-ray irradiation of radium". And in the institute he was setting up a Laboratory of Atomic Nucleus was organized from the very start. His effort to lend impetus to the development of nuclear physics was repaid a hundredfold. In the years after the Great Patriotic War, when our country faced the problem of developing nuclear weapons, FIAN played a significant role in solving this issue.

Vavilov was a highly cultured and decent man. L I Mandel'shtam once said that there are no very decent people: a person is either decent or not. However, L I Mandel'shtam himself deserves to be called a very decent person. The same applies to Sergei Ivanovich Vavilov. I M Frank appreciated S I Vavilov as a teacher, as a thoughtful supervisor, and as a highly cultured person, and he valued his perfect culture of behavior. He treated S I Vavilov with love, respect, and gratitude for his teaching and purely human and paternal care and favor. When Sergei Ivanovich passed away, I M Frank devoted considerable effort to collecting and publishing reminiscences about him. He became the editor of that collection. The collection saw three editions. In the third edition, Il'ya Mikhailovich included several new, previously unpublished articles, which were written by people who were closely acquainted with S I Vavilov. Il'ya Mikhailovich greatly enlarged his introductory article for the third edition, so that its volume doubled. Much of what he added to his article simply could not have been written earlier, in the previous editions (the first edition came out in 1979, and the second in 1981). When the third edition was under preparation for print, I M Frank was seriously ill. He feared that he would not have time to complete editing the book. When the preparation was completed and the book was ready to go to print, he told his relatives: "Now I may die." And several days later he passed away. The book was published several months after his death.

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Il'ya Mikhailovich Frank descended from a remarkable family. His grandfather Lyudvig Semenovich Frank was a military physician. He had two sons — Semen Lyudvigovich and Mikhail Lyudvigovich. Mikhail Lyudvigovich was a professor of mathematics, an outstanding educator. Under his influence his children developed an interest in the natural sciences. Mikhail Lyudvigovich had two sons — Gleb (the elder) and Il'ya. Gleb Mikhailovich, Il'ya Mikhailovich's brother, became an outstanding biophysicist, a Full Member of the USSR Academy of Sciences. Il'ya Mikhailovich Frank's uncle, his father's brother Semen Lyudvigovich Frank, was a famous religious philosopher. In 1922, under Lenin's decree he was exiled from Russia on the notorious 'philosophy steamer'. Other philosophers like Nikolai Berdyaev and Pitirim Sorokin were exiled with him. Of course, it is regretful that Russia expelled its most prominent thinkers. But, on the other hand, had Lenin not expelled them in 1922, most likely Stalin would simply have exterminated them on rising to power. And as it was, the exiles had the opportunity to work abroad. Il'ya Mikhailovich could not communicate with his uncle: it was mortally dangerous in those years. Nor did he communicate with the uncle's descendants, his cousins. I think that the foreign relatives in turn were aware of the danger which contacts with them might pose to I M Frank.

* * *

I M Frank was a remarkably restrained and polite person. His restraint and politeness reached an amazing degree. Once my friend Grigorii Markarovich Garibyan, a famous physicist who was concerned with the theory of transition radiation and discovered transition X-rays, came from Yerevan to Moscow. He informed me of the new results he had obtained. I gave him some advice: "Grisha, go to Dubna to visit Il'ya Mikhailovich Frank, and inform him. He would take a lively interest in this." Grisha went to Dubna and returned in a happy mood. He told me that Il'ya Mikhailovich listened to him quite favorably and agreed entirely with his results. Several weeks later I met Il'ya Mikhailovich at FIAN. Our conversation turned to the results obtained by G Garibyan. "For pity's sake," Il'ya Mikhailovich said, "what is new about that? All this has long been known to me. I told him: "how good it is that we share the same viewpoint." But he does not understand!"

* * *

I shall cite another example to show how civilized a person Il'ya Mikhailovich was. Somewhere in the mid-1970s I received a discovery application for review. At that time there existed a procedure whereby a person who made a discovery received a special certificate which stated: Mr. So-and-so made such-and-such a discovery. This was a purely bureaucratic procedure. What is a discovery in science? Newton had no discovery certificate. Nor did Einstein. And here a person could apply to the Committee on Inventions and Discoveries under the Council of Ministers of the USSR (CM USSR) with a written request: so, I have made such-and-such a discovery and ask for a discovery certificate. One such application was sent to me for review. On reading the application I saw that the author was making a claim for a discovery which was largely (by half or more) underlain by the works of Il'ya Mikhailovich Frank. I wrote about this in my review. I do not know how things went concerning conferment of the discovery certificate. It may well be that an affirmative resolution was adopted and the applicant did receive the certificate. About a year and a half later I told Il'ya Mikhailovich about that event. "I know," said Il'ya Mikhailovich, "he informed me that he was going to make an application. "Apply," I told him. But he should have realized that this situation is unpleasant for me." Il'ya Mikhailovich also knew nothing about the fate of the application.

* * *

Somewhere between 1970 and 1980 — I do not remember exactly when — investigations of transition radiation were nominated for a Lenin Prize. The Yerevan Physical Institute nominated for the prize a group of physicists who had played an important part in the development of the theory and its applications. Of course, the number one in that group was Il'ya Mikhailovich Frank, who had predicted that phenomenon and had, together with V L Ginzburg, constructed its theory. V L Ginzburg was not on the list of nominees: prior to that he had been awarded a Lenin Prize for investigations of the theory of superconductivity, and one could not be awarded the prize twice. The list of physicists nominated for the Lenin Prize had not been discussed with Il'ya Mikhailovich Frank beforehand. When Il'ya Mikhailovich had familiarized himself with that list, he sent a letter to the Committee on Lenin and State Prizes at the CM USSR. He wrote that there were physicists (and gave their names) who had not been nominated for the prize and who had made contributions to the theoretical and experimental investigations of transition radiation no less significant than those of the nominees. That is why he objected to the list of nominees specified in the application. A letter like this was equivalent to a refusal to accept a Lenin Prize. The Committee on Lenin and State Prizes could not change the list of nominees for the prize, could not exclude anybody from the list, and could not add a new nominee. It was evident that the Committee would refuse to consider the application when the initiator of all the investigations nominated for the prize was objecting to the nominee list. It happened precisely that way. The prize for the discovery and investigation of transition radiation was never awarded. Il'ya Mikhailovich was fully aware of all this when he wrote the letter. He familiarized me with a copy of this letter and in doing so said: "I have killed a Lenin Prize for myself."

* * *

It is customary to revile poor works in physics — fallacious works containing inaccurate measurements or incorrect physical ideas. Il'ya Mikhailovich adhered to a different opinion. He would say: "It is commonly supposed that erroneous work is detrimental to the progress of physics. I cannot agree with this. Erroneous work has no effect on the progress of physics. It is quickly forgotten."

* * *

In Il'ya Mikhailovich Frank's life there was an event that caused him years of bitter feelings.

On August 29, 1973, in the newspaper *Pravda* — the principal newspaper of the Soviet Union — a letter condemning the public activities of Academician Andrey Dmitrievich Sakharov was published. That letter bore the signatures of forty academicians, and the signature of I M Frank was among them.

In 1969, Andrey Sakharov wrote his famous article "Reflections on progress, peaceful coexistence and intellectual freedom". In that article he pondered the paths of development of the Soviet Union and the world community, and discussed the necessary conditions for the normal development of the country. In many respects, his thoughts were at variance with the official ideology which the Soviet leadership adhered to. That ideology remained unaltered up to the disintegration of the Soviet State and, in fact, was responsible for the disintegration. Andrey Sakharov's ideas were hushed up or distorted in our country, and he himself became an object of persecution by newspapers and magazines. The letter of forty academicians was one of the elements of this persecution.

Among the forty academicians who signed the letter there undoubtedly were those who did this according to their convictions. There also were those who had experienced pressure and who would not have signed the letter of their own free will. However, what pressure could the academic authorities exert on Il'ya Mikhailovich Frank, an internationally known scientist and a Nobel Laureate?

The following story was told at our institute, FIAN. Andrey Sakharov came to the Institute on August 29 and saw posted up in the vestibule a photocopy of the letter of forty academicians. He came up to the letter, read it, and reached the signatures. He studied the list and said: "Il'ya Mikhailovich Frank has signed this letter. A good person, I sympathize with him. But Vitaly Lazarevich Ginzburg did not sign it. A good person, I sympathize with him."

Those who refused to sign the letter expected to have problems from their bosses. Those who did sign the letter (at least some of them) felt pangs of conscience. Andrey Sakharov sympathized with them both.

Approximately one month after the emergence of the letter of forty academicians, a "Statement of FIAN scientists", which condemned the public activity of Andrey Sakharov, was put together at FIAN. The staff members of the Theoretical Physics Department at FIAN (the Department where Andrey Sakharov worked) refused to sign that letter. When I told Il'ya Mikhailovich Frank about this, he said: "They did the right thing."

He therefore sympathized with those who refused.

I never questioned him about anything. Several years later he told me under what circumstances he had put his signature on the letter of the forty. He was invited to the President of the Academy of Sciences, who suggested that he sign the letter. Il'ya Mikhailovich refused and the President tried to persuade him to sign. This lasted for a rather long time (if my memory does not fail me, Il'ya Mikhailovich said two hours).

"And then," said Il'ya Mikhailovich, "the President stopped trying to persuade me. He got a sheet of paper from the desk with the text of the letter already bearing the signatures. He gave the sheet to me. I saw, among others, the signatures of people whom I treated with great respect. And I thought: since such people have signed this letter, I must be wrong in my recalcitrance. And I signed the letter, but now I cannot forgive myself."

On January 3, 1990, a Dubna newspaper published I M Frank's article entitled "The truth invariably gains the upper hand". It contained the following words:

"Recently we experienced a severe shock. The great fighter for justice A D Sakharov passed away, and the mental anguish has not yet subsided. Of course, no one forgets about the persecutions which he recently endured. The blame is to be ascribed also to the USSR Academy of Sciences. I was not among those who condemned the awarding of the Nobel Peace Prize to him, and I believe this award to be well-deserved. However, a part of the blame for what the Academy of Sciences published against Sakharov should be ascribed to me. I realized it many years ago and never forget about it. Like D S Likhachev I say not only 'Farewell to you', but also 'Forgive me'."

The title of the newspaper article — "The truth invariably gains the upper hand" — is a part of a phrase which I M Frank heard from S I Vavilov: "The truth invariably gains the upper hand, but human life may turn out to be not long enough for that."

Of the forty academicians who signed the letter against Sakharov, I know of only two of them who expressed their apologies to him. They are Il'ya Mikhailovich Frank (his words are given above) and Sergei Vasil'evich Vonsovskii. Vonsovskii confessed at a general meeting of the Academy of Sciences in Sakharov's presence. And my respect for these two physicists — Vonsovskii and Frank — became even more profound after that.

* * *

The times in which Il'ya Mikhailovich Frank lived and worked were ones of rapid progress in physics in our country. This time has been superseded by a period of disorder and stagnation. It is necessary to restore much of what was lost during the last decades. To restore and go further. And the memories of those who earlier paved the way to knowledge, the comprehension of their experience, achievements and, last but not least, standards of morality will contribute to faster advancement.

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I M Frank and the development of the Joint Institute for Nuclear Research

A N Sissakian, M G Itkis

Il'ya Mikhailovich Frank belongs to the brilliant constellation of physicists in our country over the past century. He was born on October 23 (October 10 according to the Old Style), 1908 in Saint Petersburg into a family that gave Russian culture several outstanding public figures (his father, Mikhail Ludvigovich Frank, a mathematician and professor at the Crimea (Tavrichesky) University; his brother, Gleb Mikhailovich Frank, a well-known biophysicist and Full Member of the USSR Academy of Sciences; his uncle, Semyon Ludvigovich Frank, an outstanding Russian philosopher and psychologist). In 1926, Il'ya Mikhailovich entered Moscow State University. After graduating from there in 1930 he worked for several years at the State Optical Institute (SOI) in Leningrad, where he studied photochemical reactions by optical methods. His original work in this field served as the basis for conferring a doctorate on twenty-six-year-old I M Frank.

In 1934, Il'ya Mikhailovich started working at the P N Lebedev Physical Institute (LPI, RAS), which at the time was headed by S I Vavilov. Here, in 1937, in a work that became a classic, I E Tamm and I M Frank gave a comprehensive explanation of the 'mysterious Vavilov–Cherenkov glow', for which in 1958 Cherenkov, Frank, and Tamm received the Nobel Prize in Physics.

In the following years, Il'ya Mikhailovich concentrated more and more on research in the field of nuclear physics. In 1946, he became head of the Laboratory of Atomic Nucleus, newly established at LPI, RAS. One of the important problems in this field, which Il'ya Mikhailovich and his collaborators started to resolve, consisted in precise determination of the parameters of uranium–graphite lattices and in elucidating the physical regularities of neutron transport in them. The proposal put forward by Il'ya Mikhailovich to make use of a pulsed neutron source in these studies was a new idea. In 1956, I M Frank started working in Dubna, at the Joint Institute for Nuclear Research (JINR).

As is known, on March 26, 1956, in the conference hall of the RAS Presidium in Moscow an agreement was signed that established an international research organization called the Joint Institute for Nuclear Research. The institute comprised two already active laboratories: a laboratory of the Institute of Nuclear Problems of the USSR Academy of Sciences and the Electro-physical Laboratory of the USSR Academy of Sciences, which were further called the Laboratory of Nuclear Problems and the Laboratory of High Energies within the structure of the new institute. However, during the discussion of its structure at the Academy of Sciences, D I Blokhintsev, the first JINR director, proposed creating and including in the JINR structure, in addition to the two laboratories, a Laboratory of Theoretical Physics (LTP) and a Laboratory of Neutron Physics (LNP) based on a reactor with a high-density neutron flux. D I Blokhintsev's proposals were approved and reflected in the concluding announcement about the organization of JINR. He also asked I M Frank to work at JINR. Thus, in 1956 the Laboratory of Neutron Physics was organized, and it was subsequently named after its founder and first elected director, I M Frank, who occupied this position for over 30 years, and the last two years of his life he was the LNP honorary director (the person asked to be the first LTP director was the remarkable scientist N N Bogoliubov, mathematician, mechanic, theoretical physicist). Blokhintsev himself transferred to JINR from the Institute for Physics and Power Engineering in Obninsk, where in 1955 he proposed the idea of an original pulsed fast-neutron reactor of periodic action. The theory of such a reactor was fully developed in 1956, although its publication in the open press took place only in 1959 [1].

The decision was taken to create such a reactor in Dubna, and I M Frank was asked to direct the work. The choice was naturally not arbitrary. For many years Il'ya Mikhailovich had been in charge of the laboratory at LPI, RAS, the main task of which was the development of issues relevant to the creation of nuclear reactors in the Soviet Union.

Frank himself recalled: "I was instructed by Igor' Vasil'evich Kurchatov to work at and even to control operation of the first Soviet reactor nearly immediately after it was commissioned — that is, at the end of 1946, the beginning of 1947" [2].

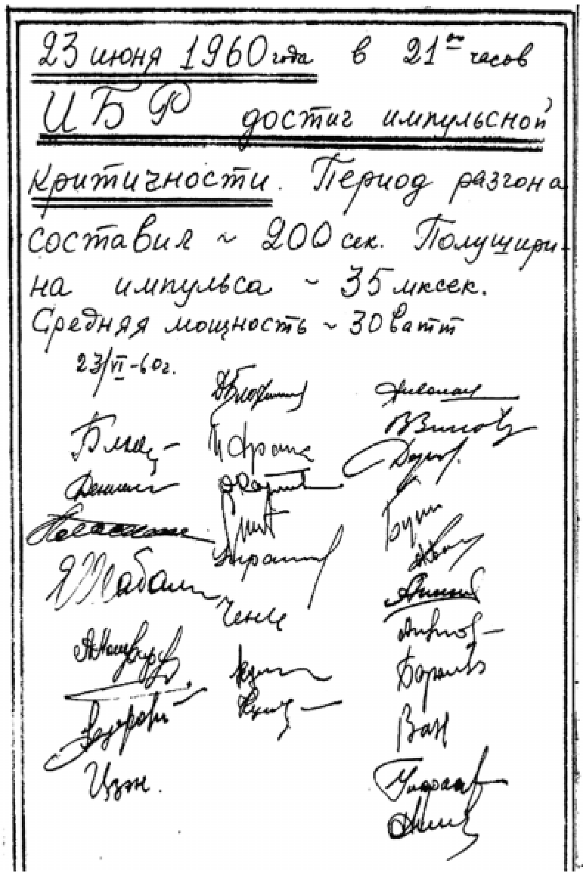
23 июня 1960 года в 21ч часов
ИБФ достиг импульсной
критичности. Период разгона
составил ~ 200 сек. Полуширина
импульса ~ 35 мксек.
Средняя мощность ~ 30 ватт
23/VI-60г.

Figure 1. Extract from the operative journal of the IBR-1 reactor, stating the achievement of pulsed criticality.

In parallel, the laboratory also dealt with other issues of nuclear physics, including the interaction of fast and slow neutrons with nuclei, nuclear fission, and the investigation of neutron reactions with light nuclei, of neutron diffusion in various media, etc.

In May, 1957 at the session of the JINR Scientific Council, Il'ya Mikhailovich presented a talk on the project of a reactor and on the potential of its application in scientific research. Immediately after approval of the project by the Scientific Council, its realization was initiated. The pulsed character of the operation of the new neutron source required development of original equipment for the control and safety systems, and for dosimetric control. For the first time in the USSR, a multichannel time analyzer was developed for time-of-flight experiments. A significant part in the implementation of this unique project was also played by staff members of the Research and Development Institute of Power Engineering (RDIPE) under the leadership of N A Dollezhal.

In 1959, the main construction work and work on creation of the equipment for the reactor called IBR (the Russian abbreviation of pulsed fast reactor) were completed, and assembly work started. On June 23, 1960 the reactor was put into operation in the mode of pulsed criticality, and its main parameters were measured and fully complied with the predictions of calculations. Figure 1 shows a photograph of an extract from the operative journal of the experimental installation, in which the signatures of all the participants, including I M Frank and D I Blokhintsev, can be seen.

At the ninth session of the JINR Scientific Council a report was presented under the title "The pulsed reactor of the Laboratory of Neutron Physics at the Joint Institute for Nuclear Research". This report described the principle of operation of this unique installation, which has no analogs in the world. The fundamental layout of IBR is depicted in Fig. 2 [3]. The pulsed character of the reactor operation was provided for by the active core *4*, which consisted of metallic plutonium, divided into two parts, in between which there was a rotating steel disk *1*, into which inserts of enriched uranium were pressed. When the uranium insert coincided with the fixed active core, the reactor for a short time underwent transition to the above-critical state and the generation of a powerful neutron pulse occurred. The average power of IBR-1 amounted to 1 kW, the length of the neutron pulse was 40 μs for a pulse repetition rate equal to 8.3 s^{-1}. The peak (pulse) power amounted to 3 MW.

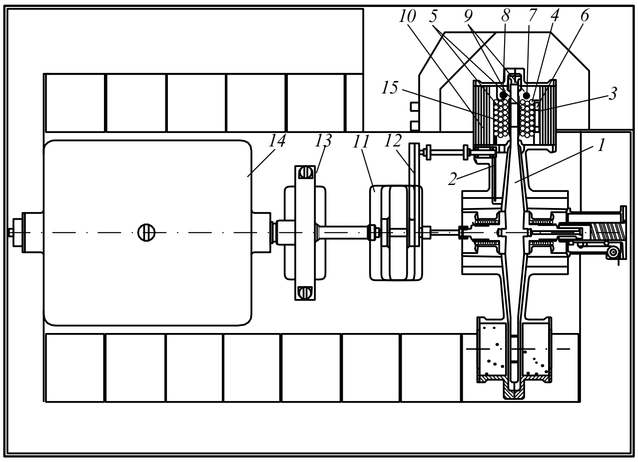

Figure 2. Layout of the reactor: *1*, main rotating disk; *2*, auxiliary rotating disk; *3*, main movable core (MMC); *4*, fixed active core; *5*, emergency rods (ERs); *6*, plate of rough regulator (RR); *7* and *8*, regulating rods; *9* and *10*, neutron reflector; *11*, gearing for enhancing the number of revolutions; *12*, driving gear for shaft of auxiliary disk; *13*, decelerating device for rapid stopping of rotation; *14*, electric motor for rotating disk, and *15*, auxiliary movable core (AMC).

Even these parameters permitted IBR to become the world's best installation for investigation of low-energy nuclear resonances and reactions exhibiting small cross sections. In Ref. [4], the parameters of the Dubna reactor are compared to the parameters of neutron sources of that period based on accelerators and stationary neutron sources.

The power of the reactor was subsequently increased to 6 kW. In 1965, for reducing the length of the neutron pulse, application of a microtron developed under the leadership of S P Kapitsa was proposed. Electrons accelerated up to an energy of 30 MeV irradiated a tungsten target and, thus, generated primary neutrons owing to photonuclear reactions. These neutrons then multiplied within the active core of the reactor. As a result, it turned out to be possible to reduce the neutron pulse length to 3 μs. In this configuration, the installation operated until 1968.

On June 10, 1969 the new reactor IBR-30 was commissioned under the guidance of I M Frank, its average power amounting to 25 kW (the pulse power of the reactor was 100 MW) for a neutron pulse length of about 60 μs and pulse repetition rate of 5 Hz. These parameters were achieved owing to the new construction of fuel elements of the active core of the reactor and to the use of two uranium inserts in the rotating steel disk, instead of one, as in IBR-1. The resulting

Table 1. IBR-30 parameters.

Date of physical commissioning Beginning of operation of electron injector	June 10, 1969 March 24, 1970
Average thermal power*	25 kW
Total neutron flux	1.3×10^{15} n s^{-1}
Average flux density of thermal neutrons on the surface of the moderator	5×10^{10} n cm^{-2} s^{-1}
Pulsed flux density of thermal neutrons on the surface of the moderator	10^{14} n cm^{-2} s^{-1}
Flux of resonance neutrons at a distance of 100 m, reduced to a power of 1 kW, in the 1 eV – 10 keV range	$F(E) = \dfrac{2.7 \times 10^6}{E^{0.9} L^2} W$ [n cm^{-2} s^{-1} eV^{-1}], where E is the neutron energy in [eV], L is the time-of-flight base in [m], W is the power in [kW]
Neutron pulse length	4 μs
Repetition rate	100 Hz
* After the Chernobyl accident (1986) work was carried out only in the booster mode at a power of not more than 10 kW.	

neutron flux from the new installation was nearly 100 times larger than the maximally attainable fluxes at neutron sources based on electron accelerators existing at the time.

On March 24, 1970 a new injector, based on the linear electron accelerator LEA-40, was commissioned. As a result, it became possible to operate the installation not only as a pulsed reactor, but also in the electron booster mode (IBR-30+LEA-40). This permitted implementing a whole series of original scientific experiments, both in the field of nuclear physics and in the field of neutron studies of condensed media, which will be briefly dealt with below. The neutron source in the IBR-30+LEA-40 configuration operated for physical experiments for nearly 80 thousand hours until June 2001. The main parameters of IBR-30 are presented in Table 1.

For the development and creation of pulsed research reactors and pulsed boosters, I M Frank, together with a group of authors, was awarded the USSR State Prize in 1971.

As mentioned above, the reactor was created for research in the field of nuclear physics. In a series of research lines pioneering results were obtained, many of which are still being actively developed at world research centers. I M Frank worked out the scientific program of research in the Laboratory of Neutron Physics in close collaboration with his deputy, friend, and closest colleague F L Shapiro. Part of the scientific program developed and realized at the LNP is briefly described below.

High-luminosity spectroscopy of neutron resonances. Having no electric charge and, consequently, no Coulomb barrier preventing a neutron from penetrating into a nucleus, neutrons can be used for obtaining excited nuclei lying in the region of beta-stable isotopes. The capture of a neutron by a nucleus results in an excited state of a compound nucleus with an energy close to the neutron binding energy with a lifetime of the order of 10^{-15} s and an energy width of about 0.66 eV. Considering the nuclear reaction to be a process proceeding via two independent stages, the reaction cross section may be represented as [5]

$$\sigma_{\mathrm{x}} = \sigma_{\mathrm{c}} w(\mathrm{x}) \,, \tag{1}$$

where σ_{c} is the production cross section of the compound nucleus, and $w(\mathrm{x}) = \Gamma_{\mathrm{x}}/\Gamma$ is the branching ratio of its decay via the channel involving the production of particle x. The energies and widths of the nuclear levels of the compound nucleus can be determined by studying resonance behavior in the energy dependences of the cross sections. Registering of various decay channels of compound states permits determining the partial decay probabilities of the compound states.

Effects of hyperfine interaction in neutron resonances. One of the most striking examples demonstrating the potential of the technique of neutron spectroscopy at the IBR-30 reactor is presented by experiments making use of hyperfine interaction effects in neutron resonances for investigation of the properties of compound states, namely, of magnetic moments and of the root-mean-square radii of nuclei. Series of such studies were carried out at the LNP in the years 1973–1976 [6, 7] and in 1981 [8].

Conventional methods for measuring the magnetic moments of nuclei (based on the Mössbauer effect and on the perturbation of angular correlations) could not be applied in the case of compound states. F L Shapiro [9] was the first to point to the possibility of measuring magnetic moments of neutron resonances taking advantage of the energy shift in neutron resonances due to hyperfine interaction of the magnetic moment of a nucleus with the interatomic magnetic field in experiments with polarized neutrons or nuclei. The mechanism by which an energy shift in the position of a neutron resonance appears is explained by the existence of an interatomic magnetic field H, the interaction of which with the nucleus exhibiting spin I, spin projection m, and magnetic moment μ_0 results in an energy shift $\mu_0 Hm/I$, a similar shift being experienced, also, by the compound nucleus; thus, the resulting shift is expressed in the form

$$\Delta E_{mm'} = H\left(\frac{\mu_{\mathrm{b}} m'}{J} - \frac{\mu_0 m}{I}\right). \tag{2}$$

To obtain the final expression describing the shift of a neutron resonance, ΔE_0, one must take the sum of $\Delta E_{mm'}$ over all possible states, taking into account the statistical weights and populations of the sublevels. Thus, in the case of zero polarization $f_{\mathrm{n}} = 0$ of the neutron beam, we arrive at

$$\Delta E_0 = -f_{\mathrm{N}} H\left\{\left[1 - \frac{1}{(2I+1)(I+1)}\right]\mu_{\mathrm{b}} - \mu_0\right\}, \quad J = I + \frac{1}{2}\,,$$

$$\Delta E_0 = -f_{\mathrm{N}} H(\mu_{\mathrm{b}} - \mu_0)\,, \quad J = I - \frac{1}{2}\,. \tag{3}$$

The quantity ΔE_0 turns out to be quite small: assuming μ_{b} and μ_0 to differ from each other by one nuclear magneton, and the field on the nucleus to amount to 10^6 Oe, the shift turns out to be equal to $\Delta E_0 \approx 3 \times 10^{-6}$ eV, which is 4–5 orders of magnitude less than the proper width of the neutron resonance.

At the IBR-30 reactor, the transmission of neutrons through metallic foils of the rare-earth elements Tb, Dy, Ho, and Er was observed by the time-of-flight method. The nuclei of these elements were polarized by deep cooling (≈ 30 mK) in a cryostat with dilute solutions of ^{3}He in ^{4}He. The internal magnetic fields on the nuclei of these elements were of the order of $(3-7) \times 10^6$ Oe, and polarization of the nuclei inside the domains was between 0.84 and 0.99. For destruction of the polarization, the temperature on the target was increased to 0.5–1.5 K. Alternating measurements with polarized and nonpolarized nuclei made it possible to take time-of-flight spectra in which the relative shift of resonances was described by expression (3). To derive the value of the shift, the spectra were fitted by the method of least squares. Prolonged measurements (for about 300 h for each element) permitted deriving the values of magnetic moments of the nuclear compound states. Analysis of the data on magnetic moments of rare-earth nuclei, in spite of its relatively low precision (here one must acknowledge the skill manifested by the experimenters and the stability of the neutron source: the shifts in the resonances measured were of the order of 10^{-4} of their proper width), permits, nevertheless, providing a general description of the magnetic moments of compound states of rare-earth nuclei and comparing them with the theoretical estimates of these values. Theoretical analysis has permitted making the conclusion that the description of magnetic moments of the compound states of nuclei within the framework of the statistical model is rightful and, thus, the model receives confirmation in one more field.

Violation of space* (P) *and time* (T) *parity in compound nuclei. In accordance with the model of universal electroweak interaction, the Hamiltonian describing the interaction of nucleons in a nucleus can be represented in the form $H = H_0 + W$, where W is a small addition, due to the weak interaction, that violates P-parity. The existence of such a term in the Hamiltonian can result in the appearance of P-odd additions in the experimentally examined quantities. Estimations made for simplest one-particle nuclear processes have shown that the magnitudes of such effects should amount to $10^{-6}-10^{-7}$; however, there have also been approaches within which it was shown that in complex nuclei the mixing of excited states of different parities and of the same spin (s- and p-resonances of the same spin in the case of excited states produced by neutron capture), resulting in P-odd effects, may be significantly heightened when they are close to each other in energy. Such heightened effects were observed in experiments starting from 1964 [10]. In the middle of 1981, publication started of experimental works carried out in the LNP of JINR at IBR-30 [11–14], in which for a number of nuclei the dependence of the total neutron cross sections on the neutron helicity was studied. Experimentally, measurement was performed of the transmission effect:

$$\varepsilon = \frac{T_+ - T_-}{T_+ + T_-}\,, \tag{4}$$

where $T_\pm = \exp(-n\sigma_\pm)$ represents the transparencies of the target for neutrons with positive and with negative helicities, and n is the target thickness expressed by the number of nuclei per square centimeter, from which the magnitude of the P-odd effect and, if the spins of the mixing resonances are known, the weak matrix element are derived. The area of the target amounted to 30 cm^2, the neutron beam polarization was at a level of 60%, which was provided for by a polarized proton target designed and made in the LNP on the base of lanthanum–magnesium nitrate $[(La_2Mg_3(NO_3)_{12} \times 24H_2O$ with a paramagnetic admixture of ^{142}Nd substituting for La in the extent of 0.4%.

The dependences of the total cross sections on the neutron helicity were measured for 14 resonances of the nuclei ^{81}Br, ^{93}Nb, ^{111}Cd, ^{117}Sn, ^{127}I, ^{139}La, ^{145}Nd, and ^{238}U. In the case of four resonances, a statistically significant effect due to the violation of spatial parity was found for the first time. Further development of these studies led to a broad international collaboration involving participants from JINR, the USA, Holland, Japan, and Canada (the Triple Collaboration). This collaboration resulted in several dozen p-wave resonances in different nuclei studied and their spins being determined, which made it possible to derive the weak matrix element from experimentally observed effects and to obtain values of root-mean-square weak interaction matrix elements that are in agreement with theoretical predictions.

The alpha decay of compound nuclei. In accordance with the notion of a nuclear reaction resulting in the production of a compound nucleus via a two-stage process, investigation of the (n, α)-reaction with resonance neutrons is interesting from two standpoints. On the one hand, it represents a line of research in neutron spectroscopy that permits studying total and partial alpha widths — a set of characteristics of neutron resonances complementary to the known neutron and radiative widths. On the other hand, it involves the alpha decay of complex highly excited compound states. Since the lifetimes of compound states are much longer than nuclear times, a compound state can be considered quasistable, and its alpha decay can be dealt with by analogy with the alpha decays of the ground states of nuclei.

In a number of cases the investigation of alpha decays of compound states permits putting aside the individual structural peculiarities of the decaying state and essentially broadening the range of energies and half-life periods studied. Thus, the alpha decay energy of the ground state of the ^{144}Nd nucleus is $E_\alpha^0 = 1.83$ MeV, while for the compound states it is $E_\alpha^c = 9.4$ MeV. This leads to a difference of 33 orders of magnitude between the half-life periods of the ground and excited states of the ^{144}Nd nucleus.

One of the possible decay paths of the excited state of a nucleus consists in the emission of a gamma quantum and the subsequent alpha decay of the produced intermediate state. Here, the energy spectrum of alpha particles will exhibit, together with narrow peaks corresponding to direct alpha transitions to the ground and excited states, a broad maximum due to the gamma–alpha process. Since a large number of intermediate states take part in a two-stage process, this will result in a good averaging of its probability and permit making quite general conclusions regarding the properties of intermediate states and the peculiarities of gamma transitions with energies $\leqslant 1$ MeV between the highly excited states (C$-$C transitions).

The calculated energy dependence of the alpha width averaged over the alpha spectrum was used for restoring the relative energy dependence of the radiation force function of the primary gamma quanta. At the same time, the precision in the absolute determination of the force function turned out to be low owing to the limited calculation accuracy of the barrier penetrability for the alpha particle. Studies of the (n, α)-reaction cross sections [15–17] averaged over the resonances permitted essentially enhancing the effective number of resonances and reducing the normalization uncertainty in calculating the barrier penetrability. All the above permitted performing straightforward restoration of the absolute value of the radiation force function of the primary soft gamma transitions from the experimental spectrum of secondary alpha particles in the $(n, \gamma\alpha)$ reaction [18] and performing for the first time comparison of experimental data on the radiation force function for gamma transitions of multiplicity E1 over the entire range of energies studied: from 0.2 up to 20 MeV.

The discovery of ultracold neutrons. In spite of the fact that many specialists working in neutron physics attribute the idea of neutron storage to E Fermi, the first work [19] in which the possibility of storage is indicated and the first estimates are given for the density of ultracold neutrons (UCNs) attainable in an installation with a liquid-helium converter was published in 1959.

UCNs are neutrons of extremely low kinetic energy: $\sim 10^{-7}$ eV. The main property distinguishing UCNs lies in the fact that they can be reflected from vacuum–medium interfaces at any angles of incidence. This is true if the neutron energy is smaller than the so-called Fermi potential

$$U = \frac{\hbar^2}{2m_n} 4\pi N_0 b \,, \qquad (5)$$

where m_n is the neutron mass, N_0 is the density of the nuclei, and b is the coherent neutron scattering amplitude. This property of UCNs underlies their attractiveness as objects for studying the properties of the neutron itself and the interaction processes of neutrons with surfaces.

In 1968, F L Shapiro once again drew attention to UCNs. While analyzing the possibility of experimental determination of the electric dipole moment (EDM) of the neutron, Shapiro proposed making use of UCNs to search for the neutron EDM [20]. This stimulated experimental work for obtaining and storing UCNs. In 1968, UCNs were registered [21] for the first time at the pulsed reactor IBR-1. Thus, it was shown that the apparently unresolvable problem of distinguishing UCNs against a background of thermal neutrons could be effectively resolved by extracting UCNs from the active core of a reactor along a bent specular neutron guide.

The improvement of UCN sources still continues. The number densities achieved are on the order of 50 n cm^{-3}, which is four orders of magnitude more than in the first experiments. There are projects in which it is planned to increase the number density up to 10^3 or 10^4 n cm^{-3}. The most accurate values of the neutron lifetime, the limits for the neutron charge ($\leqslant 10^{-25}e$), and EDM ($\leqslant 10^{-26}e$ cm) have been obtained with the aid of UCNs.

Further development of UCN sources will, doubtless, lead to an improvement in the experimental accuracy and, consequently, to new confirmations (or corrections) of modern electroweak interaction models, of the fundamental properties of the neutron, and of the astrophysical processes involving neutrons.

At the same time, the Polish physicists B Buras and E Janik have proposed experiments which have been started on neutron sources at the LNP for studying the structure and dynamics of condensed media. Diffractometers and spectrometers of inelastic scattering have been created, with which investigations have started of the structure of crystals, atomic and molecular dynamics, the structure and dynamics of liquids, the level spectroscopy of the crystalline electric field in rare-earth chemical compounds, etc. At the beginning of the 1970s, I M Frank initiated studies of the properties of biological objects making use of neutrons. Owing to this fact, an installation for small-angle neutron scattering was created at IBR-30 under the leadership of Yu M Ostanevich, which turned out to be exceptionally efficient in resolving a whole series of problems related to biology. But the most rapid advancement of studies into condensed media has taken place at the newer IBR-2 reactor.

I M Frank (to the right) and N A Dollezhal.

The IBR-2 reactor. From 1966, I M Frank and D I Blokhintsev were engrossed in the idea of creating the powerful pulsed reactor IBR-2. The prerequisites for this were the enhanced interest of the world scientific community in neutron sources, both stationary and pulsed, the successful experience of the IBR operation, and the necessity of increasing the neutron flux density in extracted beams. The idea was supported at JINR and by the USSR Government. With the active participation of I M Frank, research and design work started for creating IBR-2. The chief designer was N A Dollezhal (RDIPE) and the scientific project leader was D I Blokhintsev (1967 – 1979) and, after 1979, I M Frank. On the initiative of I M Frank a department was created at the LNP, the scope of which included scientific guidance and supervision of work for IBR-2.

In 1969, construction of this very complex, unique facility started. The construction of IBR-2 proceeded with the determined support of the Ministry of Medium Machine Building: this included financial resources, new technologies, and engineering and intellectual support by its specialized institutions. The role of I M Frank in coordinating all these efforts was great.

In 1977, successful physical commissioning of IBR-2 took place without the heat carrier (sodium) [22]; physical

I M Frank at the control panel of the IBR-2 reactor.

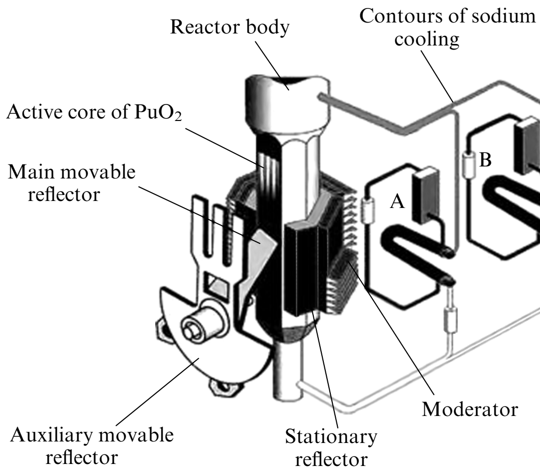

Figure 3. Schematic layout of the IBR-2 reactor.

Table 2. Main parameters of the IBR-2 reactor.

IBR-2 parameter	Value
Average power, MW	2
Kind of fuel	PuO_2
Number of RFAs	78
Maximum burnout, %	6.5
Pulse frequency, Hz	5; 25
Pulse half-width, μs	215
Average thermal neutron flux, cm^{-2} s^{-1}	5×10^{12}
Peak flux of thermal neutrons, cm^{-2} s^{-1}	10^{16}

commissioning with the heat carrier and then the power commissioning was in 1980–1984 [23]. As scientific leader, I M Frank took immediate part in all commissioning work. Figure 3 shows the schematic layout of the IBR-2 reactor.

In this reactor, the horizontal cross section of the active core made of plutonium dioxide has the shape of an irregular hexagon. Near one of the active core's sides there is a reactivity modulator which consists of the main and auxiliary movable reflectors. The blades of these reflectors rotate with different velocities, and when they cross the middle of the active core simultaneously, the reactor undergoes a transition to the above-critical state. Cooling of the active core is realized with the aid of liquid sodium. Such a scheme has permitted obtaining parameters that are truly unique from the point of view of the pulsed yield of neutrons from the reactor. IBR-2 is still the most high-flux research pulsed neutron source in the world. The main parameters of the reactor are presented in Table 2.

IBR-2 in Dubna is distinguished among other pulsed neutron sources in the world by its record high average power (2 MW) and its peak neutron flux value (10^{16} cm^{-2} s^{-1}), as well as its small pulse repetition frequency (5 Hz instead of the standard 30 – 50 Hz). A unique experimental base has been created at the reactor. The creation of most of the installations was based on international cooperation; for example, the small-angle experimental setup was prepared in collaboration with Hungary, the inelastic scattering spectrometer in collaboration with Poland, the complex of diffractometers for geological studies in collaboration with Germany, and the Fourier diffractometer in collaboration with Finland, and so forth. A distinguishing and unique feature of IBR-2 consists in the existence of a channel for irradiation over a large area — 20×40 cm in diameter — with an easy accessibility for the delivery of samples. The flux of fast neutrons in the channel is 3×10^{12} cm^{-2} s^{-1}. Moreover, the channel is equipped with a setup for irradiating small samples at low temperatures (down to 10 K); no other cryogenic setup for irradiation in a high neutron flux exists in Russia.

The presence in the neutron spectrum of the fast pulsed IBR-2 reactor of a significant fraction of epithermal and resonance neutrons provides a unique possibility for performing neutron activation analysis (NAA) with epithermal neutrons, and it thus permits enhancing the sensitivity of the method to elements with large cross sections in the epithermal energy range, primarily to rare-earth elements. Thus, the sensitivity of the pneumo transportation unit (PTU) Regata to rare-earth elements amounts to a value of the order of 10^{-5} ppm, which is two–three orders of magnitude higher than the sensitivity of NAA systems making use of thermal neutrons. Work is carried on in collaboration with Russian and foreign scientific centers with financial support via grants from JINR member states, the European Union, NATO, and others.

Thus, to conclude it can be noted that under the guidance of I M Frank from 1957 until 1989 the Laboratory of Neutron Physics at the Joint Institute for Nuclear Research achieved outstanding results in the creation and operation of periodic-action pulsed reactors utilizing fast neutrons. A scientific and technological school in pulsed neutron sources was founded, gaining recognition from the scientific community.

Many scientific lines of research, work along which started under the leadership of I M Frank, have reached a qualitatively new level and are realized today on the basis of wide international cooperation with JINR member states and numerous partners both in Russia and abroad.

Successful work at JINR on the modernization of IBR-2 and on the creation of the IREN facility (source of resonance neutrons), the commissioning of which took place in December 2008, and a large series of scientific experiments carried out at collaborating scientific centers after the death of Il'ya Mikhailovich, all serve as the best possible memorial to a remarkable scientist.

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I M Frank: founder and leader of FIAN's Laboratory of Atomic Nucleus

B A Benetskii

This talk is dedicated to the foundation and development of the I M Frank laboratory, to neutron and nuclear experiments, and to attacking the so-called nuclear problem.

In 1934, when I M Frank accepted S I Vavilov's offer to transfer from the State Optical Institute (SOI) to the Physical Institute of the USSR Academy of Sciences (FIAN *in Russ. abbr.*), the former was a young man, but, nevertheless, a fully formed researcher with about ten years of experience as a scientific worker. I M Frank performed his first work of original scholarship at the Mathematical Society of Tavrichesky University, which had been temporarily transformed into a pedagogical institute, where, although he was not a student of that institute, he attended lectures during the academic year of 1925–1926 and worked in the physical laboratory of the institution. This first work in geometry, which was most likely done under the influence of his father, Mikhail Ludvigovich Frank, a talented mathematician, was published in 1928. At the time I M Frank was a student of the Physics and Mathematics Department at Moscow State University (1926–1930), where he combined educational studies in physics (at the chair headed by L I Mandel'shtam) and mathematics, which involved formulating new problems for special training in physics. Also at that time, I M Frank, under the supervision of S I Vavilov, completed an investigation on the quenching of luminescence, which they published in 1931.

Il'ya Mikhailovich felt a profound respect and warmth for Sergei Ivanovich Vavilov, and called him Teacher, and even when he pronounced this word, it was always and truly with a capital letter. How Sergei Ivanovich estimated his pupil can be seen from his judgment of I M Frank's scientific work [1], expressed in 1938 in his recommendation for I M Frank to be elected Corresponding Member of the USSR Academy of Sciences. "Il'ya Mikhailovich Frank ... has proved to be an excellent, extremely versatile experimental physicist of outstanding theoretical erudition. In one of his first works [devoted to quenching processes in fluorescent liquids — *B.A.B.*] ... he showed good experimental skills and exceptional physical intuition.... These works [studies of photochemical reactions — *B.A.B.*] revealed initiative and originality of the experimental technique used and of I M Frank's scientific thinking. The works are interesting for the elegance of the method and the comprehensive analysis of the experimental data.... In 1933, I M Frank accepted my proposal to start working in a totally different field — in the physics of the atomic nucleus. It was with surprising speed that he accustomed himself to the technique... became familiar with the world literature and became a leading worker in the young laboratory of atomic nucleus*... I M Frank lively participated in performing and explaining P A Cherenkov's experiments.... Thus, for example, I M Frank made the brilliant guess that we were confronted with a totally new phenomenon peculiar to the propagation of electrons traveling with a velocity exceeding the phase velocity of light in a dense medium. This idea underwent complete and quite rigorous development in the theoretical work by I E Tamm and I M Frank.... I M Frank being exceptionally gifted, his erudition and excellent scientific results were already manifested in the fact that the Presidium of the USSR Academy of Sciences conferred on I M Frank the degree of Doctor of Physicomathematical Sciences in 1934, when he was 26 years old."

The doctorate thesis, which was completed in three years at SOI in the laboratory headed by A N Terenin, was devoted to experimental investigation of photochemical reactions by optical and spectrometric methods.

* The future Department of Nuclear Physics chaired by D V Skobel'tsyn at the FIAN. (*Comment by B.A.B.*)

To understand the scale of Il'ya Milhailovich's breadth of interests and capabilities, one must supplement the aforementioned with the following. In 1934–1935 he carried out an investigation of cosmic rays, applying the Wilson chamber on Elbrus; in 1937–1940, together with L V Groshev, he studied the production of electron–positron pairs by gamma quanta (a study characterized by S I Vavilov as "exceptionally thorough and complete"); in the same years he took part with N A Dobrotin and P A Cherenkov in the work of the Stratosphere Commission of the Academy of Sciences, which led to the discovery of the effect of sharp variation in intensity of the luminosity of the night sky; in 1942, by methods of classical electrodynamics, he carried out a study of the Doppler effect in refractive media, and in 1946, together with V L Ginzburg, he predicted the existence of a new phenomenon, namely, transition radiation emission.

The year 1946 happened to be one of acknowledgment and of new problems. He won the prize that is now known as the State Prize of the First Class for the discovery and explanation of the nature of Vavilov–Cherenkov radiation (he himself used this term for the radiation), was elected Corresponding Member of the USSR Academy of Sciences, and became founder and leader of a laboratory in the Physical Institute of the USSR Academy of Sciences. This laboratory was organized on April 1, 1946, when the Department of Nuclear Physics, led by D V Skobel'tsyn, was divided into three laboratories headed by I M Frank, N A Dobrotin, and V I Veksler. I M Frank's laboratory remained at the FIAN until January 1, 1971, when three FIAN laboratories — of atomic nucleus, of photonuclear reactions, and of neutrinos — were brought together to organize the Institute for Nuclear Research (INR) of the USSR Academy of Sciences (now INR, RAS).

In 1946, the main lines of research of I M Frank's laboratory were determined by the necessity of resolving the 'nuclear problem', namely, of determining the microscopic characteristics of nuclear fission processes and of neutron interactions with nuclei and the macroscopic parameters of nuclear reactors, and of studying reactions with the lightest nuclei (such as the interaction of neutrons with lithium, deuterons with deuterium, and deuterons with tritium).

The newly established laboratory had no experimental means, with the exception of the most powerful radium source in the Soviet Union, which belonged to the FIAN. Besides this, there was actually nothing [2].

When the laboratory was organized, it comprised, including its leader, five researchers, and by the end of the year, fifteen, including a specialist in electronics and three engineers. By the end of 1949 it already had 25 staff members. In these conditions Il'ya Mikhailovich showed himself to be an outstanding organizer and leader of a scientific team: work started immediately.

A witness testifies: "When we arrived in 1946, there was only the central building and nothing else. In the building was Frank's laboratory. On the second floor there were, apparently, three rooms, two of which were adjacent. There was an entrance to the room and two exits to the right and left. There were two other rooms, in which I have never been, because they were secret. As a matter of fact, it was there that work started on neutron multiplication in uranium–graphite systems for reactors. This work was conducted by I M Frank, L V Groshev, L E Lazareva, and later E L Feinberg. What went on there I don't know. There were three rooms — we were in the central one — and they ran back and forth from one room to another. There was no guard, only, so to say, internal discipline" [2].

At the time, the first task was measurement of the deviation from unity of the neutron multiplication coefficient equal to the product of the number ν of secondary neutrons produced in the fission of uranium and the probability φ of their deceleration to thermal energies and the probability of their remaining in the multiplying system, θ:

$$\nu\varphi\theta - 1\,.$$

According to V Weisskopf's pithy remark, the misfortune of humankind was the consequence of God having made this difference, albeit small, positive. If it had turned out to be equal to two-tenths, a reactor with natural uranium would have had to be excessively large. Therefore, it was necessary not only to determine this quantity, but also to try to find ways of increasing it. This was what the people running "back and forth from one room to another" were engaged in.

The rest of the laboratory was only just forming. The laboratory comprised physicists who had come back from the war, i.e., young people without work experience in this field. "We came after a year-long course. Some of us bypassed it... For the rest of the staff tasks pertaining to general nuclear physics were formulated, and the means were very limited" [2]. And further: "Il'ya Mikhailovich apparently understood the necessity of certain technical means for work in nuclear physics, and in the room on the ground floor of the main building we started to assemble an accelerating tube: the Cockroft–Walton cascading voltage multiplier. E M Balabanov (who was a specialist in electrical phenomena in gases and dealt with corona discharges) and L N Katsaurov constructed this tube. Here, E M Balabanov used his connections to procure capacitors, and a certain porcelain intended for other purposes. Anyhow, with makeshift materials they assembled an accelerating tube." At least three such accelerators were assembled, and their energy turned out to be sufficient for creating sources of fast neutrons and for studying their reactions with the lightest nuclei.

On the whole, during the period up to 1952 a new scientific team, as well as the experimental and measuring bases, were created, and theoretical foundations and measurement methods were developed. Studies were carried out in the physics of neutron interactions with matter and in the physics of interactions of fast neutrons with nuclei (including uranium for resolving the blanket problem — of the fissioning casing of a thermonuclear reactor); the cross sections of reactions with the lightest nuclei (nLi, DD, DT) were measured; the practically important characteristics of fission and reactor parameters were determined (including neutron multiplication coefficients, geometrical parameters, probabilities of deceleration to thermal energies). Here, the reactor parameters were determined by the alternative method to the method of assembling critical systems — by the 'prism method'.

At the beginning, the prism theory was developed by I I Gurevich and M Ya Pomeranchuk for a homogeneous system, but it was known *a priori* not to be the optimal version. Il'ya Mikhailovich and his colleagues investigated subcritical uranium–graphite systems in which exponential attenuation of the neutron flux was observed, when a neutron pulse was injected into such a prism (the so-called method of nonstationary diffusion). In 1946–1949, work was carried out for the investigation of equilibrium spectra and the diffusion parameters of neutrons in multiplying and decelerating media. It was revealed that the effective temperature of neutrons flowing out from the moderator can differ from the temperature of the medium. The diffusion cooling effect was discovered — the dependence of the average neutron velocity in the medium and, consequently, of the neutron diffusion coefficient on the dimensions of the moderator.

A logical continuation of this line of research consisted in the development of a method for performing the spectrometry of slow neutrons by their slowing-down time. In the laboratory, within short periods of time the project of an original slowing-down time spectrometer (STS) in lead was designed and constructed on the basis of the Cockroft–Walton generator owing to the efforts of the same group.

Back in 1944 E L Feinberg, while considering the process of neutron moderation in a medium of heavy atoms, exposed an effect that brings to mind the principle of particle autophasing in the case of acceleration. In such a medium, neutrons with higher velocities collide with heavy nuclei more often and are slowed down more effectively, while those with lower velocities are decelerated less effectively. When the deceleration process starts at the same time, a grouping takes place of the spectrum of neutrons being decelerated around the average energy $\bar{E}$. This energy is functionally related to the slowing-down time t, for example, for values of $\bar{E} \gg 1$ eV [3]:

$$\bar{E} = \frac{K}{(t - t_0)^2} \, ,$$

where K and t_0 are the parameters depending on the characteristics of the moderator and of the neutron source. Such is the principle of neutron slowing-down time spectrometry. The neutron spectrometer by slowing-down time in lead turned out to be a very efficient means for studies in the field of reactors, including measurement of neutron capture cross sections.

When in 2003 I happened to be collecting material for the 95th anniversary of Il'ya Mikhailovich's birthday, it turned out to be impossible to find any reference to the date when the first STS in the world was put into operation in I M Frank's laboratory. The explanation of such a strange fact happens to be found in the recollections by Evgenii L'vovich Feinberg. It must be noted that I M Frank many times and on different occasions stressed E L Feinberg's contribution to the establishment and development of the laboratory, even introducing a special term: 'associated member of our laboratory'.

In his paper entering the book of memories of F L Shapiro [4], Evgenii L'vovich quite clearly explained what happened: "Those 'who were supposed to keep an eye on us' read my questionnaire very carefully, and in 1950 I was no longer permitted to take part in secret work (apparently, I was admitted at the early stage of development of the Soviet Atomic Project, when there were catastrophically few people...).... But then the 'representative of the Council of Ministers at the FIAN' F P Malyshev, a general from 'security', upon estimating the success offered Fedor L'vovich (Shapiro) and L E Lazareva in registering a patent for this spectrometer and to receive a certificate for the invention. They agreed only under the condition that I was to be one of the authors. The general was opposed, but they refused to give in. So the issue come to naught."

People who worked with Il'ya Mikhailovich know he was an extremely considerate and not too open person, which to some could seem a manifestation of weakness, but actually his principles were unshakeable. Today not everybody can comprehend what courage was required of the staff and the head of the laboratory at the time (about 1948–1949) during the described confrontation.

The invention was registered about four decades later in 1988 on the basis of the results of studies of the stationary and nonstationary diffusion of neutrons. Later on, in our country and in a number of others (the USA, Japan) spectrometers similar to the first STS that was in operation in the Laboratory of Atomic Nucleus until 2005 were constructed on the basis of more powerful neutron sources. And in 2003 the first scientific results were obtained with the 'Great Cube', the new STS in the proton beam of the INR linear accelerator, exceeding in efficiency at the time of commissioning other such spectrometers by at least five orders of magnitude. As Il'ya Mikhailovich used to say, "Neutrons are the specialty of our home."

In 1953, I M Frank and six other staff members of his laboratory were awarded the State Prize 'for work on the physics of reactors and studies of nuclear reactions with the lightest nuclei'. On the whole, for this work 31 people working in the laboratory, i.e., all those who worked in the laboratory from the time it was founded up to 1950 inclusive, had awards conferred on them by the Government. Owing to the restricted time for this talk, I will no longer bring up material from a historical standpoint, and will refer to our publication [5] (see the Supplement, starting from p. 12).

If M Montaigne's assertion that an individual is a style is correct, then it most likely is also valid for a scientific or, generally, a creative community. And Il'ya Mikhailovich, as is known to all who had the luck to communicate with him, as a scientist and scientific leader manifested traits pertaining to the particular style of the 'old' FIAN. What determined this style of scientific activity? I believe it was the following:

— first, aspiration for ultimate clarity and completeness in understanding the essence of the subject studied independently of the assumed value of the result of investigation. Or, which is no less important, a clear definition of the boundaries of such an understanding;

— second, belief in the unity and equality of all the components of what we understand to be expressed by the words 'science' and, in particular, 'physics';

— third, acknowledgment of the priority of experimental methods of investigation in the physical sciences. "Love is good, but a golden bracelet is better." Here, the golden bracelet is meant to be the result of experiment (with the reservation: 'if it is not exaggerated');

— fourth, the aspiration to find the most simple (in the best meaning of this word) way of investigation, in which case the main instrument for studying Nature is the head of the experimenter and the rest is a supplement to it. In this case, his estimates were quite severe: "NN is an instrument person";

— fifth, high criticality in determining the degree of reliability of his own results and conclusions. I well remember an episode where Il'ya Mikhailovich did not 'permit' publishing experimental data obtained in a work with his participation for eight years, until he was not sure of their 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

$$U_{\mathrm{eff}} = \frac{\hbar^2}{2m}\,\frac{Nb}{\pi} \qquad (1)$$

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

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

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:

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

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 $k_{\mathrm{lim}} = \sqrt{4\pi N b'}$, 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:

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

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:

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

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]:

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

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

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

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

$$v' = \frac{h}{m}\, k' \,. \qquad (8)$$

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

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

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

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

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.

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

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.

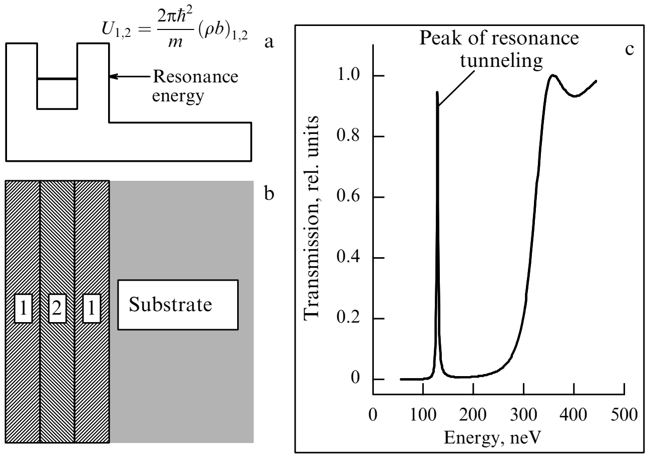

Figure 1. Fabry–Perot interferometer (FPI) for neutrons. (a) FPI potential structure. (b) Layout of the interferometer: three films of two kinds of substances are deposited on the substrate. (c) FPI transmission dependence on energy in the case of normal incidence of neutrons on it.

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

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

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.

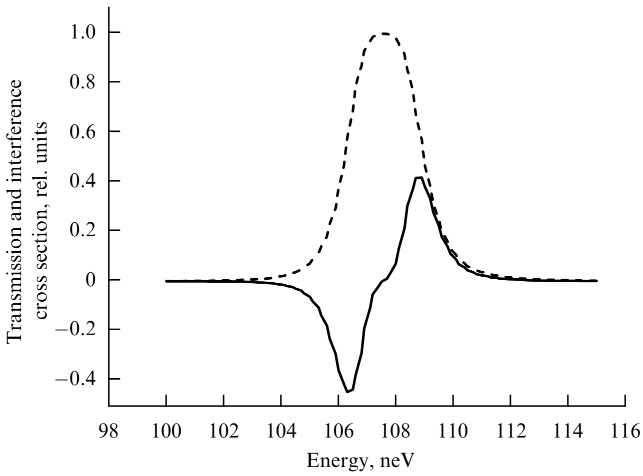

Figure 2. The interference cross section characterizing deformation of the neutron transmission line through the real FPI. The dashed line shows the position of the unperturbed transmission curve. The scale is arbitrary. The behavior of the cross section showing alternating signs corresponds to the asymmetric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

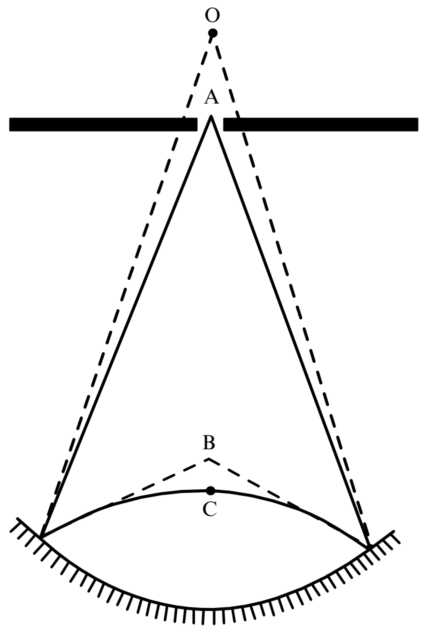

Figure 3. Sketch from an article by I M Frank in the journal *Priroda* (1972).

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:

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

where T is the amplitude of the unperturbed wave, and $f(k_{\mathrm{t}},k_{\mathrm{t}})$ 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

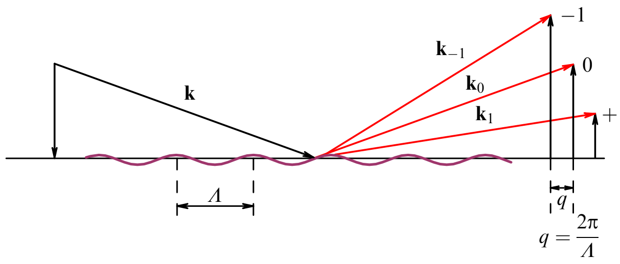

Figure 4. Neutron diffraction by a surface wave in a moving frame of reference. The wave vectors of all the waves are identical in absolute value. The normal components of waves of nonzero orders of diffraction differ from the normal component of the incident wave.

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.

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

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

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.

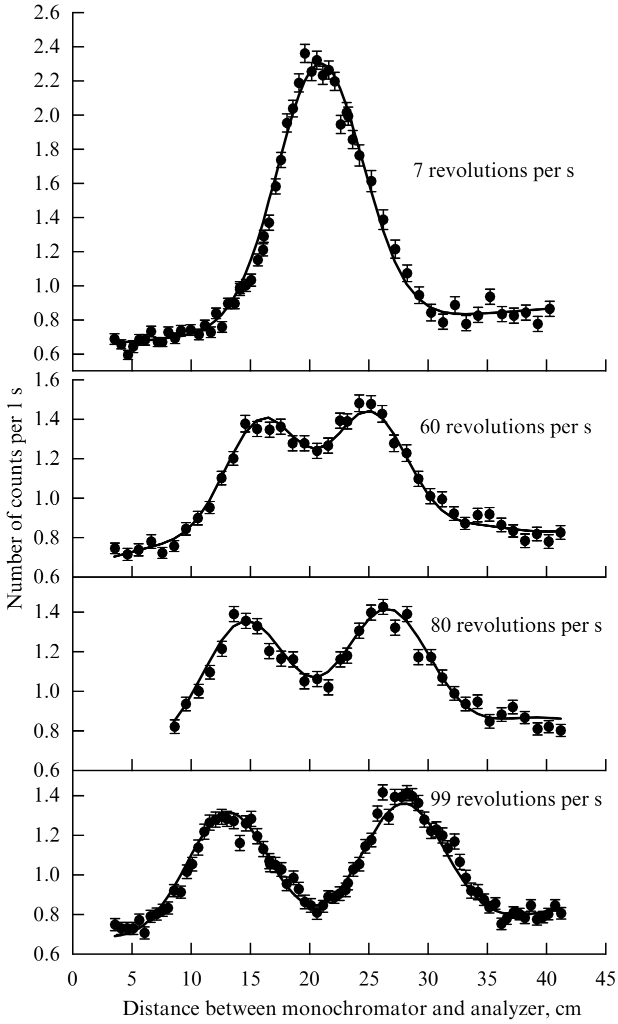

Figure 5. Spectrum of neutrons transmitted through a rotating grating. The grating rotation frequency is indicated in the figure. A change in distance between the analyzer and the monochromator of 1 cm corresponds to a change in energy of 1 neV. A grating rotation velocity of 100 revolutions per s corresponds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

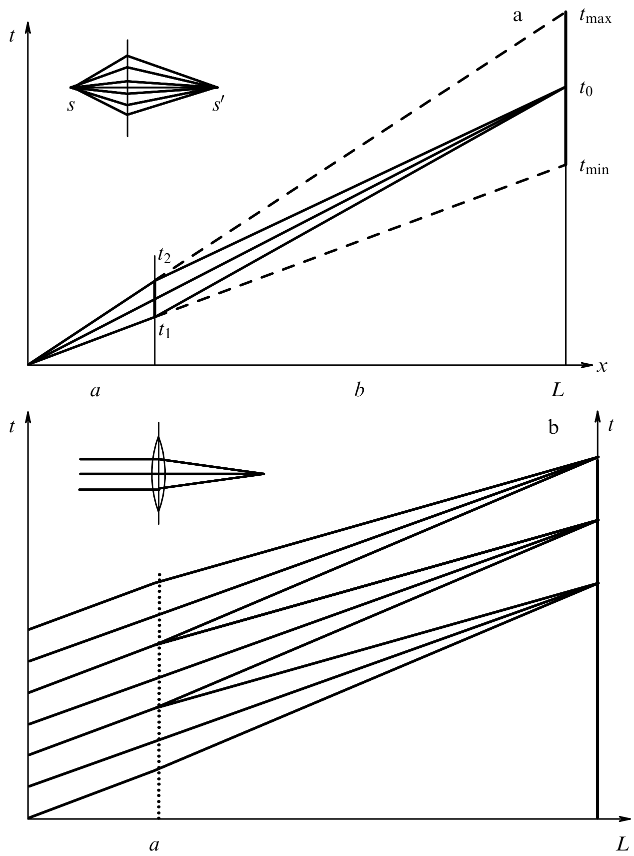

Figure 6. (a) Focusing of neutrons from a pulsed source in time. (b) Schematic of the demonstration experiment. Monochromatic neutrons of identical velocities enter the device at arbitrary instants of time. The neutron lens of periodic action alters their velocities. As a result, neutrons assemble (group)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

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:

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

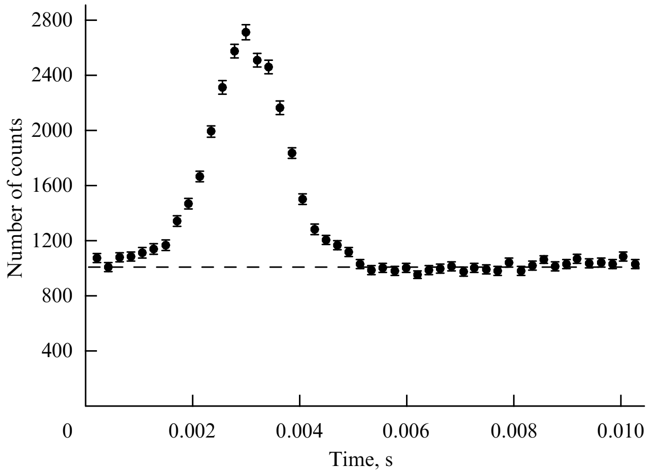

Figure 7. Demonstration of the possibility of time focusing. Monochromatic neutrons entering the device at arbitrary instants of time traverse the time lens operating periodically. The dependence of the counting rate on time clearly reveals a peak of neutrons focused in time. The time scale is equal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

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

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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 source and their time of flight t measured for this distance. Knowledge of L and t permits determining the neutron velocity v and, consequently, its energy. To realize the method, a blinking source is required in order to fix the instant of time when the neutron escapes. This method was first realized by L W Alvarez in 1938 with the aid of a blinking cyclotron. In 1947, E Fermi at a stationary reactor (continuous flow nuclear reactor) made use of a mechanical chopper of the neutron flux, which represented a rotating disk with a slit transparent to neutrons. Such a chopper — a Fermi chopper — transmits neutrons periodically during a short time interval Δt. The period of pulse repetition must be significantly longer than the measured time of flight t. The intensity of a beam of slow neutrons of energies $E_{\rm n}$ below 10 MeV, mostly used in neutron physics, was significantly higher than in accelerators. Therefore, for a long time reactors with Fermi choppers were used for realizing the time-of-flight method, and the results obtained were very important for the development of nuclear power engineering. However, as the accelerator machinery underwent development, the roles were separated. In research with thermal neutrons (10^{-3} eV $< E_{\rm n} < 10^{-1}$ eV) reactors still prevailed, while in research with resonance neutrons (1 eV $< E_{\rm n} < 10^4$ eV) accelerators were preferred.

The reasons for this are the following [1]. The resolution of a spectrometer making use of the time-of-flight method is $R = \Delta t/L$, where Δt is the error in time measurement. For $R = \Delta t/L$ [μs m^{-1}], the error in measuring the energy is given by $\Delta E = 0.028\, E^{3/2} R$ [eV]. Then, for resonance neutrons, for example, when $L = 10^3$ m and $\Delta t = 1$ μs, the resolution $R = 10^{-3}$ μs m^{-1}, while for $E_{\rm n} = 10^4$ eV the error amounts to $\Delta E = 28$ eV, and for $E_{\rm n} = 1$ eV it is $\Delta E = 2.8 \times 10^{-5}$ eV. In the case of thermal neutrons, for example, when $L = 20$ m, and $\Delta t = 100$ μs, the resolution $R = 5$ μs m^{-1}, and for $E_{\rm n} = 2.5 \times 10^{-2}$ eV the error $\Delta E = 1.1 \times 10^{-4}$ eV. Another parameter that is important for neutron spectroscopy is luminosity. Given equal conditions and a fixed resolution, the smaller Δt, the greater the luminosity. The luminosity of a reactor with a chopper is proportional to $\Delta t/\tau L^2$. Therefore, if Δt and L are decreased by a given factor, the resolution R will remain the same, while the luminosity will increase by a factor of $1/L$. However, in the case of a stationary reactor, enhancement of its luminosity is limited owing to, first, the technical difficulties in reducing Δt mechanically and, second, the fact that a decrease in Δt means utilization of a fraction of the reactor's radiation, which will be the smaller the smaller $\Delta t/\tau$, where τ is the time between the instants of time when the beam is transmitted. Moreover, during those time intervals that the chopper does not let the beam pass, the reactor's radiation not only is not utilized, but creates a parasitic background. Therefore, for neutron spectroscopy it is more advantageous to have pulsed neutron sources in which Δt can be small and all the radiation is concentrated in the pulse. Such neutron sources are created on the base of electron or proton accelerators. In the middle of the 1980s, powerful pulsed neutron sources were created on the base of proton accelerators with proton energies of about 1 GeV, which satisfied all the conditions for realization of the time-of-flight method within the whole energy interval of slow neutrons [2].

3. From the pulsed reactor to the superbooster

A separate chapter in the development of the time-of-flight method was opened by the appearance of periodic pulsed reactors (pulsating reactors) and their combination with blinking accelerators-injectors. The idea of a pulsating reactor was proposed by D I Blokhintsev [3] in 1955, and the theory of this reactor was developed by I I Bondarenko and Yu Ya Stavissky in 1956. The action of the reactor is based on mechanical modulation of its reactivity: the active core is in a subcritical state, and a piece of uranium on a rotating disk transfers the system for a short time into an above-critical state for prompt neutrons. As a result, a power impulse and pulsed neutron flux arise.

The average power of the first IBR reactor was initially low: 1 kW, later 6 kW. However, the pulse power with a repetition rate of 8 pulses per second amounted to 3 and 18 MW, respectively, while in the mode of rare pulses (once every 5 s) it was 1000 MW. In 1968, IBR was shut down, and a new reactor of the same type (IBR-30) with an average power of 25 kW took its place in 1969. The flux of thermal neutrons in the pulse amounted to 10^{15} neutrons per cm^2 per s. However, the relatively long pulse — 60 μs — provided a resolution 60 times lower than the aforementioned estimates. Therefore, research with resonance neutrons, for which the IBR reactor was made, was limited to a range of problems requiring high luminosity but quite moderate resolution.

At the same time, the IBR and IBR-30 reactors turned out to be quite efficient for studies of condensed matter. The investigation of such matter makes use of thermal and cold ($E_{\rm n} < 10^{-2}$ eV) neutrons. The time during which such neutrons are emitted by the moderator is determined by neutron diffusion and reaches approximately 100–200 μs. Therefore, the length of the pulse from the IBR reactor turned out to be totally satisfactory for the needs of neutronography. A brief review of the main results was given in Refs [4, 5].

The main result of application of the IBR and IBR-30 reactors in neutronography consisted in utilization of the time-of-flight method in neutron diffraction. The geometrical optics of neutrons coincide with the geometrical optics of X-rays for both diffraction and a grazing angle of incidence. Therefore, neutronographic experiments were arranged in accordance with the scheme of X-ray diffraction experiments. Thus, starting from the first experiments in 1936 neutron diffraction was performed as follows. A certain wavelength λ is singled out in the radiation spectrum, and the angle is empirically sought at which the Bragg–Wulf condition is satisfied: $2d \sin\theta = n\lambda$, where d is the distance between the reflecting planes in the crystal, θ is the angle between the direction of the radiation and the surface of these planes, and n is an integer; the incidence angle is equal to the angle of reflection. However, one may proceed in a different way, namely, to apply the time-of-flight method making use in the Bragg–Wulf condition of the fact that the neutron wavelength is inversely proportional to the neutron velocity [6].

The possibility of applying the time-of-flight method in neutron diffraction was first discussed by P Egelstaff in 1954. In 1961, B Buras attempted to apply this method at a stationary reactor with a Fermi chopper in Swierk (Warsaw). However, the intensity of this source happened to be insufficient. In 1962, B Buras initiated the arrangement of such an experiment at the IBR reactor. The experiments were successful, so the time-of-flight method in neutron diffraction was realized. In this field of research practically all further techniques for the IBR-30 reactor were proposed by researchers at the laboratory of neutron physics and subsequently applied in other neutron centers at pulsed sources. When high-flux pulsed neutron sources appeared in the middle of the 1980s, the time-of-flight method in neutron diffraction became widespread as a powerful method for structural studies [2].

Let us now return to the spectroscopy of resonance neutrons, for which, as was already mentioned, it is desirable to have a short neutron pulse. In principle, the solution to this problem was known. In 1958, a booster-multiplier was created at the British nuclear center at Harwell that consisted of a target for photonuclear reactions placed in a subcritical assemblage and an electron accelerator-injector. In the case of the IBR reactor, a new possibility opened up — the creation of a booster with a pulsed target, or a superbooster [1, 7]. In this case, when the neutrons are injected by a pulsed electron accelerator, with the aid of a reactivity moderator the reactor receives maximum reactivity which then rapidly falls. The process of neutron multiplication is only due to prompt neutrons, while retarded neutrons that prolong the chain reaction do not have time to contribute. Since the duration of a single link of the multiplication chain in the IBR amounts to 10^{-8} s, multiplication stops in 2 μs for a multiplication coefficient equal to 200. Thus, it is possible to amplify the pulse by a factor of several hundred with its length increasing up to 3 or 4 μs. In a stationary booster with such a multiplication the pulse will become nearly critical for the retarded neutrons, and the system will cease being pulsed.

In 1965, a microtron was installed as the injector for the IBR reactor; it was constructed at the Institute for Physical Problems (IPP) of the USSR AS. In 1969, a linear electron accelerator with a pulse current of 200 mA and pulse duration of about 1 μs was established at the IBR-30 reactor. A plutonium target was initially used, and then subsequently replaced by tungsten. In 1971, D I Blokhintsev and I M Frank, together with a group of authors, were awarded the State Prize of the USSR for the "IBR research reactor and the IBR reactor with an injector". The IBR-30 reactor operated in two modes up to 1996: as a pulsating reactor, and as a pulsed superbooster. Since 1996 the reactor mode has not been used, and until 2001 IBR-30 operated as a booster-multiplier with a pulse frequency of 100 pulses per second, an average power of the multiplier-target of 12 kW, and a pulse half-width equal to 4 μs. Since 1994 JINR has been developing a project for a new pulsed neutron source IREN (the *Russ. abbr.* for the source of resonance neutrons) [8] making use of an electron linear accelerator and a multiplier-target. At the end of 2008 the first stage should be completed — without the multiplier-target.

Creation of the pulsed booster-multiplier IBR-30 became the basis for an essential development of neutron nuclear spectroscopy, which at all stages of advancement of neutron physics served as the principal supplier of experimental data [9]. Luminous neutron nuclear spectroscopy opened the way for studying highly excited nuclear states in the interval of energies from 6 MeV up to 10 MeV with an accuracy unachievable by other methods. Besides work on neutron nuclear spectroscopy, at the IBR-30 original studies were also initiated and developed in the physics of the atomic nucleus and of fundamental interactions (see, for example, Refs [4, 5]).

4. The fast pulsed reactor IBR-2

The successful operation of the IBR reactor and of its modifications stimulated further development in this area. In the middle of the 1960s several projects were started. The first announcement concerned the pulsed reactor Sora with a moving reflector and average power equal to 1 MW. The reactor was to be built at the research center of Euroatom in Ispra (Italy). A powerful periodic pulse reactor with an average power of up to 30 MW was proposed to be constructed at the Brookhaven National Laboratory (USA). In 1964, work started in Dubna on a project for a new reactor, the IBR-2. Its essential differences from the IBR reactors consisted in modulation of the reactivity with the aid of a movable reflector and in cooling the active core by liquid sodium. Of all the proposed projects of high-flux pulsating reactors, only the IBR-2 project was implemented, which became possible owing to the experience in operating such systems in Dubna and Obninsk and to the active participation of the USSR Ministry of Medium Machine Building.[1]

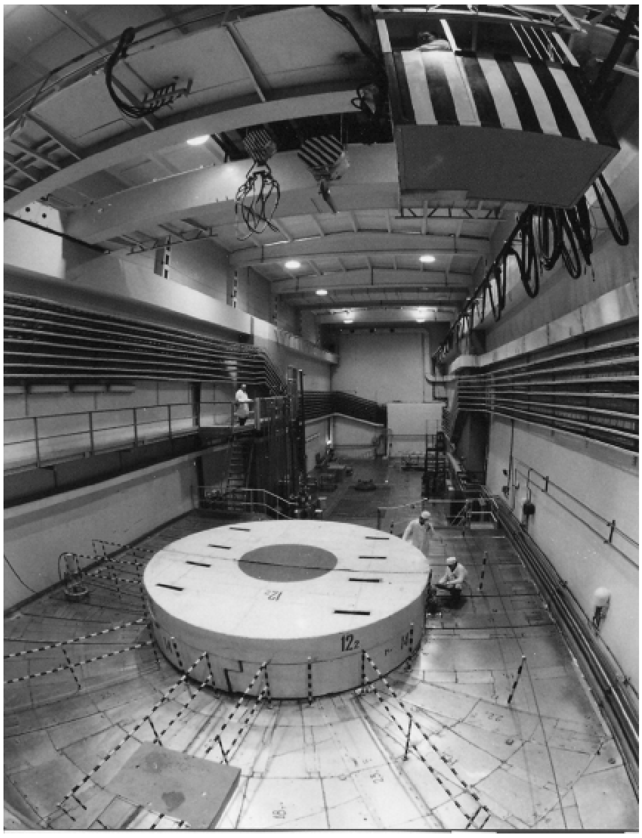
I M Frank at the control panel of the IBR-2 reactor (1976).

Officially, work on the IBR-2 project started in 1966, and actual construction in 1969. The first critical assemblage was

[1] Besides JINR and the Institute for Physics and Power Engineering (IPPE) (city of Obninsk, Kaluga region) a whole number of institutions of the USSR Ministry of Medium Machine Building took part in the construction of the IBR-2 reactor. The main designing institution was the Research and Development Institute of Power Engineering, development work was carried out by the State Specialized Design Institute, fuel elements were prepared by the All-Union (at present, All-Russian) Research Institute of Inorganic Materials and the Mayak industrial complex. For resolving other individual problems, other specialized institutions and design offices of the powerful industry pertaining to the Ministry of Medium Machine Building were recruited. It can be asserted that the creation of pulsating reactors represents one of the striking manifestations of the highest potential of nuclear and technical sciences in our country.

The hot core of IBR-2, which represents a tank with a volume of 22 l, which is filled with the fuel, 92 kg of plutonium dioxide. The tank is charged into the body of the reactor.

prepared at IPPE in 1968, and between 1970 and 1975 the model of the movable reflector was investigated at a test bench in Dubna. Physically, the reactor was put into operation (without the heat carrier) 8 years after the beginning of the construction: at the end of 1977 and the beginning of 1978. Then came preparation and launching of the power operation (with sodium), which was actually completed on April 9, 1982, when the average power attained was 2 MW for a pulse repetition rate of 25 Hz, and the first physical experiments were performed with extracted beams. After the death of D I Blokhintsev in January 1979, I M Frank became the scientific leader of



Reactor hall of IBR-2.

IBR-2. Officially, the reactor was commissioned on February 10, 1984, with implementation of the program of physical experiments starting on April 9, 1984 after the power reached 2 MW for a pulse frequency of 5 Hz.

Experimental hall of IBR-2.

The hot zone of the reactor, 22 l in volume, contained 92 kg of plutonium dioxide. Modulation of the reactivity was realized by a steel movable reflector consisting of two parts rotating with different velocities (1500 and 300 revolutions per minute). When both parts of the reflector traversed the zone, a power impulse was generated (1500 MW). During the regular operation mode of the reactor — 2500 hours per year for experiments — the hot zone was in operation for not less than 20 years without any change of fuel, while the moving reflector could be in operation for 5–7 years. In 1995, IBR-2 started operating with a new movable reflector (the third consecutive one). In 2002, the plans were to replace the active core together with the movable reflector. However, the financial situation in the 1990s did not permit starting modernization of the reactor in time. Modernization of the IBR-2 reactor is a long-term program of scientific and technical tasks, actually representing the creation of a new reactor, only without having to construct a new building, which would take 10 years. This program was initiated in 2000 with the financial support of the RF Ministry of Atomic Energy (successor to the USSR Ministry of Medium Machine Building) and personally of the minister E O Adamov. To prolong the time of operation of the IBR-2 reactor, the average power was lowered to 1.5 MW and the operation time with power was reduced to 2000 hours per year. In December 2006, the reactor was stopped in order to replace all technological systems. In 2010, a new IBR-2M reactor is planned to be put into operation with improved parameters and modern systems for safety control.

Thus, the pulsating IBR-2 reactor is an economical, relatively cheap and, as revealed by the experience accumulated in working with it, a simple and safe device to operate. Creation of IBR-2 cost about 20 million rubles (cost in 1984). Today operation, further development, and improvement of the reactor will cost less than 1 million dollars US per year. This is 10–50 times less than for other modern neutron sources in the world. At the same time, the reactor provides a pulsed neutron flux that is a record for research neutron sources and is equal to 10^{16} neutrons per cm^2 per s.

In 1996, D I Blokhintsev and I M Frank were awarded (both posthumously) together with a group of coauthors a Prize of the Russian Government for the creation of the research high-flux pulsed reactor IBR-2.

5. The inverse time-of-flight method

The IBR-2 reactor, possessing a record high pulsed flux of thermal neutrons, had a great advantage from the standpoint of the usual formulation of a diffraction experiment for studies not requiring high resolution. However, an accuracy at the level of 1% was not sufficient for precision measurements.

The resolution of a time-of-flight powder diffractometer is described by the following expression

$$R = \frac{\Delta d}{d} = \left[\left(\frac{\Delta t_0}{t}\right)^2 + (\gamma \cot\theta)^2\right]^{1/2},$$

where Δt_0 is the width of the neutron pulse, γ describes the geometric uncertainties, $t = 252.778\,L\lambda$ is the neutron time of flight from the source to the detector, λ is the neutron wavelength, and θ is the Bragg angle. Clearly, the time contribution can be reduced by either reducing Δt_0 or by increasing the path of the neutron flight, i.e., by moving the sample away from the neutron source.

For example, at one of the best powder diffractometers in the world (HRPD, or High-Resolution Powder Diffractometer) at the pulsed neutron source ISIS (In situ Storage Image Sensor) at the Rutherford–Appleton Laboratory (RAL, Great Britain), the resolution amounts to $\Delta d/d \approx 6 \times 10^{-4}$ within quite a broad interval of wavelengths. This resolution is practically the limit of the achievable value for structural studies with either neutrons or X-rays. However, with the width of the neutron pulse amounting to $\Delta t_0 \approx 15$ μs Å^{-1}, the time-of-flight base at HRPD reaches $L = 100$ m. As a result, the neutron flux hitting the sample exhibits the quite moderate value of $\Phi_0 \approx 10^6$ cm^{-2} s^{-1}.

In the case of the IBR-2 reactor, such a usual method for enhancing the resolution by increasing the flight base is of no use because $\Delta t_0 = 320$ μs. Therefore, the inverse time-of-flight method making use of a Fourier chopper was proposed and adapted for use at the IBR-2 reactor [2]. The key element of the scheme proposed was a Fourier chopper which, unlike the ordinary Fermi chopper, has many slits instead of one. In our case, it is a disk 50 cm in diameter with 1024 slits, the width of which (1 mm) equals the distance between them. The disk rotates with a variable velocity of up to 9000 revolutions per minute. At the maximum revolution velocity, the pulse length is reduced to 2 μs. Since there are many slits, the neutron flux decreases insignificantly, but the recycling effect shows itself, resulting in the registered spectra overlapping. The idea of the inverse time-of-flight method that permits deciphering overlapping diffraction spectra consists in the following. Although it is not possible to say precisely which velocity a neutron registered by the detector had, it is possible to indicate which velocities it could have had by controlling the state of the chopper and of the reactor at corresponding preceding instants of time. It turns out that by varying the revolution velocity of the chopper from zero up to a certain maximum velocity and by accumulating a large number of events sorted out in this manner, it is possible to obtain a usual spectrum of elastically scattered neutrons, evolved in time. The possibility of sorting is provided by the formation of fiducial signals coinciding with the instants of time when the reactor and chopper are in an 'open' state and controlling operation of the fast shift register through which the accumulation of detector signals proceeds. The time part of the resolution function assumes the form

$$R(t) \sim \int_0^{\Omega_m} g(\omega)\cos\omega t\,d\omega\,,$$

where $g(\omega)$ is the frequency distribution function, and Ω_m is the maximum revolution frequency of the Fourier chopper. In the simplest case, $g(\omega)$ can be approximated by the Blackman function. In this case, the half-width $R(t)$ is equal to Ω_m^{-1} and can be made equal to 7 μs. Then, one has

$$\frac{\Delta t_0}{t} = \frac{\Delta t_0}{253L\lambda} \approx \frac{10^{-4}}{d}\,.$$

The high-resolution Fourier diffractometer (HRFD) at the IBR-2 reactor has the following parameters: $\Delta d/d \approx 5 \times 10^{-4}$ ($d = 2$ Å), $L = 20$ m, and $\Phi_0 \approx 10^7$ cm^{-2} s^{-1}.

Creation of the HRFD at the IBR-2 reactor was of essential importance. First, the possibility arose of performing precise structural studies, which was immediately made use of for studying new materials, such as high-temperature

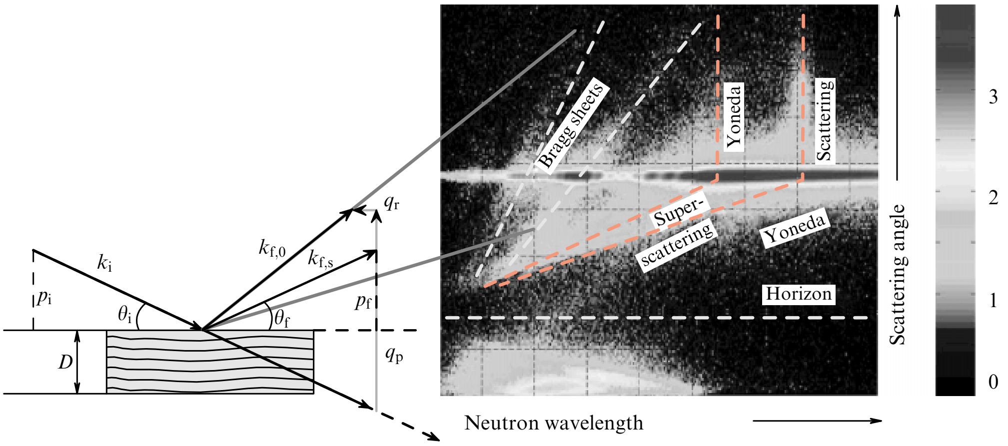


Figure 1. Layout of a reflectometric experiment. The angle $\theta_i \leqslant \theta_c$, where θ_c is the critical angle at which total external reflection occurs. If the angle of the reflected beam $\theta_f = \theta_i$, then the reflection is specular; if $\theta_f > \theta_i$, then off-specular. k_i is the wave vector of the incident neutron, $k_{f,s}$, $k_{f,0}$ are the wave vectors of the neutron in the case of specular and off-specular reflection, respectively; $p_{i,f}$ are the projections of the wave vectors onto the normal to the surface: $p_{i,f} = k_{i,fs} \sin\theta_{i,f}$.

superconductors [11] and manganites with giant magnetoresistance [12]. Second, it was shown that if sources of long-pulse neutrons are handled skillfully, they exhibit practically the same feasibilities as short-pulse sources based on proton accelerators, and the cost of the latter is one or two orders of magnitude higher. This experience is already being applied throughout the world. Thus, the new European neutron supersource (European Spallation Source, ESS) is projected as a source with a long pulse.

With the commissioning of the HRFD, the creation of a broad-profile complex of spectrometers at the IBR-2 was completed. This complex permitted obtaining a number of original results in studies of the structure of materials. For the development and realization of new methods of structural neutronography at pulsed and stationary reactors, a team of authors from JINR, the B P Konstantinov Petersburg Institute of Nuclear Physics of the Russian Academy of Sciences, and the Russian Research Centre 'Kurchatov Institute' was awarded the RF State Prize in science and technology in 2000.

6. IBR-2 in studies of nanomaterials

The parameters of the IBR-2 reactor — the record high thermal neutron flux in the pulse, and a high fraction of cold neutrons in the spectrum — are ideal for carrying out research into the condensed state of matter. Today, the IBR is applied effectively in studies of problems of the physics of condensed media, chemistry, the materials science, molecular biology, the synthesis of composites for pharmacology and creating materials for medicine, as well as in the engineering sciences and geophysics [5]. Among the objects of research there are also materials that have recently been considered a separate class of nanomaterials. The IBR-2 reactor is also efficient as a physical device for interdisciplinary studies, exhibiting radiation parameters in the nanorange, as well as for nanodiagnostics and investigations of nanomaterials (see, for example, Ref. [13]).

I M Frank supported studies of condensed media, being particularly interested in the problems of biology and biophysics and in the development of methods for neutron optics. Thus, for example, he was attracted by the problem of describing optically the behavior of neutrons in the case of their grazing incidence on the surfaces of dense materials. This branch of neutron optics started developing rapidly in the middle of the 1980s after the appearance of high-flux pulsed neutron sources, such as IBR-2. It turned out to be that reflectometry (this is the term used for methods of studying surfaces, thin films, and interfaces in layered structures based on neutron optics in the case of grazing incidence angles), like diffraction, has its advantages for time-of-flight experiments. The utilization of polarized neutrons is of particular interest for neutron reflectometry [14].

The JINR's Laboratory of Neutron Physics was among the pioneers in creating a new scientific line of research — the optics of polarized neutrons for grazing incidence angles (reflectometry of polarized neutrons), and all the issues related to establishment of this line of research were discussed with I M Frank. At present, the reflectometry of polarized neutrons has been established as one of the powerful currently available methods for diagnostics and investigation of nanostructured materials. Neutron reflectometry constitutes an ideal method for studying and diagnosing nanostructured materials, for example, layered systems and systems with structured surfaces. The weak interaction of neutrons with matter makes this method nondestructive when the radiation penetrates deep into the sample. In the case of objects containing hydrogen there exists an excellent contrasting method with the aid of deuterium exchange. Finally, new research methods taking advantage of the magnetic moment of the neutron open up new possibilities for studying magnetic and nonmagnetic nanosystems.

During the last decade, on a level with advancing the technique of specular reflection, which provides information on the in-depth structure of a sample (say, along the z-axis), successful development is also proceeding on the technique of nonspecular (diffuse) scattering, which permits obtaining information about the structure variations in the plane of the sample along one of the coordinates (say, along the x-axis). Finally, in recent years the technique of small-angle scattering close to the grazing angle (Grazing Incidence Small-Angle Neutron Scattering, GISANS) has started to develop, and it yields information on structural changes in the plane of the sample along another coordinate (coordinate y). Thus, the possibility arises of the complete investigation of the structure of low-dimensional systems at the nanolevel. Typical examples of nanosystems investi-

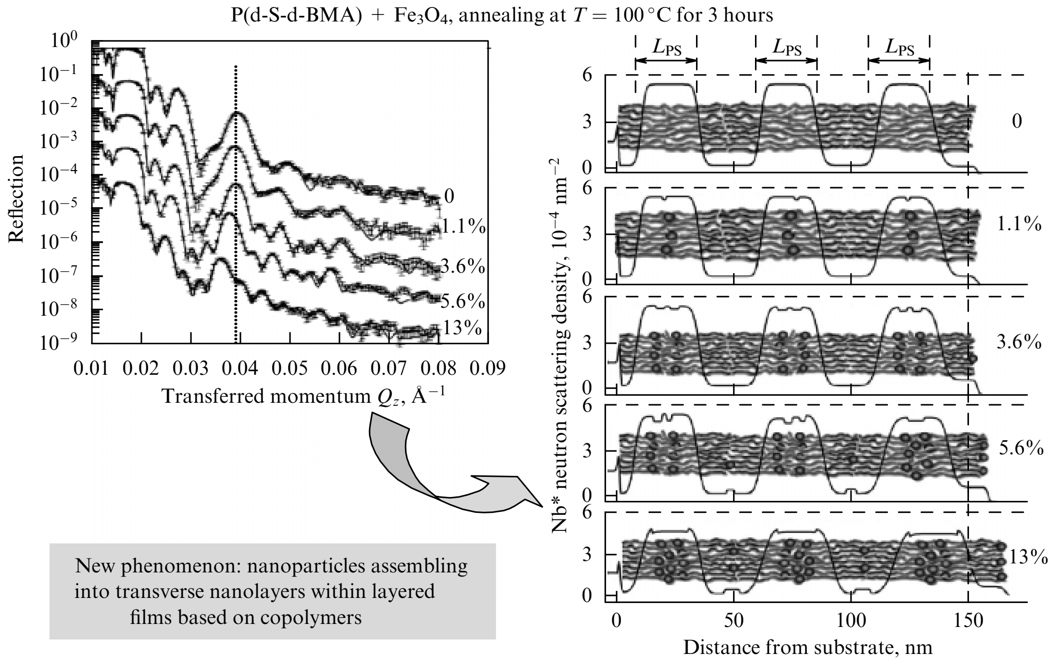


Figure 2. Distribution of magnetite nanoparticles (points) in P(d-S-d-BMA) depending on their concentration and obtained from experimental data on specular and off-specular neutron scattering [15]. The respective percentages of nanoparticles in the samples are indicated to the right of the curves.

gated with the aid of neutron reflectometry include magnetic multilayer films, stripe structures, quantum dots, nanowires in porous silicon, polymers with the inclusion of magnetic nanoparticles, multilamellar vesicular bodies, and magnetic liquids.

The layout of a reflectometric experiment is essentially simple (Fig. 1). A neutron beam with a wave vector k_i is incident on the surface of the sample at a small grazing angle θ_i. In the case of specular reflection, when the angle of the reflected beam $\theta_f = \theta_i$, the transferred momentum $q = k_f - k_i$ (where k_f is the wave vector of the reflected beam) is perpendicular to the substrate. In the case of nonspecular reflection ($\theta_f > \theta_i$) there appears a component, parallel to the surface of the substrate, of the transferred momentum, q_x, that carries information on distortions of the surface in this direction, for example, of roughnesses or of nanoparticles introduced into the medium. In the case of a time-of-flight experiment, the intensity of the specular reflection on the detector, which depends on the neutron wavelength, is registered at a fixed point (at the angle of reflection). The intensity of the nonspecular scattering is 'seen' at points above and below the line of specular reflection in the form of wings of the Bragg scattering, responsible for the condition $q_0 = p_i + p_f =$ const, or Yoneda scattering, for which $k_i = k_c$ or $k_f = k_c$, where k_c is the critical value of the wave vector, for which the condition of total external reflection of the neutrons is satisfied.

The advantage of a time-of-flight experimental technique consists in the fact that the direct beam does not come close to the line of intensity of the specular reflection as it does in the case of constant-wavelength reflectometers, where it is necessary to rotate the sample. As a result, when the time-of-flight technique is applied, the intensity of the background for the critical angle and large wavelengths in the region of Yoneda scattering turns out to be very low compared to the background intensity in the method where the angle θ_i is variable and the wavelength is constant.

In a reflectometric experiment, specular reflection from an ideal flat multilayer structure, i.e., without any roughnesses on the surface or at the interlayer boundaries, gives the value of the film's thickness D, which is determined by the position of oscillations of the reflection coefficient R at points of the inverse space, $q = 2\pi n/D$. In the case of a multilayer system, the positions of the Bragg peaks $q = 2\pi n/d$ yield the values of the layer thicknesses d. The intensity of the Bragg peaks grows with increasing the contrast of neutron scattering between the layers. Nonspecular scattering arises when there are roughnesses at the boundaries between the layers and on the surface. Magnetic inhomogeneities may also be sources of nonspecular scattering.

The intensity of nonspecular scattering depends not only on the intensity of scattering from the roughnesses in the layers, but also on the change in amplitude of the neutron wave field inside the multilayer system, caused by multiple reflections and passages of neutrons through the interlayer boundaries. These processes of resonance amplification are taken into account by the Born approximation of distorted waves. In single-layer thin films, for example, in liquid films, these effects are absent and, subsequently, no high-intensity Bragg wings arise.

As an example of neutron nanodiagnostics, we shall consider investigation of a magnetic polymer layered structure, representing a thin film of a symmetric diblock-polymer made of deuterized polystyrene (d-PS) and polybuthylmethacrylate (PBMA). Such a system, P(d-S-d-BMA), constitutes a self-assembled matrix for lamellar arrangement of nanoparticles in the magnetite Fe_3O_4 [15]. Self-organizing polymer films are quite promising artificially created functional materials in which the polymer matrix serves as a medium for nanoparticles of various properties. As a result, a new functional material is obtained with properties formed on a nanoscale.

In the example considered, the material is created by mixing the components layer-by-layer by rotation (spin-

Table 1. Parameters of the nanocomposite P(d-S-d-BMA) $+Fe_3O_4$.

Parameter	$x = 0$	$x = 13\,\%$
D, nm	153.3 ± 1.0	170.5 ± 1.0
L, nm	50.2 ± 0.5	55.3 ± 1.0
L_{PS}, nm	24.4 ± 0.5	29.0 ± 1.0
ξ, nm	600.0 ± 5.0	400.0 ± 5.0
σ, nm	3.5 ± 0.5	5.8 ± 0.5
ζ	6	4

coating). The base matrix in the form of a lamellar structure results from annealing. The magnetic nanoparticles introduced into one of the diblock-copolymers form nanosheets of dimensions depending on the concentration of nanoparticles. One problem consists in investigating the stability of the structure of such a composite polymer film. The stability problem of structures obtained by self-assemblage is common for nanotechnologies. When the conditions for the stability of a new material are found, its physical properties (in our case, magnetic) can start to be studied.

As seen from Fig. 2, the nanoparticles of magnetite assemble into PS-layers and thus avoid interaction with PBMA. This represents a new phenomenon. Already in 1907 S U Pickering found that mixtures are stabilized by nanoparticles that are resided at the interfaces between the components. But here, nanoparticles assemble into nanosheets within the layers of the copolymer multilayer film.

The parameters of the composite determined from the neutron experiment are given in Table 1 for a pure system (the admixture concentration $x = 0$) and for a system with the admixture concentration $x = 13\%$.

From a structural point of view, the introduction of admixtures results in the following changes. The total thickness D of the composite film increases. This increase is due to the thickness L of each bi-layer increasing, which, in turn, is caused by enhancement of the thickness L_{PS} of the PS layer.

A noticeable enhancement of the roughness parameter σ is observed, which signifies weakening of the composite's stability. This is also testified to by the behavior of the correlation length ξ in the layer (the size in the domain plane). A decrease in ξ signifies a change in the parameters of the boundaries between the layers and a decrease in the elasticity γ between the two polymers. This serves as one more indication that the composite's stability is reduced.

The decrease in the conformity parameter ζ signifies an enhancement of the noncoincidence between the interlayer roughness boundaries and the boundaries of the domains.

The structural data presented on the arrangement of nanoparticles and on their influence on thicknesses and other parameters of the layers represent important information for technologists.

7. Conclusion

Thus, the pulsed nuclear reactors created at the Joint Institute for Nuclear Research with the active participation of I M Frank have during the nearly 50 years of their operation permitted forming a whole series of scientific lines of research in neutron physics that have become determinant throughout the world. The scientific school in neutron optics that arose under the leadership of I M Frank is still being developed by several generations.

While appreciating the enormous contribution by I M Frank to the development of world and domestic science and to the defensive capability of our country, I believe that at the same time one may conclude that his legacy includes the no less important influence he exerted on the people surrounding him, which still continues to be felt. No one can better express this influence than he himself. In his memoirs about his teacher, I M Frank wrote [16]: "...the creative legacy of such physicists, like S I Vavilov, does not only include works signed by him, or works done by his collaborators and pupils, who continue to work on the same problems. There exists something no less important, which, however, cannot be quoted in published works. This is the ideological influence, direct or indirect, exerted by a scientist.... Precisely this represents the influence that must be considered the scientific school of the scientist, which cannot be simply identified with all those who worked or work under his direct leadership. Here, I also mean something more significant than help in organizing the work, although, in the conditions of modern science, it does play a most important role. Also essential is another thing — the individual influence of the scientist which in many respects cannot be separated from his human characteristics."

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