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 Physicomathematical 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 coauthorship. 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)].

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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."

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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.

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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.

* * *

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.

* * *

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."

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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.

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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].