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Vavilov–Cherenkov radiation: its discovery and application

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Abstract. **The history of the discovery of the Vavilov–Cherenkov effect is outlined. Several important applications of the effect are discussed.**

In mid-1932, Sergei Ivanovich Vavilov, who had been elected a full member of the USSR Academy of Sciences only a short time previously, was appointed head of the Physics Department of the Institute for Physics and Mathematics, the USSR Academy of Sciences. At that time, the Institute for Physics and Mathematics, was situated in Leningrad (then the name of St. Petersburg). Before long, the Physics Department led by S I Vavilov was transformed into the Physical Institute of the Academy of Sciences and moved from Leningrad to Moscow, and Vavilov became director of the Physical Institute. This happened later, in 1934. On Vavilov's initiative, the institute was named after Petr Nikolaevich Lebedev, a famous Russian scientist and the founder of the scientific school to which Vavilov himself belonged. That took place seventy five years ago. Over the span of those years, the institute has gained wide recognition by both the domestic and the international scientific communities. In Russia, the institute is referred to as FIAN, which is the acronym of its title in Russian: Fizicheskii Institut Akademii Nauk (Physical Institute of the Academy of Sciences). Abroad, it is customary to use the shortened name Lebedev Institute.

With Vavilov's accession to the institute, the scientific activities of the Physics Department intensified. Nikolai Alekseevich Dobrotin, FIAN's elder staff member, who was a postgraduate student of the Physics Department at that time, recalls [1] that those changes concerned postgraduates as well; not all postgraduate students were sufficiently grounded in physics and mathematics. This applied primarily to those who had come from provincial institutes or universities to become postgraduate students. Several lecture courses in mathematics and physics were organized for the postgraduates. In his memoirs, N A Dobrotin gives an impressive list of the lecturers: S L Sobolev, A A Rukhadze, V D Kupradze, I N Vekua (in mathematics); V A Fock, Yu A Krutkov, G A Gamov (in physics). Furthermore, all postgraduate students were given personal scientific supervisors. Vavilov assumed the scientific supervision of three postgraduates: Nikolai Alekseevich Dobrotin, Pavel Alekseevich Cherenkov, and Anton Nikiforovich Sevchenko. Subsequently, all three came to be famous physicists, and two of them — Cherenkov and Dobrotin — became FIAN staff members from the day of the Institute foundation.

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Vavilov suggested subjects of investigation for his postgraduates. Dobrotin and Cherenkov were invited to choose from three subjects:

(i) the luminescence of uranyl salt solutions under the gamma-ray radiation of radium;

(ii) the investigation of the properties of neutrons;

(iii) the study of isotopic effects.

Dobrotin and Cherenkov selected their research subjects by mutual consent: Cherenkov opted to take up the glow of uranyl salts and Dobrotin neutron scattering by protons.

A notable fact is that Vavilov, an outstanding expert on optics and luminescence, who made significant contributions to these areas of physics, proposed three subjects to his students related to the physics of the atomic nucleus, which was still in its infancy at that time. The neutron had been discovered only a year before, and the structure of the atomic nucleus was still under discussion. Few researchers foresaw the great future of nuclear physics, but Vavilov was among those few. Several years later, Vavilov, as Director of FIAN, ensured that investigations into the physics of the atomic nucleus would occupy a prominent place in the research plans of the institute. As a consequence, when the Soviet Union was faced with the task of developing nuclear weapons at the end of the Second World War, FIAN played a role in its fulfillment, and far from a minor one at that.

In 1934, the Lebedev Physical Institute moved from Leningrad to Moscow. Vavilov's student I M Frank described the atmosphere at FIAN in those days in his memoirs [2]:

"In my youth, I had the good fortune of finding myself, even during the student years, in an environment in which the perception of scientific influence was especially intensive and versatile. I mean the scientific school of L I Mandel'shtam, which comprised my direct teachers and outstanding physicists S I Vavilov, G S Landsberg, and I E Tamm — scientists so unlike in their individuality. However, there was a feature common for all of them: permanent scientific communication. Theoretical problems and experimental findings were invariably and constantly discussed, and no one considered these talks (which also occurred besides the scientific seminars) frequent and lengthy, to be a loss of time. At first it seemed strange to me that these outstanding people were spending hours of their precious time, during which they could have dove something remarkable, for talks, in which much space was given to what produced no outcome or turned out to be rubbish. Nor did I understand then that these conversations quite often saw the emergence of new ideas, long before their publication and, of course, without the fear that they could be published by someone else. In addition, no one spared effort to promote the formation of new understanding, without a thought about coauthorship. In the moral atmosphere inherent in Mandel'shtam's school, that was only natural.''

This passage adequately depicts the remarkable creative atmosphere that existed in FIAN in those years (to a certain degree, it persisted in subsequent years as well) and which was imprinted on Frank's memory. To a marked extent, this atmosphere was to be credited to the Director of FIAN S I Vavilov. I think the above passage is nevertheless inexact in one aspect. Frank wrote that Vavilov belonged to Mandel'shtam's school of science. This is not so. Vavilov was a student of P P Lazarev, one of the closest collaborators of P N Lebedev. When the student Vavilov was selecting the subject of his research work, he wanted to work in Lebedev's laboratory. At that time, Lebedev was already seriously ill and the subjects for students research were given by his closest collaborator, Lazarev, at that time a privatdocent and subsequently academician. The subject of Vavilov's first research was suggested by Lazarev, and Vavilov thereby joined Lebedev's school of science to subsequently become the founder of a school of science. So, why did Frank rank Vavilov with Mandel'shtam's school of science, which was indeed an equally remarkable school of science but nevertheless not the one which Vavilov had come from? The reason may lie with the following. Vavilov as director of the institute believed it was his duty to see that the conditions were highly favorable for the fruitful work of the staff. Science, institute, staff members — these ranked highest for him, and he consciously ranked himself second. Seeing Vavilov's highly respectful attitude to Mandel'shtam, the young Frank might have related Vavilov to Mandel'shtam's school of science.

However, ascribing members of the scientific community to schools of science is ambiguous, especially so when two schools are intimately interrelated. One way or the other, Frank had grounds to write what he wrote.

On obtaining the subject of investigation, Cherenkov started mastering his new range of effects and measurement techniques.

Luminescence is the cold glow of a substance. When exhibiting luminescence, excited molecules of the substance transit to the ground state and emit visible light. The methods of excitation may be quite different: ultrasound, chemical reactions, pre-irradiation by visible light, or gamma rays. The essential feature that defines the luminescence phenomenon is that an excited molecule radiates not immediately but resides in an excited state for some time. The lifetimes of excited states differ widely for various luminescent media: from days to hundred millionths of a second. It is significant that the molecule residence time in the excited state is much longer than the period of the light wave emitted in the luminescence. This distinguishes luminescence from other phenomena involving light emission — reflection, refraction, diffraction, and other kinds of radiation. In these phenomena, unlike in luminescence, secondary radiation terminates upon completion of excitation, in a time comparable to the period of the light wave.

Vavilov made a decisive contribution to the theory of luminescence. In particular, the above definition of luminescence in terms of the emission time is credited to him. Together with his collaborators, he developed experimental techniques that enabled determining the main characteristics of luminescent media, including the emission time.

The glow that Cherenkov was to observe (the luminescence of uranyl salt solutions under the gamma-ray radiation of radium) was quite weak, although a relatively large (for those times) amount of radium, tenths of a gram, was used. The glow intensity was close to the visibility threshold. Sensitive light detectors had not been made by those days, and the human eye was selected for the measuring instrument. Shortly before Cherenkov took up his postgraduate studies, Vavilov and Brumberg developed a photometry method based on the visibility threshold [3], the so-called quenching method. This method turned out to be well suited for the investigation of weak radiation, and Cherenkov used it in his measurements.

The apparatus on which Cherenkov carried out his measurements is depicted in Fig. 1. Vessel *1* contains the liquid whose glow characteristics are measured. Located under the vessel is an ampoule with the radioactive radium sample, which excites the glow. In some measurements, the ampoule was placed on the side of the vessel (where it was required to determine the dependence of radiation polarization on the gamma-ray propagation direction). The light emanating from the liquid is reflected by silver mirror *2* onto round aperture *3* with a diameter of 3 mm. Optical wedge *4* is located behind the aperture. The optical wedge is a strip of glass that is transparent on one side, i.e., transmits all incident light. The transmittance of the optical wedge gradually decreases toward the other end according to a certain law to make the wedge opaque at the other end. The wedge migrates along the slots in the direction perpendicular to the drawing plane. Eyepiece *7* produces a magnified aperture image on the retina.

This facility was used to measure not only the brightness but also the spectral composition and polarization of the glow. To determine the spectral composition, color light filters were used, which were slid into an additional slot, *5*. A Glan prism, *6*, was used to measure the polarization degree. The prism was removed in the measurements of the brightness and spectral composition of the glow.

To protect the observer from radioactive emission, the instrument was mounted on a massive lead block, *8*, which shielded the observer from the source. This shield was also required because the radiation of radium excited the glow not only of the liquid under investigation but also of the transparent substance that fills observer's eyeball.

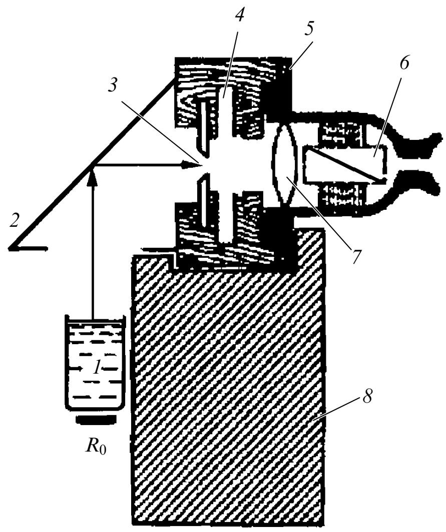

Figure 1. Cherenkov's apparatus for measuring the brightness of liquid glow by the quenching method.

The measurements were performed as follows. Prior to every measurement session, the observer had to stay an hour or an hour and a half in complete darkness for his eyes to adapt to the dark. As a consequence, the eye sensitivity increased by a factor of tens of thousands. Then the measurements started. The optical wedge or, to be more precise, its transparent end was placed between the light source and the eye. The wedge was moved to the position whereby the eye ceased to see the glow of the liquid. In this case, the optical wedge absorbed the excess of source brightness over the perceptibility threshold. Of course, the brightness of the light source had to exceed the perceptibility threshold (tens of visible light photons per second). From the position of the optical wedge, it was possible to assess the source brightness; the darker is the portion of the wedge that effects quenching, the brighter the source. This photometry technique is based on the fact that the visibility threshold of a given observer is constant.

All measurements were performed in total darkness. The observer could not even measure the position of the optical wedge: doing this required illuminating the wedge, but unwanted light immediately upset retinal adaptation to darkness. That is why the wedge readings were taken by an assistant. Prior to that, the observer covered his head with a thick opaque cloth; then the assistant switched on the light and took the optical wedge readings. After that, the light was turned off and measurements were resumed. To avoid visual fatigue, individual measurements were separated by 3–5 min breaks. The overall duration of the measurements did not exceed 2–2.5 h per day; otherwise, eye strain and consequential errors emerged.

Cherenkov quickly mastered the procedure of measurements and performed them thoroughly and with the maximum accuracy attainable under the arduous conditions described above. None of his findings were later proved to be fallacious. In his experiments, he was assisted at one time by N L Grigorov — then a laboratory technician and subsequently a professor at Moscow State University and a famous lecturer in high-energy physics; by M N Alentsev, who was Vavilov's collaborator for many years and a remarkable person in many respects, both as a physicist and as a person; lastly, by Frank, Vavilov's student and (despite his young age) a mature scientist by that time. Frank's participation in the capacity of assistant in Cherenkov's experiments meant that he knew the state of affairs quite well. Also noteworthy is the fact that in those years, Cherenkov and Frank shared an apartment and hence could discuss the scientific problems of interest during their off hours as well. The communal apartment they lived in was unique as regards the set of its dwellers. There were four rooms in the apartment. One room was occupied by the family of the future Nobel Laureate Cherenkov and another room by the family of the future Nobel Laureate Frank. The third room was occupied by the future honorary member of the Royal Danish Academy of Sciences L V Groshev. The fourth room was occupied by a person who was not on the staff of FIAN. In a way, the apartment was no less remarkable than the apartment on Sadovaya Street described by M Bulgakov in his novel *The Master and Margarita*.

Being Cherenkov's scientific supervisor, Vavilov participated in these measurements from the very beginning. During the first days of the work, he familiarized his postgraduate student with the technique of measurements performed with low-intensity light sources. Later on, as the results were being accumulated, he would cross-check them. Once or twice a week, Vavilov performed, so to say, a check experiment. Prior to the measurement, he would, as required, sit an hour and a half in complete darkness. His students and collaborators used this time to discuss the daily state of affairs, to listen to the opinion of their leader, and to lay down the program of their further work. After that, the 'outsiders' were driven away from the room and Vavilov started his measurements.

Cherenkov investigated the glow of uranyl salt solutions under gamma-ray irradiation. Once, in the autumn of 1933, it so happened that glass *1* (see Fig. 1) in his apparatus was filled with a pure solvent, sulfuric acid [1]. And it turned out that sulfuric acid glowed under gamma-ray irradiation, the glow intensity being of the same order of magnitude as the glow of the uranyl salt solution in the same sulfuric acid.

Cherenkov was confused by this result, because the existence of a background — the glow of pure solvents — substantially hindered measuring the principal effect, the glow of solutions, which was the subject of his thesis research [4].

However, on learning that sulfuric acid glowed under gamma-ray irradiation, Vavilov became interested in this fact and suggested that Cherenkov investigate other solvents. It turned out that all other pure solvents, water in particular, glowed when irradiated by gamma rays, and the glow of pure solvents was not negligible in comparison with the glow of solutions. The glow brightness turned out to be about the same for liquids of quite different chemical compositions. It was believed at that time that pure solvents should not glow under gamma-ray irradiation and that the glow, if nevertheless observed, was due to impurities, contaminants. But it turned out that it was precisely the pure solvents that glowed. Cherenkov distilled ordinary tap water sequentially thrice and measured the gamma-ray-induced glow intensity each time after the next distillation. The glow intensity remained almost invariable.

Then Vavilov proposed that the glow of pure liquids be measured using standard techniques elaborated in his laboratory for the investigation of luminescence. These were experiments for luminescence quenching.

Because a molecule takes some time to transit from an excited state to the normal state with the emission of light, it is possible to act on excited molecules during this time such that they transit to the normal state without radiating light. In this case, the stored energy is released not in the form of radiation but in a different way, for instance, it is transferred from the excited molecule to a molecule of a different sort, which does not emit light. Luminescence quenching occurs. The quenching may be achieved in several ways. For instance, special substances — quenchers — may be added to the solution of luminescent substances. Silver nitrate, potassium iodide, and nitrobenzene are active luminescence quenchers. In the collision with a quencher molecule, the excited molecule of substance transfers its energy to the quencher and transits to the normal state without radiating light. Luminescence may be weakened in a different way, for instance, by heating the glowing solution. On heating, the kinetic energy of the molecules increases, their mobility increases, and they experience more frequent collisions with each other; in the collision, the molecule that resides in the excited state transfers the excitation energy to a 'foreign' molecule.

Cherenkov commenced experiments involving the application of the two above techniques (the addition of quenchers and heating) to glowing pure liquids.

Both of these quenching techniques are based on the fact that the excited state of the molecules of a glowing substance has a finite lifetime. For luminescence quenching to occur, this time must allow an excited molecule to collide once or several times with quencher molecules or with 'foreign' molecules. By varying the temperature of the solution of the glowing substance or the density of quenchers, it is possible to determine the most important characteristic of the glowing substance, the lifetime of the excited state. Measurements of the glow brightness in relation to the quencher density showed that the glow brightness hardly changed when the quencher density changed by a factor of several hundred. We note for comparison that increasing the quencher density by a factor of 10–30 in luminescence suffices to decrease the glow brightness several fold. It turned out that heating the liquids also left the glow brightness practically unaffected.

Cherenkov also determined the polarization of the glow and its spectrum. Within the limits of the capabilities of the experimental apparatus, it was determined that the electric vector was primarily directed parallel to the gamma-ray beam. Measurements of the spectral composition showed that the glow brightness peaked in the blue part of the spectrum. Were the observer able to discern the brightness color, it would have appeared bluish. But the human eye does not discern colors near the visibility threshold (''when the candles are out all cats are grey''). The blue color of the novel glow was determined with the aid of color filters.

The first reports on the discovery were sent to the journal *Doklady Akademii Nauk* (DAN) SSSR in late May 1934 and were published several months later. One of the papers was written by Cherenkov [5] and the other by his supervisor Vavilov [6]. These were two brief papers: DAN publishes papers no longer than four pages in journal format. These two papers were actually two parts of one investigation, which resulted in the discovery of a new, previously unknown effect, a special kind of radiation later named for its discoverers, the Vavilov–Cherenkov radiation. Outlined in the paper by Cherenkov were the results of experiments involving the addition of luminescence quenchers, the heating of glowing liquids, and the findings of experiments staged to measure the properties of the new glow: the brightness, the polarization, and the spectral composition. Vavilov's paper, ''On the possible causes of the blue gamma-glow in liquids,'' followed immediately after Cherenkov's paper. Proceeding from the experiments conducted, Vavilov made an assertion that the observed blue glow ''cannot be any kind of luminescence, for which a finite lifetime of excitation is an immanent feature.''

In that paper, Vavilov next expressed his view on the nature of the blue glow. He took into account that hard gamma rays knock electrons out of the atoms of liquids. When moving through the liquid, these electrons produce the radiation that was observed in the measurements. At that time, only one kind of radiation by electrons — bremsstrahlung — was well known. That is why Vavilov conjectured that the observed blue glow was the bremsstrahlung of electrons that were knocked out of atoms by the gamma rays of radium.

As it became clear later, the blue glow was not electron bremsstrahlung: it had a different nature. As for Vavilov's assertion that the radiation was caused by electrons, it proved to be quite correct and determined the course of further investigations. Vavilov himself, although he had made assumptions about the nature of the glow, did not regard these considerations as being final. He would discuss the state of affairs with his colleagues, these discussions taking place both at seminars and in daily conversations. These discussions served the purpose of outlining future experiments aimed at elucidating the nature of the glow.

The following expression by Vavilov is well known: ''There are observations and there are experiments.'' An observation describes the face of a phenomenon without revealing its nature. An experiment is staged with precisely the aim of understanding the nature of the regularities observed.

That the source of radiation was precisely due to electrons was confirmed as follows: the source of gamma-ray radiation was replaced with a source of beta particles (electrons), a radioactive radium source in a thin-wall glass ampoule. This source excited a glow with the same characteristics as the glow excited by gamma rays.

During the discussions of the new phenomenon, an experiment was proposed that played a crucial role in the explanation of the new glow. Specifically, it was suggested that the vessel with the liquid under irradiation should be placed in a magnetic field. Now it is hard to tell who was the first to propose this experiment. Different people ascribe this suggestion to different physicists. Mentioned in this connection are V V Antonov-Romanovskii [7], M A Leontovich, and I M Frank. It is likely that several people at about the same time came up with the idea of placing the apparatus in a magnetic field. The primary purpose of this experiment was to elucidate the relationship between the radiation polarization and the direction of electron motion through the liquid. The magnetic field deflects moving electrons. If the observed radiation is indeed emitted by electrons, variations of the direction of motion should be attended with changes in the radiation polarization. It turned out that the radiation polarization did change in a magnetic field. This result became another confirmation that the electrons moving through the liquid are the source of the radiation.

The experiments with the magnetic field yielded one more significant new result. It turned out that the magnetic field changed not only the radiation polarization but also the glow brightness. Hence, it followed that the radiation was anisotropic. The angular radiation distribution rotated upon rotation of the electron beam induced by the magnetic field. The glow brightness measured by the observer then either increased or decreased, depending on the direction of the magnetic field. As a rule, the intensity changes induced by the magnetic field were significant, which was evidence of a pronounced radiation directivity.

The radiation directivity turned out to be the key factor that enabled constructing the theory of the phenomenon. Frank reminisced [2]: when he told I E Tamm that the radiation was directional, Tamm immediately made a remark: ''This signifies that there occurs coherent emission over the electron path comparable to the wavelength of the light wave.'' The directivity of radiation is related to the radiator size. When the size of the radiating domain is small compared with the radiated wavelength, any radiation directivity is ruled out. When the size of the radiating domain is large compared with the wavelength, the radiation becomes directional; the angular spread (the width of the angular distribution) $\Delta\varphi$ is by the order of magnitude given by

$$\Delta\varphi = \frac{\lambda}{L}\,, \tag{1}$$

where λ is the radiation wavelength and L is the linear size of the radiating domain. The above magnitude of $\Delta\varphi$ essentially defines the diffraction-limited radiation divergence.

The greater the dimensions of the radiating domain (in comparison with the wavelength), the smaller the angular divergence.

Tamm's remark implied yet another significant feature of the radiation observed. The radiation could not stem from the interaction of a moving electron with an individual atom of the medium. The radiation directivity implies that the radiating domain size exceeds the wavelength, and the wavelength is such that a large number of atoms (from a hundred to a thousand) fit into the corresponding distance.

Tamm's remark received the full attention of Frank, who used a simple model to study the composition of waves emitted by a moving source from each point in its path. He used the illustrative formulation of the Huygens principle in the form it appeared in numerous courses of physical optics (i.e., in almost the same form as in C Huygens' book *Treatise on Light*, which had appeared two and a half centuries prior to the events under description). The simple picture obtained by Frank immediately supplied a qualitative explanation of the angular directivity of the new glow.

Figure 2 shows the field pattern for a moving source, obtained by directly applying the Huygens principle.

A charged particle moves from left to right with a constant speed v along straight line O_1O_4. At the moment depicted in the drawing, the particle is at point O_4. Spherical waves emanate from the points the particle had passed. The propagation speed of these waves is equal to the phase speed of light c/n, where c is the speed of light in the vacuum and n is the refractive index of the medium. We assume that the charged particle travels the distance O_1O_4 in a unit time, i.e., this distance is numerically equal to the charged particle speed v. When the particle is at O_4, the wave emanating from O_1 has traveled the distance c/n from that point. The waves radiated from subsequent points of the path have traveled through shorter distances, because their propagation time is shorter: it is proportional to the time the particle takes to travel from the corresponding point to O_4. It is easily verified that all these spherical waves have a common envelope — a conical surface with an apex at O_4 and an axis that coincides with the particle trajectory. In accordance with the Huygens principle, this conical surface is the front of the wave radiated in the motion of the charged particle. The propagation direction of this wave coincides with the normal to the conical surface, and the angle θ between the normal and the particle velocity is defined by

$$\cos\theta = \frac{c}{nv}\,, \qquad (2)$$

as can be easily seen from Fig. 2.

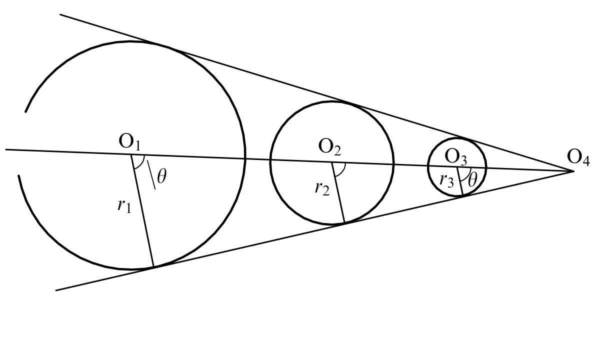

Figure 2.

Because $\cos\theta$ does not exceed unity for real angles θ, it follows from formula (2) that a conical wave is produced when

$$v > \frac{c}{n}\,, \qquad (3)$$

i.e., when the particle speed exceeds the phase speed of light. This is also clear from Fig. 2: the particle leaves behind all the waves it produces.

Not only did the simple consideration given above explain the radiation directivity but it also gave a value for the radiation angle θ defined by formula (2).

Frank discussed his simple treatment based on the Huygens principle with several colleagues. Among his first audience were N A Dobrotin, M A Markov, and M A Leontovich. Frank's treatment did not provoke objections, but his audience did not express keen interest in his explanation (true, many years later Leontovich would half seriously say when the conversation turned to Frank: "[Frank] is a serious man, he should be listened attentively. At one time I did not, and missed a Nobel Prize.") By contrast, Vavilov listened to Frank's considerations with interest and approval, and anticipated their further development. Lastly, Tamm viewed Frank's ideas quite seriously and with enthusiasm that was so characteristic of him. We recall that it was precisely Tamm's primary remark (that the radiation is collected from a long path compared to interatomic distances) that came to be the starting point for the treatment used by Frank.

Tamm told Mandel'shtam about the results of his discussions with Frank, and Mandel'shtam made a remark that cast doubt on the qualitative picture of the emission outlined above. He pointed out the well-known fact that a charged particle that executes a uniform rectilinear motion through empty space does not radiate. This followed from the Maxwell equations. In this connection, he raised the question: will the result change if the speed of light in the medium c/n replaces the speed of light in the vacuum in the wave equation? To state it in different terms: while a charged particle that executes a uniform motion in the vacuum does not radiate, will the charged particle emit radiation in its uniform motion through a medium? The answer to this question was not evident at that time.

In the autumn of 1936, after several discussions with Frank, Tamm wrote the system of Maxwell equations for the field of a point-like charged particle executing a uniform motion through a medium with dispersion and obtained a solution of this system. Tamm immediately called up Frank and asked him to come to his home. Later on, Frank reminisced [2]:

"I found Tamm sitting at his 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 both the course of the solution proposed by Tamm and the validity of calculations, as well as the physical foundations of the theory, in which much was still unclear. I only remember that we sat for a long time.

I returned home by foot at daybreak, because the urban transport had finished (or had not yet resumed) working."

A joint paper by Tamm and Frank [8] was submitted to the journal *DAN SSSR* in the first days of 1937. This paper was an outline of the complete theory of the radiation discovered by Cherenkov. The authors considered the field of a point-like charge moving uniformly and rectilinearly through an infinite uniform medium with dispersion, i.e., a medium whose refractive index $n(\omega)$ depends on the frequency ω. It was shown that when the charged particle speed v exceeds the phase speed of light $c/n(\omega)$ in the medium, a directional radiation at the frequency ω occurs. The radiated waves propagate in the direction that makes an acute angle θ with the particle motion direction, such that

$$\cos\theta = \frac{c}{n(\omega)v} \,. \tag{4}$$

Therefore, the angle θ depends not only on the speed v of the charged particle but also on the frequency of the wave (because the refractive index $n(\omega)$ depends on the frequency ω of the wave).

Much later, in the mid-1950s in Dubna, V P Zrelov made a beautiful photograph illustrating formula (4). It follows from (4) that the greater the refractive index n, the larger the angle θ at which the wave is radiated. Normally (in the case of normal dispersion), the refractive index for blue rays is greater than for red ones. That is why the angle θ at which blue waves are emitted is larger than the angle of red-wave emission. In general, as the frequency ω increases, so does the angle θ. The emission is spectrally decomposed.

The setup of the experiment performed by Zrelov is depicted in Fig. 3. A transparent plate is placed in the path of 660 MeV protons, which produce radiation in passing through the plate. Waves whose phase speed c/n is lower than the proton speed are radiated. All radiation angles are confined between two conical surfaces. The cone angle of the inner conical surface is equal to the radiation angle for the lowest-frequency wave (the red part of the spectrum), and the outer cone angle is equal to the radiation angle for the highest-frequency wave (the blue part of the spectrum). It is worth noting that in reality, radiation also occurs in other parts of the spectrum, at radio frequencies in particular. However, photography is involved in this case, and therefore only the visible part of the spectrum is considered. If the photographic plate is placed perpendicular to the radiating proton beam, a colored annular domain is recorded on it, a particular color corresponding to each value of the radius. Figure 3b shows a part of the annular domain photographed on a color film.

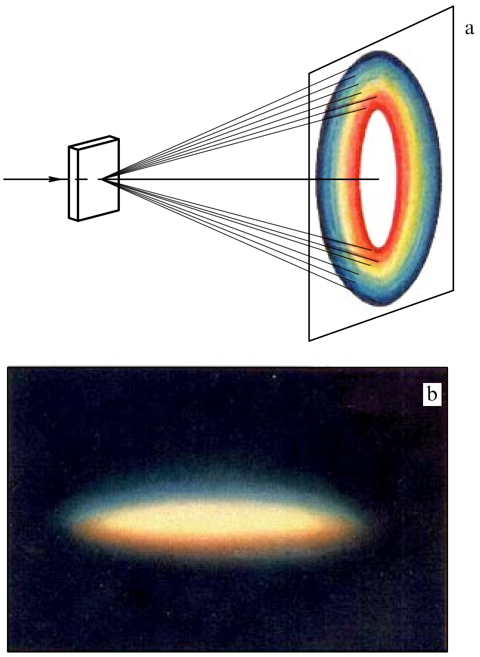

Figure 3. (a) Schematic of the experiment carried out by Zrelov. (b) Vavilov–Cherenkov radiation photographed on a color film.

Tamm and Frank calculated the emission intensity $I(\omega)$, i.e., the energy radiated by an electron at a frequency ω per unit time per frequency interval $d\omega$,

$$I(\omega)\,d\omega = v\,\frac{e^2}{c^2}\left[1-\frac{c^2}{v^2n^2(\omega)}\right]\omega\,d\omega\,, \tag{5}$$

where e is the charge and $n(\omega)$ is the refractive index at the frequency ω. Expression (5) is physically meaningful when the difference in the square brackets is positive. This condition implies the inequality

$$v > \frac{c}{n(\omega)}\,, \tag{6}$$

i.e., the speed of a charged particle should exceed the phase speed of the wave at the frequency ω. This inequality was obtained above proceeding from other considerations [see inequality (3)].

The total radiation energy losses for a charge moving uniformly through a refractive medium are obtained by integrating expression (5) over all frequencies that satisfy inequality (6):

$$\frac{dW}{dx} = \frac{e^2}{c^2}\int_{(nv/c>1)}\left[1-\frac{c^2}{v^2n^2(\omega)}\right]\omega\,d\omega\,; \tag{7}$$

the inequality in parentheses under the integral defines the integration domain. Formula (7) gives the energy loss per unit path length. As regards the spectral composition of the radiation, it follows from the above relations that the higher the radiation frequency, the higher the energy radiated at this frequency. In the normal-dispersion spectral region (where the refractive index increases with frequency), the radiation intensity also increases with frequency. When the refractive index varies only slightly as the frequency varies, we can assume in the first approximation that the glow intensity is proportional to the frequency. The blue component in the visible spectrum is therefore the highest in brightness, which was indeed observed in the measurements. Tamm and Frank also determined the polarization of the radiated waves. They showed that the electric vector $\mathbf{E}$ of the radiated wave is perpendicular to the wave vector $\mathbf{k}$ and lies in the plane that contains the wave vector and the charged particle velocity. In other words, when a plane wave of the form

$$\mathbf{E} = \mathbf{E}_0\exp\left[i(\mathbf{kr}-\omega t)\right]$$

is radiated, the vector $\mathbf{E}_0$ is aligned with the vector

$$\mathbf{v} - \frac{\mathbf{k}(\mathbf{kv})}{k^2}\,.$$

Not only did the theory constructed by Tamm and Frank provide an explanation for all observations published by Cherenkov but it also contained additional information about the properties of the new glow.

It is pertinent to note that the explanation provided by Tamm and Frank did not gain unreserved recognition immediately. According to their theory, the glow was due to electrons that were traveling through a refractive medium at a speed exceeding the speed of light. In this connection, two objections were most frequently raised against Tamm and Frank's theory in the discussion of the theoretical findings.

The first objection was as follows: according to the relativity theory, no material body can move at a speed exceeding the speed of light. But the relativity theory asserts that the limiting speed for material bodies is the speed of light in the vacuum, $c = 300{,}000$ km s^{-1}. It is precisely this value that cannot be exceeded by particles. The phase speed of light in a medium with a refractive index n is c/n, i.e., n times lower than the speed of light in the vacuum. For instance, for a transparent plastic with the refractive index $n = 1.5$, the speed of light is equal to 200,000 km s^{-1}. An electron having a moderate energy 700,000 eV moves with a speed exceeding 200,000 km s^{-1}. For a higher electron energy, the electron speed becomes even higher, but it never exceeds the speed of light in the vacuum, in complete agreement with the relativity theory. Therefore, the speed of a particle can exceed the in-medium phase speed of light but remain below the speed of light in the vacuum.

The second objection against the explanation provided by Tamm and Frank proceeded from the well-known fact that a uniformly moving charged particle does not radiate electromagnetic waves. The answer to this objection is essentially contained in the plot shown in Fig. 2. As is evident from the plot, the charged particle emits waves at each point in its path. The resultant field is the composition of waves emitted from all portions of the trajectory. This picture applies for any law of the charged particle motion, including uniform motion. For a charge moving uniformly in the vacuum, it can be shown that the radiation from different portions of the trajectory cancels, with the effect that a uniformly moving charged particle does not radiate. The same occurs when a charged particle propagates at a constant speed through a refractive medium when this speed is lower than the phase speed of light in the medium. But if the charged particle speed exceeds the phase speed of light, then, as is evident from Fig. 2, the radiation from different portions of the trajectory no longer cancels but is coherently combined.

Interestingly, Vavilov was among the first to accept the theory constructed by Tamm and Frank. He even demonstrated a beautiful experiment to his collaborators — a hydrodynamic analogy for the blue glow. M N Alentsev told me about this. Vavilov took a plane glass cuvette, poured some water into it, and placed a lamp below the cuvette.

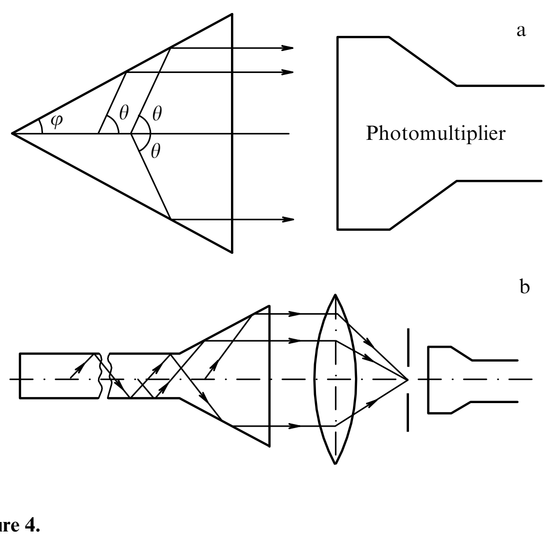

Figure 4.

When the lamp was turned on, a magnified image of the cuvette appeared on the ceiling. Vavilov took a sharp pencil and passed its point over the water surface in the cuvette. On the ceiling, two waves were seen to diverge, making an angle with the pencil point at its vertex.

After the emergence of the theory, Cherenkov performed several experiments to verify its theoretical predictions. His measurements turned out to agree nicely with the theory. Following Vavilov's advice, Cherenkov summarized the main facts about the new effect — both experimental data and some theoretical results — in a brief paper in English and sent this paper to the well-known London natural science journal *Nature*. The paper was entitled "Visible Radiation Produced by Electrons Moving in a Medium with Velocities Exceeding that of Light." But the editors of the journal did not accept the paper for publication. The reason undoubtedly lay with a distrust created by the content of the paper, beginning with its title. For the sake of fairness it should be admitted that distrust in the entire complex of problems related to the blue glow was at that time expressed by some well-known and respected physicists not only abroad but also in the USSR. Doubt was aroused both by the measurement techniques and the data obtained at the visibility threshold, as well as by the theoretical explanations.

Vavilov advised Cherenkov to send the rejected paper to the American physical journal *Physical Review*. The paper was published there in 1937 [9]. Next year, the same journal published paper [10], which was motivated by Cherenkov's paper [9] and concerned with experimental verification of relation (2). American physicists Collins and Reiling [10] measured the angular distribution of the glow excited in thin platelets of substance by the beam of electrons accelerated to the energy about 2 MeV. The beam current was equal to 10 μA. The glow in the experiments staged by Collins and Reiling was much brighter than in Cherenkov's experiments. Photographing this glow required the exposure time 10 s (Cherenkov needed an exposure time of three days when he was photographing the glow). The accelerator turned out to be a considerably more intense source of fast electrons than the small amounts of radium with which the measurements at FIAN were performed. The data of Collins and Reiling were in perfect agreement with the theory constructed by Tamm and Frank. However, the authors did not understand (or did not accept) the foundations of the theory by Tamm and Frank. This is what they wrote in their paper: "Electrons constantly lose energy as they pass through a medium. The resultant acceleration is responsible for Cherenkov's radiation." Collins and Reiling believed that the cause of radiation was precisely the acceleration (to be more precise, deceleration) of particles in the medium. Meanwhile, according to the theory constructed by Tamm and Frank, the radiation emerges in the uniform motion of a charged particle.

The quotation from the paper by Collins and Reiling comes as no surprise considering how novel and unconventional the conclusion was that a uniformly moving charge becomes a radiation source when its speed exceeds the speed of light. We emphasize, by the way, that Collins and Reiling were the first to use the term "Cherenkov radiation" in their work. Presently, the names "Cherenkov radiation" and "Cherenkov effect" are commonly accepted in the West. As for Russia, even when Vavilov was alive, his students, collaborators, and in general those physicists who witnessed the discovery proposed that the blue glow should be termed "Vavilov–Cherenkov radiation" or the "Vavilov–Cherenkov effect" in order to emphasize the decisive role played by Vavilov in its discovery. Vavilov would invariably object to such proposals and he himself resorted to the name "Cherenkov glow." However, several years after Vavilov's death, several Soviet physicists would nevertheless use the term "Vavilov–Cherenkov effect." I believe that this name does not diminish the role played by Cherenkov and reflects both the history of the discovery and the role of Vavilov much better. However, we do well to bear in mind that the name "Cherenkov effect" is rooted in modern physics. The future will show how the glow discovered by Vavilov and Cherenkov will finally be referred to. In the long run, it is not a matter of the name: it is important to know how the discovery was made. As for me, I use the term "Vavilov–Cherenkov radiation."

In 1940, Cherenkov defended his doctoral thesis entitled "Radiation of Electrons in Their Motion at Superluminal Velocity in Substance." During the defense procedure, Mandel'shtam raised the question of what regions of the medium — those close to the path of a superluminal electron or distant ones — were responsible for the Vavilov–Cherenkov radiation. The answer to this question was provided in a paper by Ginzburg and Frank [11] seven years later. They considered the motion of an electron along the axis of a cylindrical channel made in a medium with a permittivity ε_1 and filled with a medium with a permittivity ε_2. Ginzburg and Frank solved the problem exactly; for brevity, we here give only the qualitative result of their treatment in the case of an empty channel (i.e., $\varepsilon_2 = 1$). Let the electron speed exceed the phase speed of light outside the channel. Then outside the channel, the Vavilov–Cherenkov radiation exists, with the radiation intensity depending on the channel radius R. For radiation of a frequency ω, the dependence of the intensity on the radius is qualitatively as follows. When the channel radius R satisfies the inequality

$$R < \frac{2\pi v}{\omega\sqrt{1-\beta^2}} \qquad (8)$$

(where $\beta = v/c$), the radiation is little different from what would be the case for a channel-free continuous medium. When the opposite inequality holds, the intensity of the Vavilov–Cherenkov radiation decreases rapidly with an increase in the channel radius. It is assumed that the speed v of an electron that travels along the channel axis exceeds the phase speed of light in the medium. For a qualitative estimate, the electron speed v in the numerator in (8) may be replaced with the speed of light in the vacuum c. The quantity $\lambda = (2\pi c/\omega)$ is the wavelength in the vacuum that corresponds to the radiation of the frequency ω. The quantity $\gamma = (1-\beta^2)^{-1/2}$ is the so-called Lorentz factor. This quantity is proportional to the particle energy. Therefore, the quantity $\lambda\gamma$ may be regarded as the critical parameter for the channel radius. For high particle energies, $\lambda\gamma$ becomes much greater than the wavelength. This signifies that the main role in the formation of the Vavilov–Cherenkov radiation is played by the regions of the medium that are remote from the particle trajectory, this remoteness increasing proportionally to the particle energy.

In the years that saw the discovery of Vavilov–Cherenkov radiation and the finding of its explanation, its possible applications were not yet considered. The radiation was so weak, indeed, that the very observation of this radiation ran into serious problems. The situation changed when photomultipliers — devices that enabled reliable detection of so weak a radiation as Vavilov–Cherenkov radiation produced by a single charged particle — emerged. In 1947, ten years after Tamm and Frank constructed the complete theory of the effect, *Physical Review* published Getting's suggestion [12] that photomultipliers be used to record Vavilov–Cherenkov radiation. The use of Cherenkov counters goes back to precisely this suggestion. The simplest devices of those proposed by Getting are depicted in Fig. 4.

A fast charged particle that travels along the axis of a cone made of a transparent plastic produces Vavilov–Cherenkov radiation (Fig. 4a). The cone angle is selected such that the radiation experiences the total internal reflection from the conic surface, is normally incident on the plane base of the cone, and emanates in the form of a parallel beam of rays. A lens focuses this beam onto the photocathode of a photomultiplier. The part of the Cherenkov counter in which the radiation is generated is called a radiator. Figure 4a shows a conic radiator.

Figure 4b depicts a radiator consisting of a cylindrical part and an adjacent conical part. This radiator also produces a parallel beam of rays; in this case, the charged-particle energy losses due to the Vavilov–Cherenkov radiation in this radiator may far exceed those in the conical one, because the path of the particle in the cylindrical part of the radiator is rather long. Accordingly, the energy that reaches the photomultiplier is also higher than the conical radiator flash energy, which facilitates detection.

We emphasize that because we are considering the history of the discovery, we here discuss the first simplest designs of Cherenkov counters. Nevertheless, even these simplest versions offer several advantages over, say, a Geiger counter. For example, once a Geiger counter operates, an observer knows that a charged particle has traversed the working volume of the counter. But the observer cannot determine the direction the particle has passed: from right to left or from left to right, or downwards, or in some other direction. By contrast, the Cherenkov counter not only detects the passage of a charged particle but also determines the direction of its motion owing to the directivity of Vavilov–Cherenkov radiation. When a parallel beam emanates, e.g., from the base of the radiator depicted in Fig. 4a, this signifies that the charged particle has traversed the radiator in the direction from the apex to the base of the cone.

The second advantage of a Cherenkov counter consists in its fast response, which is faster than that of a Geiger counter by many orders of magnitude. In passing through the working volume of the Geiger counter, a charged particle excites a gas discharge, which permits recording the particle. The charge duration is of the order of 10^{-4} s. If another particle passes through the counter during the discharge, the counter would record the two particles as one. In the Cherenkov counter, a charged particle produces a radiation flash that is several orders of magnitude shorter in duration than the Geiger counter discharge.

When comparing a Cherenkov counter with a Geiger counter, perhaps it would be appropriate to speak about their differences rather than about the advantages of one of them over the other. Each counter has a field of application of its own, and is widely used within this field. For instance, Cherenkov counters cannot record particles whose speeds are lower than the phase speed of light in the radiator material, while the Geiger counter does detect such particles.

After the publication of Getting's proposal, a rapid development of the Cherenkov counter technology started.

Counters designed to determine the speed, charge, total energy, and other characteristics of a charged particle emerged. Cherenkov counters were rapidly incorporated into the arsenal of high-energy physics.

Tamm, Frank, and Cherenkov were awarded the 1958 Nobel Prize in Physics "for the discovery and the interpretation of the Cherenkov effect." In the Soviet Union, the importance of the discovery had been recognized much earlier: in 1946, Vavilov, Tamm, Frank, and Cherenkov were awarded a Stalin Prize of First Degree — at that time, the highest official sign of scientific recognition.

* * *

Interestingly, the properties of Vavilov–Cherenkov radiation give researchers a unique chance: it is possible to make a Cherenkov counter such that it is simultaneously the site of a nuclear reaction and the means for its recording.

In the early 1960s, a large Cherenkov counter was made at the Lebedev Physical Institute of the Russian Academy of Sciences. It was used to investigate the production of muons under the action of high-energy protons, which are a constituent of cosmic rays. The counter was made in the Laboratory of Cosmic Rays by a team led by A E Chudakov. The function of the radiator in the counter was fulfilled by water, which filled a huge tank welded of steel sheets. The tank was a truncated cone in shape (Fig. 5). The base of the truncated cone measured 6.5 m in diameter, the upper cone base measured 2.5 m in diameter, and the height was 5 m. To record light, 16 photomultipliers accommodated symmetrically about the cone axis on its surface were used. The inner tank surface was painted white to prevent the wall from absorbing the radiation that did not immediately find its way into the photomultipliers. The water filling the facility was purified for the same purpose, to minimize absorption of the Vavilov–Cherenkov radiation.

On entering the volume of such a counter, a high-energy particle produced an electron–photon or electron–nucleus shower. From the integral Vavilov–Cherenkov glow produced by reaction products, it was possible to assess the primary particle energy.

This counter was operated for several years. It was used, in particular, to investigate multiple production of muons in high-energy nuclear interactions [13]. In the mid-1960s, the counter was disassembled. At that time, this was the world's largest Cherenkov counter.

* * *

In 1996, a gigantic Cherenkov detector was put into service in Japan. It is accommodated in a mine one kilometer beneath the surface of the Earth in the Kamioka region, about 300 km north of Tokyo. The detector is a cylindrical tank of welded stainless steel (Fig. 6). The tank measures 41.4 m in height and 39.3 m in diameter, and holds 50,000 t of water, the water being carefully purified to minimize the absorption and scattering of light in it. Located on the walls as well as on the lower and upper bases of the tank are 11,146 photomultipliers.

This detector received the name Super-Kamiokande. The three last letters stand for Nuclear Decay Experiment. This detector was intended for use in the quest for proton decay. This quest is underway but so far has not yielded definite results. However, the Super-Kamiokande detector has enabled obtaining significant results (making important discoveries) in neutrino physics. The neutrino is still a mysterious particle in many respects, exhibiting an extremely weak interaction with other elementary particles. The gigantic size of the counter permits recording individual and infrequent events of the interaction of neutrinos with protons and neutrons in the atomic nuclei of the elements that make up water (oxygen and hydrogen). Fast charged particles are produced in the collision of energetic neutrinos with nucleons. The fast particles produce Vavilov–Cherenkov radiation in their passage through the water column of the counter. The

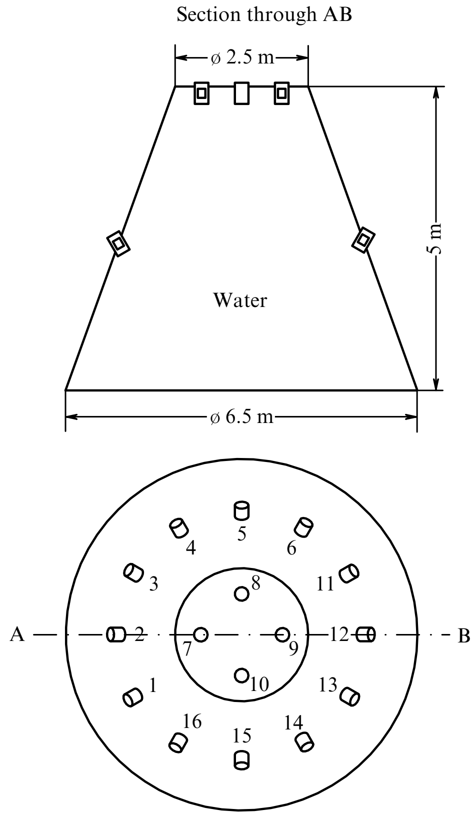

Figure 5. Large total-absorption Cherenkov counter.

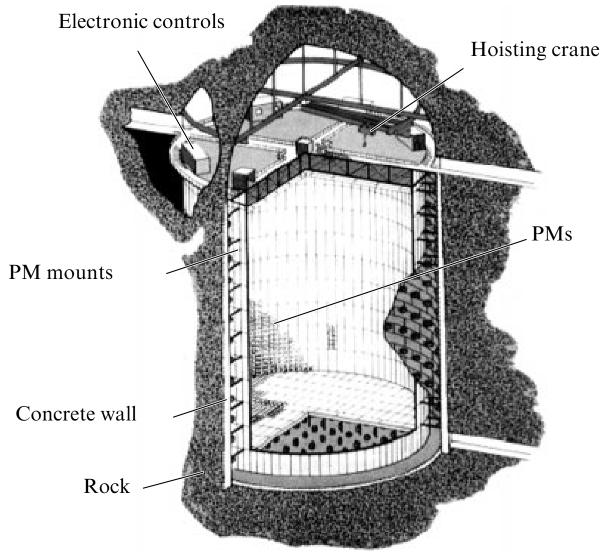

Figure 6. Water Cherenkov detector, 50 thousand tons of water, 11200 photomultipliers (PMs).

radiation is detected by the photomultipliers mounted on the inner surface of the tank and is minutely analyzed. This analysis enables sufficiently accurately determining the kind of neutrino that has caused the reaction, as well as the energy and the momentum direction. As is generally known, there are three types of neutrinos — electron, mu-meson (muon), and tau-meson (taon), in accordance with the three different kinds of nuclear reactions in which these particles are produced or absorbed.

Measurements performed with the Super-Kamiokande detector [14] have given firm evidence in favor of neutrino oscillations. The effect consists in the neutrino experiencing 'in-flight' changes: a neutrino of one type transforms into a neutrino of another type. Neutrino oscillations were predicted by B Pontecorvo in 1957.

The Super-Kamiokande detector is simultaneously the site of nuclear reactions and the means for their detection.

Furthermore, using large Cherenkov detectors like Super-Kamiokande and the previously constructed Kamiokande detector, it has been possible to record neutrinos coming from distant cosmic objects. In 1987, neutrinos produced in the supernova outburst in the Large Magellanic Cloud were detected [15]. Today, it is valid to say that neutrino astronomy has come into being.

* * *

The glow of different liquids under gamma-ray irradiation had been observed prior to Cherenkov's experiments. In particular, in 1926–1929, the French physicist M Mallet observed such a glow and even photographed its spectrum [16]. But Mallet believed that the glow he had observed was luminescence and did not undertake any further investigations. It took Vavilov's knowledge and experience to determine that the glow discovered by Cherenkov was different in nature from luminescence.

As regards Tamm and Frank's theory, which interprets the Vavilov–Cherenkov radiation, here, too, it is possible to indicate earlier papers containing some quite close physical ideas but, of course, not so complete an explanation. For instance, back in 1904, the famous German theorist Arnold Sommerfeld calculated the field of a charged particle that moved in the vacuum at a constant speed exceeding the speed of light [17]. Sommerfeld showed that radiation of directional electromagnetic waves occurred. However, the special theory of relativity was formulated shortly thereafter, the motion of material bodies at a superluminal velocity turned out to be impossible, and Sommerfeld's work was forgotten. When Tamm and Frank were discussing their work with A F Ioffe, he remembered Sommerfeld's work and informed Tamm and Frank about it. A reprint of the paper by Tamm and Frank was sent to Sommerfeld. The authors received a letter of thanks from him. This exchange of letters had taken place before the Second World War broke out. Later, Sommerfeld included an article entitled "Cherenkov radiation" in his textbook *Optics*.

Tamm and Frank had another precursor who had approached their theory rather closely, even more closely than Sommerfeld. However, his work was consigned to oblivion for a longer time than Sommerfeld's work. It was not recalled until the mid-1970s. The author of this work was the famous English physicist, mathematician, and engineer Oliver Heaviside. In 1889, proceeding from the Maxwell equations, Heaviside calculated the field of a charged particle moving at a constant velocity through a medium with a given dielectric constant (or through a medium with a given refractive index, which is the same) [18]. It followed from his calculations that the particle radiated electromagnetic waves when its speed exceeded the speed of light in the medium. Heaviside determined the radiation angle, and it turned out that the angle was defined by relation (2). He also determined the radiation spectrum. Heaviside's theory was not as complete as the theory constructed by Frank and Tamm. In particular, Heaviside did not take dispersion into account, and therefore his expression for the total radiation loss diverged. Furthermore, Heaviside did not regard the speed of light in the vacuum as the speed limit for all material bodies. In his theory, for instance, the charged particle could travel through the refractive medium at a speed exceeding the speed of light in the vacuum. But in many respects, his theory was close to the theory by Frank and Tamm.

Heaviside's work was forgotten even more so than Sommerfeld's. This was attributable to the fact that Heaviside had been ahead of his time. In particular, as indicated above, he considered the field of a point-like charged particle moving at a constant speed in a refractive medium. But no charged particles had been discovered by that time, not even the electron, to say nothing of the other particles carrying electric charge. Furthermore, Heaviside considered the case where the charged-particle speed exceeded the speed of light in the medium. Such speeds seemed to be inconceivable for material bodies at that time. The first fast particles were obtained in the decay of radioactive elements, but the radioactivity itself was discovered only ten years later. That is why Heaviside's work appeared to be distant from reality and was promptly forgotten. It was remembered many years later, in the mid-1970s.

By contrast, when Tamm and Frank set themselves the task of interpreting the Vavilov–Cherenkov glow, they were to explain a physical effect observed in reality.

When these old studies by Heaviside became known, I recall, Frank was recovering in the Uzkoe academic sanatorium. On his request I took the third volume of Heaviside's book *Electromagnetic Theory* — a part of the volume was dedicated to the radiation of superluminal sources — and brought it to him. After reading the book, he returned it to me saying: "It is a great honor to have such a predecessor."

* * *

During the past years, Vavilov–Cherenkov radiation has found numerous applications. The technology of Cherenkov counters has made rapid strides. Nowadays, they are complicated devices, combining the achievements of optics, electronics, and radiophysics. Using the Vavilov–Cherenkov radiation, they ensure high-efficiency detection of fast charged particles that pass through the radiator. Moreover, it has become possible to make detectors that need not be placed in the path of fast particles: these detectors are capable of detecting particle fluxes at a distance. The idea of making these detectors was conceived by Askar'yan [19, 20]. Let a high-energy electron enter the terrestrial atmosphere from space. In its path, it interacts with the nuclei of atoms that constitute the atmosphere. The electron produces bremsstrahlung in the field of a nucleus, the emitted photon energy being of the same order of magnitude as the electron energy. This photon next interacts with the nucleus or electron of another atom to produce an electron–positron pair. Each of the particles that make up the pair also emits bremsstrahlung photons (second-generation photons, so to say). These second-generation photons in turn produce electron–positron pairs, and so on: a so-called electromagnetic shower develops.

It was assumed that an electromagnetic shower did not produce electromagnetic radiation because a shower was electrically neutral, the electrons and positrons in the shower being equal in number. In Ref. [19] and in the subsequent paper [20], Askar'yan showed that the shower actually contains an excess of electrons. This is because the electrons and photons that make up the shower ionize the atoms of the air in their path (ionize the atoms of gases that compose the air) and knock electrons out of them, and these electrons become part of the shower. That is why the shower turns out to be negatively charged, the excess of electrons amounting to several dozen percent of the total number of particles in the shower. The shower may therefore be a source of Vavilov–Cherenkov radiation in the atmosphere. The emission occurs at those frequencies for which the phase speed of electromagnetic waves is lower than the speed of shower particles. Askar'yan estimated the intensity of the Vavilov–Cherenkov radiation produced by the shower at radio frequencies (e.g., at the wavelength 10 cm). Its intensity was found to substantially exceed the intrinsic noise of radio receivers, which opened up the possibility of recording cosmic showers by their radiation (including the Vavilov–Cherenkov radiation) at radio frequencies. This signifies that the recording unit need not be placed in the shower shaft, it may be located away from the shower. In recent years, recording showers through Vavilov–Cherenkov radiation at radio frequencies has been taken up by many radio astronomical stations.

Speaking of applications that involve Vavilov–Cherenkov radiation, we have so far considered only high-energy physics. But the ideas underlying the interpretation of this effect are actually widely used in many fields of physics. The principal idea — the idea of wave–particle synchronism — is at the heart of several radiophysical applications; this idea is basic to the explanation of wave damping in collisionless plasmas, as well as of several acoustic and hydrodynamic effects. Owing to space limitations, we cannot discuss the subject at greater length in this paper.

Relatively recently, Vavilov–Cherenkov radiation happened to bear on the interpretation of an interesting phenomenon. All deep-sea fish have eyes, but it was unclear until recently why they have retained the organ of sight. Sea water exhibits a high electric conductivity, and hence it follows that the daylight is strongly attenuated with depth in sea water and complete darkness should reign at a depth of several hundred meters. Eyes are not needed in total darkness, and the organ of sight should have died out according to the laws of evolution. It turns out, however, that there is no complete darkness at great depths. A radioactive isotope of calcium dissolved in seawater emits fast electrons. These electrons are responsible for Vavilov–Cherenkov glow in seawater, and therefore twilight reigns at great depths — "the Vavilov–Cherenkov twilight." The illumination at great depths turns out to be such that vision may well prove beneficial to fish [21].

In the late 1960s — early 1970s, several papers were published concerned with the action of fast particles that are constituents of cosmic radiation on human vision. These questions arose in connection with the development of astronautics, specifically in connection with the Apollo-11, Apollo-12, and Apollo-13 space missions aimed at achieving a lunar landing of a human being. The Apollo-11 mission took place in July 1969. The astronauts Neil Armstrong and Michael Collins landed on the Moon, and Edwin Aldrin remained in the command module, which orbited the Moon. The astronauts stayed on the Moon for about a day, and Aldrin stayed in the cabin the entire time. For a significant portion of this time, the cabin was isolated from external light. On returning to Earth, Aldrin reported that he observed point-like short-duration flashes in white color. Similar flashes were seen by Armstrong as well. The astronauts who participated in the following missions also observed short-time flashes when they were in the darkness or closed their eyes [22]. The possible causes of these flashes were discussed in Ref. [23]. The authors considered two possible causes: the ionization produced by primary or secondary cosmic radiation particles in or near the retina of the eye, and (or) Vavilov–Cherenkov radiation induced by fast particles traversing the transparent substance in the eyeball. In this connection, we note that the glow of the transparent substance in the eyeball caused by radioactive radiation was known long before the onset of the age of spaceflight.

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