Physics of Our Day

SOVIET SCIENTISTS WIN THE 1958 NOBEL PRIZE FOR PHYSICS

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THE Nobel Prize for physics in 1958 has been awarded to three Soviet scientists: Pavel Alekseevich Cerenkov, Il'ya Mikhailovich Frank, and Igor' Evgen'evich Tamm; these men won the prize for their discovery and interpretation of an effect which is known as the Vavilov-Cerenkov effect in the U.S.S.R. but is more widely known in the West as the Cerenkov effect.

It has been twenty-four years since Cerenkov[1] first observed this effect and twenty-one years since it was explained by Frank and Tamm. It may be of interest to summarize the history of this discovery.

In 1934 Cerenkov, who was then an aspirant under Academician S. I. Vavilov, was investigating the luminescence of uranium salt solutions under the effect of gamma radiation from radium. A strange effect was noted in these experiments — even pure solutions were faintly luminescent when irradiated by gamma rays from radium.

This radiation from liquids under the action of gamma rays had been known for a long time. In particular, the luminescence observed by Cerenkov was very reminiscent of the so-called "blue" radiation of liquids under the effect of intense ultra-violet which had been observed and studied in 1929 by Vavilov and L. A. Tumermann[2] (see also reference 7).

These authors showed that the "blue" optical radiation from liquids was due to the presence of unidentified contaminating materials. The properties of this radiation were the same as those of ordinary fluorescence and it exhibited all of the characteristics expected for a radiator with a finite lifetime (10^{-10} sec or greater). In luminescence this lifetime is determined by the probability for a transition from an excited state of the atom or molecule to a state which is lower in energy. Thus, by affective the environment of the excited atom or molecule it is always possible, to some extent, to quench luminescence. Methods for doing this are, for example, elevation of the temperature (which also reduces the degree of polarization of the radiation since the thermal motion "scrambles" the orientation of the molecules), or addition of "quenching" materials (these quenching materials interact with the excited molecules).

PAVEL ALEKSEEVICH CERENKOV

However, the radiation discovered by Cerenkov was found to exhibit a number of properties which differed from those of ordinary fluorescence. Even when the liquids were carefully purified and all contaminating materials removed there was no reduction in the intensity of the radiation. For example, the radiation from ordinary tap water was found to be the same after triple distillation as before distillation. This new radiation could not be quenched by introducing quenching materials such as potassium iodide, silver nitrate, or nitrobenzol. The introduction of these materials in either small or large amounts had no effect on the intensity of the radiation. For this reason it was necessary to reject the suggestion that the radiation was due to small amounts of fluorescent foreign materials.

To study the effect, Cerenkov carried out several experiments, usually employed in Vavilov's laboratory for investigating the fluorescence of solutions of luminous dyes. These experiments consisted of determining the intensity and polarization of the radiation under various conditions (variation in temperature or amount of quenching material). In principle, it was possible to use the results of these measurements to ascertain certain properties of the radiator (especially the lifetime in the excited state).

However, in the case of the radiation discovered by Cerenkov it was found that temperature variations or quenching agents had absolutely no effect. This meant that the lifetime of the excited state of the radiator, if any, was, in any case, several orders of magnitude smaller than that associated with usual luminescence. For this reason Vavilov[3] proposed that "the effect in question could not be any form of luminescence, since the finite duration of excitation is a primary characteristic of luminescence." In this paper by Vavilov,[3] which was also the first publication of Cerenkov, there were some indications of the possible origin of the effect.

As is well known, the mechanism by which gamma rays are absorbed in material involves the transfer, in total or in part, of the energy of the gamma photon to an electron in the so-called photo or Compton effect. These electrons then move in the medium, gradually losing their energy and slowing down. In particular, these electrons may cause fluorescence in atoms or molecules of the medium. However, since the experiments indicated that the radiation in question could not be fluorescence, Vavilov proposed that the radiation was due to the electrons themselves. A natural mechanism known at this time for the radiation of a free electron in a medium was bremsstrahlung. Vavilov proposed that the new radiation could be explained as bremsstrahlung of electrons which had been ejected from atoms by gamma rays. This hypothesis explained almost all of the properties of the radiation which were known at that time — the absence of a finite lifetime for the excited state, the polarization, and its universality, i.e., the fact that the radiation was observed in all pure liquids which had been investigated, regardless of their chemical composition.

Later it was shown that the mechanism for the radiation of free electrons in a medium discovered by Vavilov and Cerenkov was not bremsstrahlung and that this part of Vavilov's interpretation was incorrect. However, Vavilov's suggestion that the effect was not ordinary luminescence and that it was due to the radiation of the electrons themselves was correct and had an important bearing on the course of future research.

Experiments carried out by Cerenkov with beta-ray sources (thin-walled ampules filled with radium emanation) showed that electrons actually excited radiation in the liquids and that this radiation was identical with that produced by the gamma rays. In order to obtain direct proof that the radiation in liquids irradiated by gamma rays was produced by electrons, he carried out experiments to determine the effect of a magnetic field on the radiation. If the radiation were produced by electrons the polarization should be determined by the direction of electron motion. (The magnetic field acts on the electrons, modifying their trajectories). Hence, by applying a magnetic field it should be possible to change the polarization of the radiation. On the other hand, if the radiation were not produced by electrons, but directly by the gamma rays, the magnetic field should have no effect. It was found that the magnetic field had a pronounced effect. Thus it was shown that the radiation was due entirely to electrons. However, the mechanism by which the electrons radiated in the medium remained unexplained. The suggestion that the radiation was bremsstrahlung of free electrons could not explain the observed intensity and the fact that the intensity was approximately the same in liquids with different Z, and so on.

It was also shown in these experiments carried out by Cerenkov that the radiation is highly directional. An intensity maximum is observed at some definite angle with respect to the direction of motion of the electrons.

Before considering the theory of the effect we may mention that the spectrum of this new radiation is continuous and limited on the short-wave side only by the absorption limits of the liquid itself or the absorption limits of the optical system being used in the investigation.

To gain further understanding of this new radiation, Cerenkov carried out a series of difficult and delicate experiments. There is an old saying, frequently made in jest, that all great discoveries are made in the dark; in Cerenkov's case this saying is literally true. The intensity of the gamma ray sources available to Cerenkov was very low. For this reason it was impossible to use usual photometry methods for making quantitative measurements. At that time the most convenient method for studying the new radiation was a method based on the visual perception threshold which had been developed by E. M. Brumberg and S. I. Vavilov for quantitative measurements of weak optical sources.[4] Each day, before the measurements, Cerenkov (Vavilov frequently also helped in the measurements) remained in a darkened room for an hour or an hour and a half. During this time the sensitivity of his eyes increased by a factor of 10,000. Then the measurements were started. Each measurement was made after a rest period (3 – 5 minutes) to avoid eye fatigue. To maintain the dark adaptation of the eye, and to avoid the possibility of subjective errors, the actual recording of the data was carried out by an assistant. After two or two and a half hours the measurements had so fatigued his eyes that the work was stopped for the day in order to avoid errors.

Although the radiation is observed in all transparent materials, liquid or solid, these measurements were made in liquids. This choice was made on the basis of the fact that almost all solids, both natural and synthetic, exhibit rather intense luminescence under the effect of bombardment by radioactive sources. Since the intensity of the radiation being investigated was much weaker than the intensity of this spurious luminescence the latter would create a number of additional experimental difficulties.

The radiation discovered by Cerenkov in 1934, which is now called Cerenkov radiation, was explained in 1937 by I. E. Tamm and I. M. Frank.[5] They showed that the Cerenkov radiation could be explained both qualitatively and quantitatively within the framework of classical electrodynamics. These authors showed that even a charge which moves uniformly in a medium should radiate light if its velocity is greater than the phase velocity of light in the medium. For an electron moving in water this critical velocity is achieved at approximately 250 kev. It is known that a considerable fraction of the electrons emitted by radioactive materials or produced by gamma rays have such high energies.

The conditions under which a charge which moves uniformly in a homogeneous medium can radiate can be derived from either a classical or a quantum-mechanical analysis.

Suppose that a charge which moves with uniform rectilinear motion radiates a wave. Since the charge moves with uniform rectilinear motion in a homogeneous medium the electromagnetic field must be carried along with the charge, i.e., the field must depend on the argument $\mathbf{x} - \mathbf{v}t$, where $\mathbf{v}$ is the velocity of the charge. The radiated wave is given by the expression

$$e^{i\mathbf{k}(\mathbf{x}-\mathbf{v}t)}, \tag{1}$$

where $\mathbf{k}$ is the wave vector which characterizes the direction of propagation of the wave. As is apparent from (1), the frequency of this wave (the factor which multiplies t in the exponent) is given by the expression

$$\omega = kv = kv \cos \vartheta, \tag{2}$$

where ϑ is the angle between the direction of wave propagation and charge velocity. On the other hand, the frequency of any electromagnetic wave in a medium is related to its wave vector $\mathbf{k}$ by the relation

$$\omega = \frac{ck}{n}, \tag{3}$$

where n is the index of refraction at the given wavelength and c is the velocity of light in vacuum. From (2) and (3) it follows that

$$\cos \vartheta = \frac{c}{nv} = \frac{1}{n\beta} \left(\beta = \frac{v}{c} \right). \tag{4}$$

The condition in (4) determines the angle between the velocity of the charge and the direction of propagation of the wave radiated by the charge. It is clear that the wave can actually be radiated only in the case in which

$$\frac{vn}{c} = n\beta > 1, \tag{5}$$

i.e., when the velocity of the charge is greater than the phase velocity of light in the medium.

A similar radiation condition is obtained if one makes a simple quantum mechanical analysis, such as that first carried out by V. L. Ginzburg.[6] If we write the momentum of a photon in the medium as $p_\gamma = \hbar\omega n/c$ and apply the laws of conservation of energy and momentum in the radiation of the photon, an expression is obtained for $\cos \vartheta$ which shows that the relation in (4) is valid except for a term given by the ratio of the de Broglie wavelength of the electron h/p_e to the wavelength of the radiated photon. This quantity is extremely small in actual cases; this situation emphasizes the classical nature of the effect.

Tamm and Frank obtained the following expression for the energy loss of a charged particle due to Cerenkov radiation (per unit length of path)

$$\frac{dW}{dx} = -\frac{e^2}{c^2} \int\limits_{n\beta > 1} \left(1 - \frac{1}{n^2\beta^2} \right) \omega \, d\omega, \tag{6}$$

IL'YA MIKHAILOVICH FRANK

where the quantity under the integral sign is the spectral intensity of the Cerenkov radiation at frequency ω and the integration is carried out over all frequencies for which the condition in (5) is satisfied, i.e., for waves whose phase velocity is smaller than the velocity of the particle. This formula is now known as the Frank-Tamm formula in the literature.

The analysis given by Frank and Tamm made it possible to determine the polarization of the Cerenkov radiation. In particular, the electric vector of the Cerenkov wave is perpendicular to the wave vector (as is the case for any light wave) and lies in the plane formed by the particle velocity **v** and the wave vector **k** of the radiated wave. The direction of the polarization vector is given by

$$\mathbf{v} - \frac{\mathbf{k}(\mathbf{kv})}{k^2}. \quad (7)$$

The properties of the radiation predicted by the Frank-Tamm theory were found to be identical with those observed by Cerenkov.

As far back as 1904 — 1905 Sommerfeld[8] had shown that if an electron moves in vacuum with a velocity that exceeds the velocity of light the electron should lose energy, being slowed down by its self-field, i.e., it should give off electromagnetic radiation. Later, however, it became obvious that it was impossible for an electron to move with a velocity greater than the velocity of light in vacuum and Sommerfeld's work was forgotten. After the work of Tamm and Frank the meaning of Sommerfeld's work became clear: the Sommerfeld formulas apply if the velocity of light in vacuum is replaced by the velocity of light in the medium. Under these conditions the charged particle can move through its own field and produce a Cerenkov effect.

During the twenty odd years since its discovery and interpretation, the Cerenkov effect has been the object of a great deal of experimental and theoretical work and has found important physical applications.

The Cerenkov effect has been investigated in detail both for isotropic and crystalline media. The Cerenkov effect in crystals exhibits a number of interesting features; these were first considered by Ginzburg. Since space does not permit us to go into details we refer the reader to survey papers on the Cerenkov effect[9,10,11] which contain detailed bibliographies. Frank has analyzed a number of theoretical problems — the Cerenkov radiation of multipoles, interference effect in Cerenkov radiation, the duration of the light flash, and so on. Tamm has considered the transformation properties of the Cerenkov effect (that is, the Cerenkov effect in a coordinate system in which the charge is at rest while the medium moves with a "super-light" velocity). This analysis lies at the basis of several versions of a coherent method of particle acceleration which has been recently proposed by V. I. Veksler.

Ginzburg and Frank have also considered the Cerenkov radiation that is produced in the motion of a particle along the axis of a channel in a dense medium. This analysis lies at the basis of methods of generating radiowaves by means of the Cerenkov effect.

Cerenkov radiation has a number of unique properties and these find wide application in the physics of high-energy particles. A fast particle which emits Cerenkov radiation acts as though "calling attention to itself." The beginning of the development of Cerenkov counter techniques goes back to 1947, when Getting proposed the use of photomultipliers as a means of observing Cerenkov radiation. During the subsequent years there have appeared a large number of designs for Cerenkov counters for determining various properties of charged particles — velocity, charge, direction of motion, and total energy. The velocity of a charged particle can be determined with accuracies as high as 0.1% by the angular distribution of the Cerenkov radiation (measurements of Mather on proton energies from the 184-inch cyclotron at Berkeley in 1951).

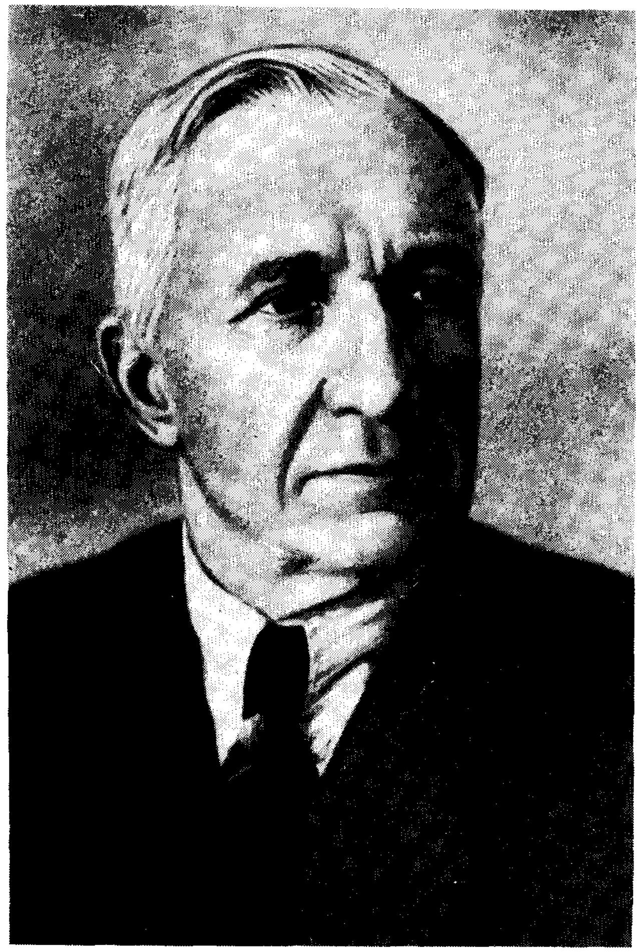
Cerenkov velocity selectors have been built and were, in fact, used in the discovery of the antiproton. The Soviet artificial earth satellites carried Cerenkov counters which were used to detect multiply charged ions in cosmic radiation.

The Cerenkov effect is very widespread in nature. This effect is encountered in a great number of fields of physics: radiation of the night sky, luminescence, physics of the electron plasma, controlled thermonuclear reactions, generation of radiowaves by means of the Cerenkov effect, study of the polar aurora and various new methods of particle acceleration.

And now several words about the Nobel laureates themselves. All are on the staff of the P. N. Lebedev Institute of Physics, Academy of Sciences, U.S.S.R. Cerenkov and Frank were students of Academicians S. I. Vavilov, whose untimely death was great loss to science and prevented his sharing in the achievements of the new Nobel laureates.

P. A. Cerenkov was born in 1904 in a peasant family in Voronezh Province. At the age of two he was left without a mother. He finished school at the age of twenty since his studies were carried on while he worked for a living. After finishing school, Cerenkov entered Voronezh University. He was graduated from the University in 1928 and then taught physics for two years in the intermediate schools in Michurinsk Province. In 1930 he was admitted as an aspirant at the Institute of Physics, where he worked under the guidance of Academician Vavilov. In 1935 he defended his candidate's dissertation "Luminescence in Solutions of Uranium Salts Under the Effect of Gamma Rays;" in 1940 he defended his doctoral dissertation, which described the investigation of the effect which now bears his name. He has worked on the construction of high-energy electron accelerators (in particular the 265-Mev accelerator of the Institute of Physics, Academy of Sciences). In recent years Cerenkov has been concerned with various aspects of photonuclear reactions.

I. M. Frank was born in 1908 in Leningrad.



IGOR' EVGEN'EVICH TAMM

Frank's mother worked as a doctor in the city hospital while his father was a mathematics teacher (later he became a professor at Leningrad Polytechnic Institute). In 1926, after finishing the secondary school, Frank entered Moscow State University. His diploma work was carried out under the direction of Academician S. I. Vavilov. Between the time in which he finished the University in 1930 and 1934 Frank worked in the State Optics Institute in Leningrad. In 1934 he joined the staff of the Institute of Physics. In March 1935 he received the degree of Doctor of Physico-Mathematical Sciences for his dissertation on the subject "Elementary Processes in Optical Dissociation."

In 1946 Frank was made a Corresponding Member of the Academy of Sciences, U.S.S.R.

Frank still works on various aspects of the problem of the motion of charged particles through refractive media (Cerenkov effect, Doppler effect, transition radiation). At present Frank directs the nuclear laboratory of the Institute of Physics.

The work of Frank and his group on important problems in neutron physics and nuclear physics is well known.

I. E. Tamm is an outstanding theoretical physicist. His work in the theory of metals, the theory of nuclear forces and the interaction of elementary particles, and the theory of avalanche processes in cosmic rays (and of course the work on the theory of the Cerenkov effect) has earned for him outstanding distinction. Together with A. D. Sakharov he is one of the pioneers in work on controlled thermonuclear reactions in the Soviet Union.

Tamm was born in 1895 in Vladivostok in the family of an engineer who worked on the construction of the Ussurisk Railroad. In 1898 his family moved to Elizavetgrad where Tamm completed the gymnasium in 1913. In that same year Tamm became a student at the University of Edinburgh in Scotland, where he spent one year. At the beginning of the war, in 1914, Tamm transferred to the Physics-Mathematics Faculty of Moscow State University. After graduation in 1918 he remained in the University in training for a professorship. From 1919 Tamm was a physics teacher in the Institution of Higher Learning at Simferopol and Odessa and (from 1922) at Moscow.

In 1933 Tamm became a Corresponding Member of the Academy of Sciences, U.S.S.R. In the following year, without defense of thesis, he was awarded the degree of Doctor of Physico-Mathematical Sciences. Since that year Tamm has worked at the Institute of Physics of the Academy of Sciences where he has been the Director of the Theoretical Division. In 1953 he was made a Member of the Academy of Sciences, U.S.S.R.

All three laureates still do a great deal of teaching. For several decades Tamm has been the head of the Division of Theoretical Physics of Moscow State University, which he organized. Frank also teaches at Moscow State University, where he heads the section on radioactive radiation; P. A. Cerenkov is a professor at Moscow Institute of Mechanics.

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