West Antarctica to be in approximate isostatic equilibrium.

7) The crust of West Antarctica is continental in character, but the Mohorovičić discontinuity has the relatively high elevation (exclusive of the mountainous areas) of about 30 kilometers below sea level.

8) The Mohorovičić discontinuity deepens at least to − 36 kilometers, forming a continuous trough beneath the Sentinel, Horlick, and Queen Maud mountains and indicating their general topographic continuity with the Palmer Peninsula.

9) The thinnest crustal sections are found beneath the Ross and Filchner ice shelves, but the elevation of the Mohorovičić discontinuity in these areas is not greatly different from that beneath the large channel in Marie Byrd Land.

10) From the configuration of the ice and rock surfaces it is concluded that the ice sheet in West Antarctica originated as two separate icecaps in the two mountainous areas, one in the vicinity of the Executive Committee Range, the other between the Horlick and Sentinel mountains. As the caps expanded they converged over the open water between and were probably initially joined by a floating ice shelf which then grew thick enough to fill the trough completely and produce the present single-grounded ice sheet.

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Radiation from High-Speed Particles

Visible radiation that is shown to differ from luminescence phenomena has important applications.

P. A. Cherenkov

The experimental investigation and demonstration of the notable properties of radiation which appears during the motion of fast, electrically charged particles through a substance extends back some twenty-five years. As early as 1934, two reports were published—one by S. I. Vavilov and the other by myself (*1*)—in which it was shown that the gamma rays from radium produce a weak visible radiation of the solvent in addition to the luminescence of the solution.

In these reports, the universal character of this radiation and its unusual properties were described, and the conviction was expressed that the newly discovered radiation could not be a luminescence phenomenon because of its properties.

It was established by further experiments that this radiation is not released directly by the gamma rays, but by rapidly moving Compton electrons, which arise under the action of the gamma rays on the basis of the Compton effect. Attempts to produce a radiation with the same properties by the action of x-rays ($h\nu_{max} = 30$ kev) gave negative results.

One might have thought that such radiation of the solvent would be of no special interest, since radiation phenomena, produced in various ways in solids and in liquids, represent a rather widespread effect. Aside from the generally well-known "classical" luminescence phenomena, one could, for example, mention the weak radiation of practically very "pure" liquids which arises under the action of ultraviolet radiation (*2*). Many liquids emit radiation upon the incidence of x-rays (*3*). Radiation has even been noted in liquids under the action of ultrasonic waves (*4*). Numerous cases of radiation from fluids and solids under the action of radioactive radiations have been well known from the time of Pierre and Marie Curie (*5*).

As a rule, such radiation phenomena are nothing else than ordinary luminescence and are emitted in the case of the so-called "pure" liquid as a result of the presence of a minute amount of luminescence-producing impurities. Therefore, one was inclined to believe that this radiation produced by the gamma rays was one of the many luminescence phenomena. This was presumed by Pierre and Marie Curie, who were undoubtedly among the first to have observed such radiation—of course, under conditions in which this radiation was rather strongly masked by ordinary luminescence.

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This article is a translation of the lecture he gave in Stockholm, Sweden, on 10 Dec. 1958, when he was awarded the Nobel prize in physics for 1958, a prize which he shared with I. Y. Tamm and I. M. Frank. It is published here with the permission of the Nobel Foundation. We are indebted to R. T. Beyer for translating the article from the German.

Other observers later reached the same conclusion. Among these was Mallet (*6*), who not only observed this radiation but even photographed its spectrum.

Phenomenon of a New Type

However, a thoroughgoing, quantitative investigation of this radiation process revealed a series of remarkable properties which provided incontestable proof that one was dealing in this case not with trivial luminescence but with a phenomenon of a wholly new type, which was of extraordinary interest not only because of its fundamental meaning but also because of the manifold possibilities for practical application.

Of course, it would be an error to think that so characteristic a phenomenon might not have been discovered earlier by an accidental "error."

The unusual nature of this newly discovered phenomenon could be investigated only through quantitative determination of the most important radiation characteristics and the establishment of their dependence on particular experimental conditions.

Nowadays, since the researcher has at his disposal very intense sources of fast-moving, electrically charged particles, and very sensitive measuring apparatus, such measurements do not present any particular difficulties. However, the means which were available to the physicist a few decades ago were not so satisfactory. Then he had available as sources of electrically charged particles only naturally radioactive preparations, whose intensity was rather slight. For this reason, the intensity of the radiation produced by them in liquids (*7*) was so weak that the radiation could be detected by the observer only after he had spent some time in absolute darkness. It stands to reason that, under such conditions, the ordinary methods of photometry for the quantitative determinations do not enter into the picture (*8*). A new and much more sensitive method was necessary for carrying out such determinations. At the Institute of Physics, Academy of Sciences of the U.S.S.R., where this phenomenon was discovered, the method developed shortly before by E. M. Brumberg and S. I. Vavilov (*9*) was applied. This was the method of visual photometry based on the sensitivity limit of the eye, or, as it is otherwise known, the method of extinction. This method made use of the human eye (*10*) in place of the light-measuring device. Since the sensitivity of the dark-adapted eye is at least several tens of thousands of times greater than the sensitivity of the eye in daylight, this method is distinguished by a rather high sensitivity in comparison with other methods. Notwithstanding the subjectivity of the method, and the admittedly large error which was associated with the measurements, it was at the time a very useful method, which permitted a quantitative determination of extremely small light intensities.

It is of fundamental importance to note that this method first permitted a transition to quantitative determinations, the proving of the unusual properties of the observed radiation, and the demonstration of their particular origin.

Luminescence Hypothesis Ruled Out

It has already been pointed out that the first and most plausible hypothesis in explanation of this radiation referred to luminescence phenomena. The correctness of this assumption was now to be confirmed only by showing experimentally, for this radiation, the presence of only the characteristic properties of luminescence.

But there now exist a great number of luminescence phenomena, which are distinguished among themselves by the method of excitation, the duration of the decay, the character of the spectrum, the properties of the luminescent substances, and other marks. In the case of interest to us, it is not a question of simply determining the presence or absence of signs of luminescence but of determining the important characteristics which clearly identify the luminescence phenomenon for what it is.

As was pointed out by S. I. Vavilov, one such characteristic of luminescence is the total duration of the excited state ($\tau > 10^{-10}$ sec). This property of luminescence has its influence on the decay process. For example, one can weaken the brightness considerably or, in other words, "quench" the luminescence either by heating the luminescent solution or by adding material which is capable of quenching the luminescense. In both cases, a weakening of the luminescence results as a consequence of an energy transfer from the excited particles to the unexcited, and of the subsequent transformation of the energy into heat.

Likewise, the polarization of the luminescence can be changed if the mobility of the particles is changed—for example, by heating.

But the corresponding experiments with this radiation showed that the brightness of radiation of the liquid cannot be affected either by heating or by dissolving in the solution such active fluorescence-quenchers as potassium iodide, silver nitrate, and so on. It has also been pointed out that the perceptible polarization appearing in this radiation is likewise unchangeable. It is of fundamental importance that in experiments intended for study of the quenching of fluorescence of undoubtedly fluorescent solutions (such as a water solution of esculin), carried out in parallel and under identical conditions, a visible quenching effect was in all cases exhibited.

These results indicated a virtually inertia-free character of the decay process and excluded the hypothesis of luminescence. This conclusion also found support in the unusual character of the polarization of this radiation. The direction of the electric oscillation vector was not perpendicular to the exciting beam of radiation, as is the case in polarized fluorescence, but was rather parallel to it.

Spatial Asymmetry of Radiation

The sum of the results collected during this first stage led to the conclusion that the radiation produced in the liquid under the action of gamma rays was no trivial phenomenon. However, these facts were not sufficient for construction of an objection-free theory of the phenomenon on such a basis. This problem was solved somewhat later, after a new, especially noteworthy, property of this radiation—its pronounced asymmetry, its directional character—was discovered, in 1936 (*9*, *10*).

It turned out that the radiation showed an extremely pronounced spatial asymmetry. This radiation is sent only forward, in a direction which forms a definite angle with the exciting beam of gamma rays.

The discovery of this fundamental property of the radiation proved to be a decisive step toward explanation of the true physical nature of this phenomenon and toward formulation of a theory. The creation of this theory was the contribution of I. M. Frank and I. E. Tamm (*11*).

True Nature of the Emission

This theory starts out from the idea that the described radiation is produced by electrons which move uniformly in the substance with a velocity which exceeds the phase velocity of light in this medium.

It is of interest that as early as 1901, Lord Kelvin (*12*) maintained that the emission might be produced by particles which travel with a superlight velocity.

Somewhat later, in the years 1904 and 1905, shortly before the appearance of the theory of relativity, Sommerfeld (*13*) considered theoretically the hypothetical case of the motion in a vacuum of an electron with a superlight velocity.

However, the appearance of relativity theory, which maintained that material bodies are not capable of achieving the velocity of light in their motion, much less a superlight velocity, allowed the conclusions of Sommerfeld to fall under a shadow, as being of little significance.

It is apparently due in some measure to this circumstance that the problem of the motion of electrically charged particles in a substance has generally been little considered, since this was thought not to be reconcilable with the theory of relativity.

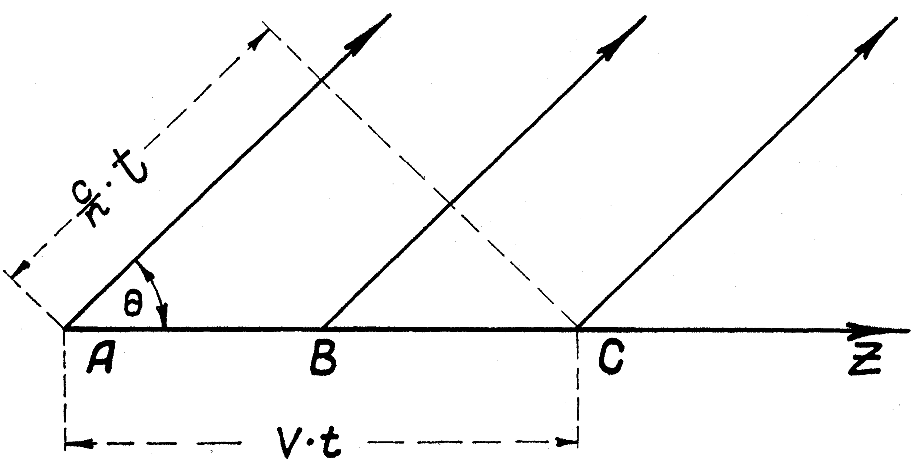


Fig. 1. Radiation mechanism.

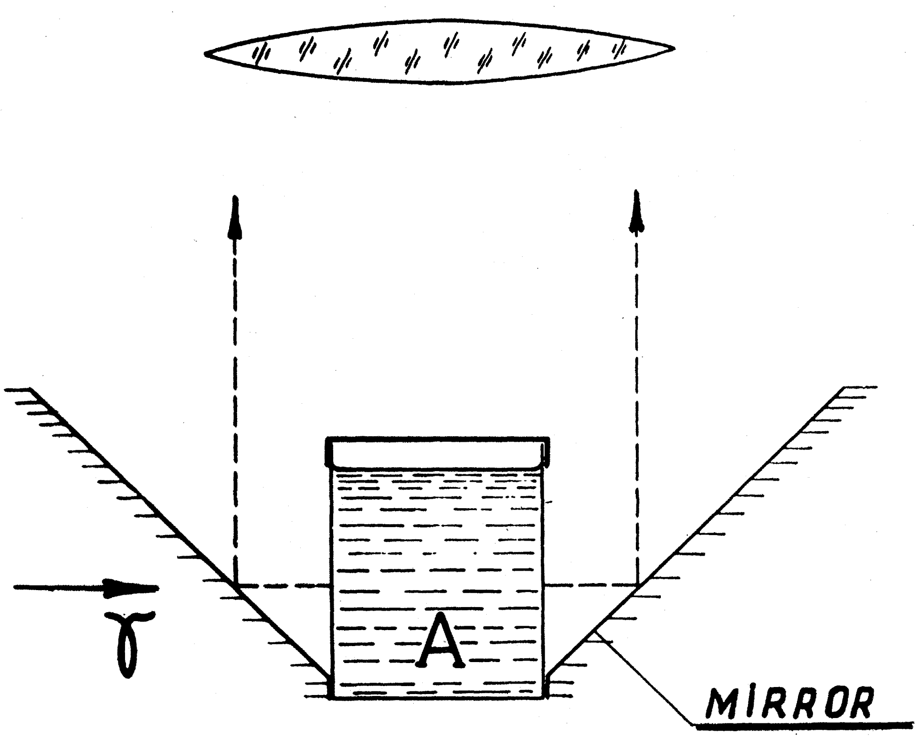


Fig. 2. Arrangement of apparatus for determination of the angular distribution of the intensity.

In the case of the motion of the charge in a substance, there are velocities which exceed the velocity of light, which are possible without being in conflict in any way with relativity theory.

This fact is explained by the circumstance that the propagation velocity of light waves in a substance differs from the velocity of light in a vacuum by a factor n, where n is the index of refraction of the medium in which the motion takes place.

Since $n > 1$ for visible light, and since the propagation velocity of the light waves in the medium is equal to c/n, this is consequently smaller than c, the velocity of light in a vacuum.

On the other hand, it has long been known that the velocity of beta particles, which are emitted from radioactive substances, can come very close to the velocity of light c. These particles, in their motion in a given substance, can possess a velocity which is greater than the light velocity c/n in this substance and yet remains smaller than c, in complete agreement with the requirements of relativity theory. Therefore, the motion of the particles with superlight velocity is not only possible in principle but can be achieved experimentally.

If we assume that the velocity of an electron moving in this medium exceeds the velocity of light, we can determine the preliminary conditions for the appearance of such radiation on the basis of simple qualitative investigations and obtain some very important properties of this radiation. Let us assume that an electron executes a uniform motion in the medium in the direction of the z-axis with a velocity $v > c/n$. At each point reached by the electron, an electromagnetic excitation is produced which is propagated in the form of a retarded wave from that point.

If we consider the components of a particular frequency ω of the waves, which leave the various points at an angle θ to the path of the electron (see Fig. 1), then we can easily be convinced that the waves will be canceled by interference in all directions other than in that for which

$$vt \cos \theta = ct/n, \text{ or } \cos \theta = 1/\beta n \quad (1)$$

On the other hand, in the direction which satisfies condition 1, the waves reach the observer with an optical path difference equal to zero, and accordingly the radiation takes place only in this direction.

This radiation has its analog in acoustics in the form of the so-called ballistic wave which is produced by a projectile or airplane which moves with supersonic velocity (Mach waves). A surface analog is the well-known bow wave.

It follows from Eq. 1, which forms one of the most reliable results of the theory of Tamm and Frank, that the appearance of the radiation is possible only under the condition $\beta n > 1$—that is, when the velocity of the particle v exceeds the velocity of light c/n. As a consequence, the equation $\beta n = 1$ expresses the threshold energy value of the radiation. The value E_0 of this threshold is determined by the index of refraction. Since the condition for the determination of this limit contains the velocity of the particle rather than the energy directly, it is evident that E_0 also depends on the mass of the particle.

In order to illustrate what has been developed above, values of the threshold energy E_0 are given in Table 1 for electrons, π-mesons, and protons for three different values of n.

Table 1. Values of the threshold energy for electrons, π-mesons, and protons for three different values of n.

Type of particle	Value of threshold energy (mev)		
	$n = 1.3$; $\beta = 0.769$	$n = 1.5$; $\beta = 0.67$	$n = 2.0$; $\beta = 0.50$
Electron	0.29	0.2	0.078
π-Meson	79	47	21.5
Proton	520	320	143

Experimental Confirmation

The theoretical relation among the quantities θ, β, and n, which is given by relation 1, was experimentally proved. The results obtained agreed completely with the deductions of the theory. The experimental arrangements for the determination of this dependence are illustrated in Fig. 2.

The beam of gamma rays is incident on a thin-walled tube, filled with liquid (A in Fig. 2). The radiation arising in this liquid upon its emergence from the canal falls on a conical mirror and is reflected to the objective of a photographic apparatus. The luminescence produces a picture in the form of a closed ring, since it exhibits no asymmetrical properties.

On the other hand, the radiation of the particles with superlight velocity does not form a closed ring in the picture, but rather two spots, the angle between them being equal to 2θ.

Figure 3 (right, middle) shows a sample of such photographs for two pure liquids (water and ethyl cinnamate). For comparison, a photograph of the luminescence of an aqueous solution of esculin is also shown in Fig. 3 (left).

The angular distribution of the radiation intensity (for four liquids) determined by measurements on these photographs are shown in Fig. 4. For each of these liquids, two curves are obtained, which correspond to the excitation of radiation by gamma rays of ThC″ (the upper curves) and by the gamma rays from Ra (the lower curves).

It is a simple matter to determine the angle θ by means of the graph in Fig. 4. The value of this angle increases with increase in the index of refraction n, exactly as the theory requires. For one and the same liquid, results were obtained which yielded larger values of θ in experiments with the gamma rays of ThC″ than in experiments with the gamma rays of Ra. This difference in the measurements for $\theta_{\mathrm{ThC''}}$ and θ_{Ra} permits one to use relation 1 for determination of the "effective" velocity ($\beta_{\mathrm{eff.}}$) of the Compton electrons which excite the radiation. These velocities are 0.869 and 0.847, respectively. This result corresponds exactly to the higher energy of the gamma rays of ThC″.

If the picture is observed not in the plane but in space, then the radiation must spread out along the surface of a cone whose axis is the path of the electrically charged particle, while the generating line of the cone makes the angle θ with this axis.

If the photographic plate is placed perpendicular to the beam of fast-moving particles (Fig. 5), a photograph of the radiation in the form of a ring is obtained (Fig. 6), in addition to the picture of the trace of the beam. Figure 6 was obtained by means of a narrow beam of protons ($E = 660$ Mev) on the accelerator of the Combined Institute for Nuclear Research at Dubna.

Thus far, we have considered only a definite frequency ω. Actually, however, the radiation spectrum is continuous. Since the medium exhibits dispersion properties—that is, since the index of refraction is dependent on the frequency—the light of different wavelengths departs at angles which differ somewhat from one another, even for a constant particle velocity.

The radiation is therefore split up in spectral analysis. The radiation cone then exhibits a definite strength, in which, in the case of a medium with normal dispersion, the red spectrum lies at the inner side of the cone, while the violet lies at the outer side.

Thus, interpretation of the radiation mechanism proposed by Tamm and Frank, even in a qualitative consideration, gave an explanation of the especially characteristic properties of this radiation—such as, for example, the asymmetry, the short decay time, the presence of an energy threshold, and the universal character of the radiation. Moreover, the rigorously quantitative theory yields an expression for the energy W which the electron furnishes in this radiation. This expression has the form

$$W = \frac{e^2 l}{c^2} \int_{\beta n > 1} \omega \left(1 - \frac{1}{\beta^2 n^2}\right) d\omega \quad (2)$$

where l is the path length of the electron. It also follows from this that the energy of the radiation spectrum is proportional to $1/\lambda^3$—that is, that it increases sharply in the direction of short wavelengths.

The radiation ceases in the x-ray region, since in this interval, $n < 1$.

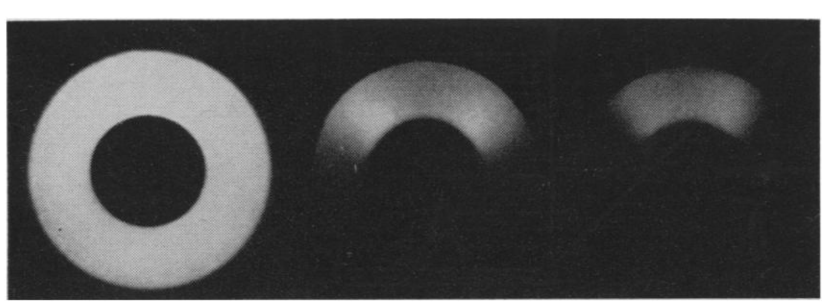


Fig. 3. Photograph of the angular distribution of intensity for (left) ordinary luminescence (solution of esculin in water); (middle) radiation from ethyl cinnamate ($n = 1.5804$); (right) radiation from water ($n = 1.3371$).

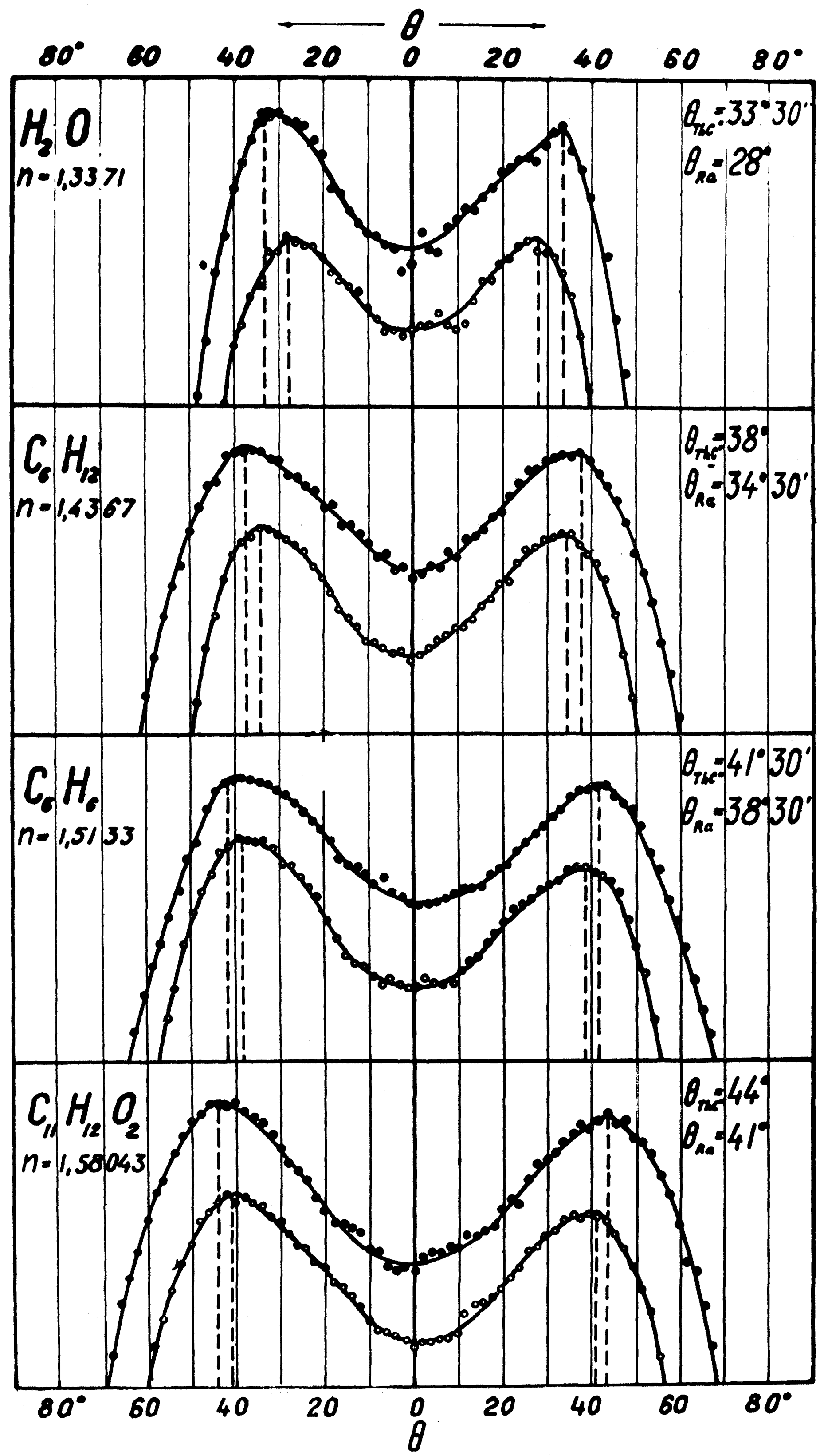


Fig. 4. Angular distribution of intensity for liquids with different n, obtained from photographs like Fig. 3. The curves through the solid circles correspond to the excitation of radiation by Compton electrons from the gamma radiation of ThC″. For these, $\beta_{\text{eff.}} = 0.869$ (according to Eq. 1). Curves through the open circles correspond to excitation by Compton electrons resulting from the gamma rays of Ra. In this case, $\beta_{\text{eff.}} = 0.847$.

Finally, it was deduced from the theory that the radiation must exhibit polarization; indeed, it must have the same polarization which was determined in the first experiments: the vector of the electric oscillations lies in the plane containing the ray and the direction of motion of the particles.

All this shows that the theory under discussion comprehended all the currently known properties of the new radiation in an exhaustive fashion. The development of this theory concluded a great cycle of investigations which included the discovery, the over-all experimental investigation, and the development of the theoretical foundations of the phenomenon, all of which gave rise to the establishment of a new area of physics, the optics of beams which move with superlight velocities.

As a consequence of the lack of sufficiently sensitive and convenient measuring apparatus, interest in the new radiation was great, to be sure, but was only of an abstract character. Its inherent potentiality for practical application, especially in experimental physics, remained untried.

However, in recent years, as a result of the development and production of photomultipliers, radiation from fast, electrically charged particles took on an important practical meaning, especially in the domain of physics of high-energy particles.

Measurement of Intensity

Although the intensity of the radiation flashes produced by individual particles is vanishingly small, it is, today, measurable. It follows from Eq. 2 that when $\beta \cong 1$, the number of photons in the visible portions of the spectrum which are sent out by an electrically charged particle which moves in a medium with $n \cong 1.5$ amounts to 200 to 300 photons per centimeter. By a correct choice of the shape and position of the radiator (this name is given to the medium in which the radiation-producing charged particles move), a significant portion of this light can reach the cathode of the photomultiplier. As a result of the great amplification, a current pulse appears at the anode of the multiplier which is a million times greater than the initial current. This pulse can be determined by an appropriate electronic circuit, and hence the particle can be detected. Such an apparatus represents a counter in which the radiation emitted by the particle serves directly for its measurement.

This type of counter is strongly reminiscent of the so-called scintillation counter, in which the luminescence which arises in the absorption of the energy of the particle in a scintillator is used for the measurement of an electrically charged particle. This measurement is also carried out with the aid of a photomultiplier. However, in comparison with the scintillation counter, this counter has a number of important advantages. These advantages are as follows. (i) The short duration of the decay permits counters to be developed which exhibit a very high resolution. (ii) The presence of an energy threshold makes counters of this type insensitive to slow particles which are below the threshold energy. This property of the counter is especially valuable in cases in which there is present a significant radiation spread produced by gamma rays. (iii) The asymmetry of the radiation permits a measurement of only those particles which move in the radiator in the direction of the cathode of the photomultiplier. Particles which move in the opposite direction will not be measured by the counter. In other words, the counters of this type are distinguished by the presence of a definite directivity.

This property of the counter was used by Winckler (*14*) for determination of the "albedo" of cosmic rays in the upper layers of the atmosphere.

At present, a great number of counters of the type mentioned, which are distinguished by their original construction, are described in the works of Jelley, Marshall, and others (*15*).

Applications

The methodological value of the radiation of fast-moving particles lies not only in the possibility of their use as particle detectors. The exploitation of the singular properties of this radiation (often in conjunction with other methods) enlarges—in a number of cases, significantly—the possibilities of physical experiment.

Thus, it is known, for example, that determination of one of the most important parameters of a particle—its mass—can be carried out on the basis of measurements of its momentum and its velocity. Usually, experimental difficulties are encountered in the velocity measurements. It is clear, without further comment, that the velocity of a particle can be easily computed from the measured value of θ and the known index of refraction, within the velocity range of the particle over which β (which satisfies the condition $\beta n > 1$) differs sufficiently from unity.

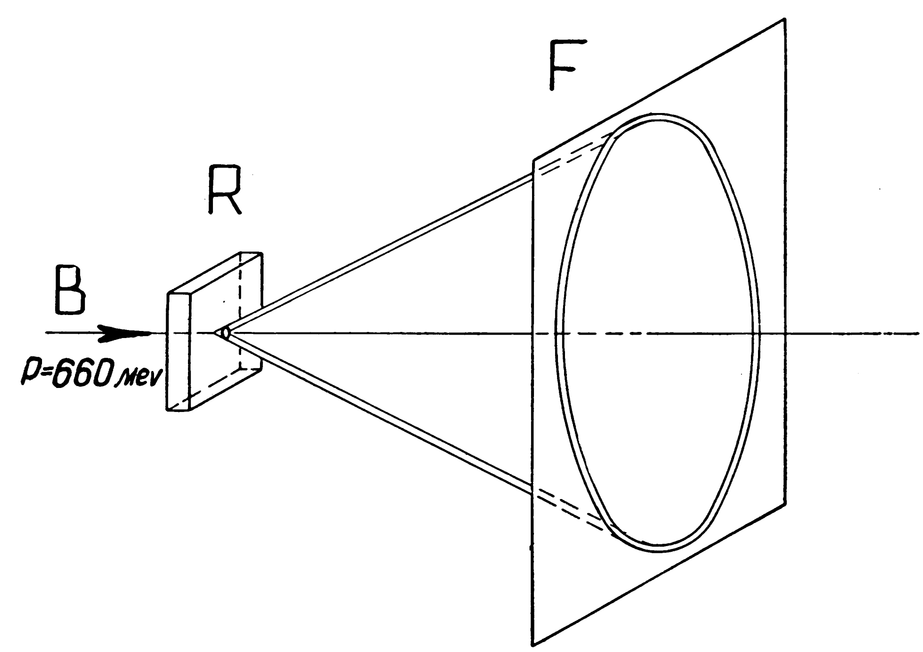
If the type of particle is known, velocity measurements also permit the energy to be measured. Especially good results are yielded by this method in the measurement of the energy of protons from accelerators for energies which lie in the range of several hundred Mev (see Table 1). The accuracy of such energy measurements is within 0.25 percent (*16*).

It has been noted above that the circumstance that the radiation possesses an energy threshold makes the counter insensitive to particles of low energy. The possibility therefore exists of changing the threshold energy E_0 by selecting a radiator with a suitable value of n.

It is clear that two counters which have been previously set up with different values of the threshold energy, E_0' and E_0'', and are connected in appropriate sequence in an anticoincidence circuit will record only those particles whose velocity is in the range from E_0' to E_0''.

Such an arrangement was successfully applied by Segré and his co-workers in their outstanding work which led to the discovery of the antiproton.

Another interesting region of application of the properties of the rays was found in their use in the investigation of broad cosmic-ray showers. In the study of these showers with ordinary counters, only those particles are measured at a certain height which are the distant "descendants" of the primary



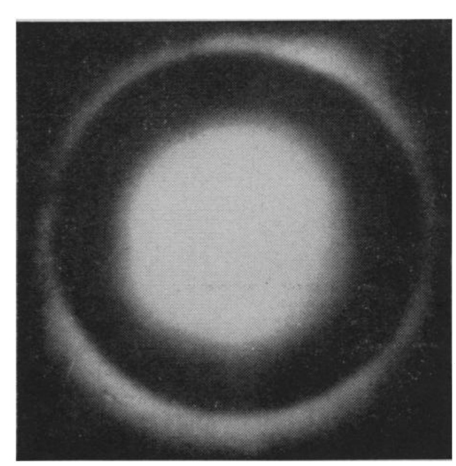


Fig. 5 (left). Experimental arrangement for obtaining photographs of the conical cross section in the plane of the photographic plate. Fig. 6 (right). Photograph of a cross section of the radiation cone which was obtained in an experiment in which the arrangement shown in Fig. 5 was used. The central spot is the trace of the proton beam. [A. P. Srelow] particle. None of the other particles which appear and disappear during the previous development stages of the shower can be measured by this apparatus. But since the shower particles possess enormous energies, they are capable of producing radiation in the air of the type under discussion, which is propagated in virtually the same direction. This radiation, under favorable conditions, reaches the earth's surface and can be measured by a photomultiplier. This method furnishes a more complete picture of the shower and valuable information about the process of its development.

For cosmology, the problem of the distribution of nuclei in the cosmic radiation (outside the earth's atmosphere) which are heavier than the hydrogen nucleus is of great importance. Appropriate experiments are being carried out on the sputniks at the present time. In these experiments, reliance is placed on the circumstance that the intensity of the radiation of particles which move with superlight velocity is proportional to the square of the particle's charge. Therefore, the pulses coming from particles of different charges and recorded by the counter may be distinguished by their amplitudes. Analysis of the amplitude distribution will permit one to make judgments on the distribution of heavy particles in the cosmic radiation, corresponding to their ordinal number.

The last thing on which I would like to speak is the application of the radiation from fast-moving particles to measurement of the energy itself when this energy is rather large. In this case measurement of the energy of the particles by means of their deflection in a magnetic field is no longer possible. However, one can try to determine it by measuring the total energy which the particle gives to the radiation of the type under consideration. For this purpose, very transparent, thick radiators must be used, which give off radiation of a sufficient intensity and which permit a complete development of the shower.

Water is a suitable radiator in this case. Equipment has been constructed in the Institute of Physics, Academy of Sciences of the U.S.S.R., which should serve for the measurement of the energy of cosmic particles by means of this method.

The examples we have given show the great importance to experimental physics of the radiation produced by particles which travel with superlight velocity (*17*).

However, not all the possible applications have been discussed. It is undoubtedly true that the region of application of this radiation will continue to expand rapidly in the years to come.

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Machine Searching for Chemical Structures

The Wiswesser notation provides an effective key to literature searches for functional groups.

Elbert G. Smith

The use of punched-card machines for organizing and retrieving chemical data has been described by a number of workers in recent years (*1*). These techniques make it possible to find and arrange information about large numbers of items very rapidly and efficiently, provided that the information about each item is not too extensive. Since this is precisely the situation we face in dealing with data about chemical compounds (large numbers of compounds but rather limited data, such as structure or properties, about each one), it would seem feasible to organize and search this kind of information with punched-card techniques.

A principal difficulty has been that of devising a means of identifying chemical compounds in an intelligible way which is concise enough for efficient use on punched cards. Ordinary names are usually too long to be efficient and do not allow use of the machine's potential ability to search for units of molecular structure in the identifying name. A solution of this difficulty lies in the concept of a new chemical notation in which units of chemical structure are designated by single letters and numbers, so that structural formulas may be spelled out much as one spells out words. Such notations can be designed so that they are intelligible both to the chemist and to the machine, and in such a happy combination we might look for practical and reasonable means of accomplishing the mechanical organization and retrieval of much chemical information.

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