

PAVEL A. ČERENKOV

## Radiation of particles moving at a velocity exceeding that of light, and some of the possibilities for their use in experimental physics

*Nobel Lecture, December 11, 1958*

Research into, and the experimental proof of, the remarkable properties of the radiation arising from the movement in a substance of fast electrically charged particles stretches over a period of nearly twenty-five years. As early as 1934 two reports were published - one by S. I. Vavilov, the other by me<sup>1,2</sup> - in which it was indicated that the gamma rays of radium besides causing luminiscence of solutions, also calls forth a visible, faint light from solvents.

In these reports the universal character of this light and its unusual properties were described and the conviction expressed that the newly discovered light could not, in view of its properties, be a luminescence phenomenon at all.

By further experiments it was established that this light was not released directly by the gamma rays, but through high-speed Compton electrons which appear under the influence of the gamma rays by reason of the Compton effect. Attempts to produce a light with the same properties by the action of X-rays ( $h\nu_{\text{max}} = 30 \text{ keV}$ ) were without result.

To begin with, one might suppose this sort of light from the solvent to be of no especial interest, since luminosity is a widespread phenomenon with very different causes in solids as well as fluids. Apart from the generally known « classical » luminescence phenomena one could, for example, point to the faint light from actually very « pure » fluids which arises by the effect of ultraviolet rays<sup>3</sup>. Many fluids emit light when struck by X-rays<sup>4</sup>. It has even been established that fluids emit light by the action of ultrasonic ray<sup>5</sup>. From the time of Pierre and Marie Curie numerous cases of light emission from fluids and solids by the action of radioactive radiations have been known<sup>6</sup>.

As a rule, light emissions of this kind are nothing else than the usual luminescence and, in the case of the so-called « pure » fluids, are produced by the presence of tiny quantities of admixtures capable of luminescence.

Hence we were inclined to think that this light produced by the gamma rays was one of the many luminescence phenomena. Pierre and Marie Curie thought so and they were incontestably among the first to observe this kind of light, at any rate under conditions where it was fairly heavily masked by the ordinary luminescence.

Other observers later took the same view, among them Mallet<sup>7</sup>, who had not only observed this light phenomenon but had even photographed its spectrum.

However, a more detailed quantitative investigation of this light process enabled us to find a range of properties so remarkable as to afford incontrovertible proof that here we were dealing with no ordinary everyday luminescence, but with a phenomenon of an entirely new kind; and one of extraordinary interest not only on account of its significance in principle but also in regard to the many practical possibilities for its use.

It would nevertheless be a mistake to believe that such a characteristic phenomenon had not been discovered earlier merely through being accidentally « overlooked ».

The unusual nature of this newly discovered phenomenon could only be investigated by way of quantitative determination of the most important radiation characteristics, and by finding out their dependence on definite experimental conditions.

Nowadays, when researchers have at their disposal powerful sources of fast electrically charged particles and very sensitive measuring devices, measurements of this kind do not involve any especial difficulties. But a few decades ago, the means available to the physicists were nothing like so adequate. In those days absolutely the only sources of electrically charged particles available to them were natural radioactive preparations whose intensity was fairly weak. For this reason the intensity of the light, even in fluids\* which had helped to excite it, was so weak that the observer could only perceive the light after he had spent a certain time in complete darkness. It is quite clear that under such conditions there was no question of the usual methods of photometry for quantitative determinations.\*\* To carry out determinations of this kind a new and much more sensitive method was

\* Research into the above phenomenon was chiefly undertaken with fluids because fluids are easier to purify from luminescent admixtures. With fluids it is easier to change such parameters as viscosity, refractive index, density, etc. Moreover, in this case the experiments in quenching the luminescence become much simpler.

\*\* We must remember that at that time photomultipliers had not yet been developed.

necessary. In the Physical Institute of the Academy of Sciences of the U.S.S.R. where this phenomenon was discovered we made use of the method of visual photometry depending on the threshold vision developed shortly before by E. M. Brumberg and S. I. Vavilov<sup>8</sup>, otherwise called the quenching method. This method makes use of the human eye instead of a light-measuring device\*. Since the sensitivity of an eye adapted to darkness is some tens of thousands of times greater than its sensitivity by daylight, this method was superior to others by virtue of its higher sensitivity. Notwithstanding its subjectivity and the comparatively large errors in the measurements, this method was at the time the only one that could be used which permitted a quantitative determination of those extremely low light intensities.

It is of fundamental importance to notice that it was only the transition to quantitative determinations which permitted the unusual attributes of the rays in question to be demonstrated and hence their particular origin to be shown.

It has already been indicated that the first hypothesis, and the most credible of all regarding this light, attributed it to a luminescence phenomenon. Now the correctness of this assumption could only be confirmed if it could be proved experimentally that only those characteristics proper to luminescence were present in this light.

There is indeed a large number of luminescence phenomena which are distinguishable from one another by the excitement method, by the fluorescent lifetime, by the character of the spectrum, by the properties of the luminescent substances, and by other peculiarities. In the case in which we are interested it is not a question simply of establishing the presence or absence of luminescence characteristics; but it is important to determine features which characterize a luminescence phenomenon as such unequivocally and universally.

One of these universal characteristics of luminescence is, as S. I. Vavilov has indicated, the total duration of the excited state ( $\tau > 10^{-10}$  sec). This property of luminescence permits of influencing the dying-out process. We can, for example, reduce its brightness considerably or, in other words,

\* The quenching method, which is now only of historical interest, depends on the following properties of the human eye:

- (a) The fact of a visual threshold.
- (b) The permanence of the energy threshold relative to one and the same observer (when the conditions are constant).

« quench » the luminescence either by heating the luminescent solution or by adding materials which are able to quench the luminescence. In both cases there follows a reduction of luminescence as a result of the excited particles giving up energy to those not excited, and by the consequent transformation of energy into thermal energy.

Likewise, the polarization of the luminescence can be altered as one influences the mobility of the particles, e.g. by heating.

Suitable experiments have, however, shown that the intensity of the light of fluids cannot be influenced either by heating or by dissolving in them such active fluorescence quenchers as potassium iodide, silver nitrate, and many others. It has also been shown that the perceptible polarization which appears in this light cannot be altered either. It is of fundamental significance that experiments aimed at quenching the fluorescence of undoubted fluorescent solutions (as, for example, the aqueous solution of aesculin), carried out parallel and under the same conditions, showed in all cases a visible quenching effect.

These results prove a practically inertialess character of the dying-out process and excluded the hypothesis of a luminescence phenomenon. Confirmation was forthcoming also in the unusual character of the polarization of this light. The main direction of the vector of the electric vibrations did not run perpendicularly to the exciting beam, as is the case with polarized fluorescence, but parallel to it.

Taken all together, the results collected even during the first stage consequently gave rise to the statement that the light produced in fluids by the action of gamma rays is not a trivial phenomenon. But these facts were not sufficient for us to build an incontestable theory on this basis. This problem was solved somewhat later after the discovery in 1936 of a new especially remarkable property of this radiation, namely its pronounced asymmetry.

It becomes apparent that the light exhibits a grossly marked spatial asymmetry. This radiation is only emitted forwards in one direction which forms a certain angle with the exciting gamma-ray beam.

The investigation of this fundamental property of the radiation proved to be a decisive step towards clarifying the true physical nature of this phenomenon and propounding a theory. We owe the formation of this theory to I. M. Frank and I. E. Tamm<sup>11</sup>.

This theory proceeds from the fact that the light described is produced by the electrons which move uniformly in the substance at a speed exceeding the phase velocity of light in this medium.

It is an interesting fact that as early as 1901 Lord Kelvin<sup>12</sup> maintained that the emission of particles was possible at a speed greater than that of light.

Somewhat later, in 1904 to 1905, shortly before the theory of relativity came into being, Sommerfeld<sup>13</sup> submitted the hypothetical case of the movement of an electron at a speed greater than that of light in a vacuum to a theoretical study.

But the coming of the theory of relativity which affirms that material bodies are unable to move at the speed of light, still less to exceed it, overshadowed Sommerfeld's conclusions which seemed less to the purpose.

It is, seemingly, to this circumstance that we may to some extent ascribe the complete neglect of the problem of the movement of electrically charged particles in a substance, because it could not be reconciled with the theory of relativity.

In the case of the movement of the charge in a substance, velocities exceeding that of light are possible without in any way contradicting the theory of relativity.

This fact is explained thus: The speed of propagation of the light waves in a substance differs from the speed of light in a vacuum by the power  $n$ , where  $n$  is the refractive index of the medium in which the movements takes place.

As for visible light  $n > 1$  and as the speed of the propagation of the light waves in the medium is equal to  $c/n$ , this will consequently be smaller than the velocity of light in the vacuum  $c$ .

On the other hand it has been known for a long time that the velocity of the beta particles emitted from radioactive substances can come very near to the velocity of light  $c$ . In their movement in a substance these particles can possess a speed which is greater than that of light in this substance ( $c/n$ ) while yet remaining less than  $c$ , in complete agreement with the requirements of the theory of relativity. Hence the movement of particles at a speed greater than that of light is not only possible in principle but can also be obtained experimentally.

While we accept that the velocity of an electron moving in the medium exceeds that of light, we can also, on the basis of simple qualitative experiments, determine the prerequisites for the formation of this type of radiation and find out a few of its most important properties. Let us assume that an electron achieves an equal movement in the medium in the direction of the axis  $z$  at a speed  $v > c/n$ . At every point which the electron touches an electromagnetic excitement is set up which is propagated in the form of a delayed wave from these points.

If we consider the components of a certain frequency  $\omega$  of the waves issuing from the various points at an angle  $\theta$  to the path of the electron

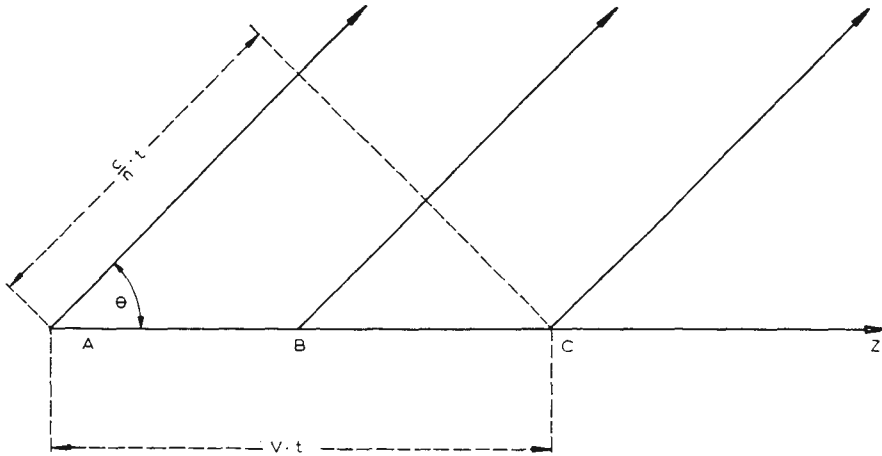


Fig. 1. Mechanism of radiation.

(see Fig. 1), it is easy to satisfy ourselves that in all directions except that in which

$$vt \cos \theta = \frac{c}{n} t \quad \text{or} \quad \cos \theta = \frac{1}{\beta n} \quad (1)$$

the waves are quenched through interference. On the contrary, in the direction which satisfies condition (1) the waves reach the observer with an optical path-length difference equal to zero, and accordingly the radiation will only result in this direction.

This radiation has an analogy in acoustics in the form of the so-called shock waves produced by a projectile or an aeroplane travelling at an ultra-sonic velocity (Mach waves). A surface analogy is the generally known bow wave.

From Eq. (1), which represents one of the most visible results of the theory of Tamm and Frank, it follows that it is possible for the radiation to be produced only under the condition  $\beta n > 1$ , i.e. when the velocity of the particle  $v$  exceeds the velocity of light  $c/n$ .

Consequently, the equation  $\beta n = 1$  expresses the energetic threshold of the radiation. The quantity  $E_0$  of this threshold is determined by the refraction coefficient  $n$ . Since it is not directly the energy of the particle that is

required for the determination of this threshold, but its velocity, it is therefore obvious that  $E_0$  is also dependent on the mass of the particle.

To illustrate the above, the following Table 1 shows the values of the threshold energy  $E_0$  for electrons,  $\pi$ -mesons and protons, given three different values for  $n$ .

Table 1.

Type of particles	Threshold energy in MeV		
	$n = 1.3$ $= 0.769$	$n = 1.5$ $= 0.67$	$n = 2.0$ $= 0.50$
Electrons	0.29	0.2	0.078
$\pi$ -mesons	79.0	47.0	21.5
Protons	520	320	143

The theoretical interdependence of the quantities  $\beta$ ,  $\gamma$ , and  $n$  which is expressed by the relationship (1) was tested experimentally. The results obtained are in complete agreement with the requirements of the theory. Fig. 2 is a diagram of the experiment to determine this interdependence.

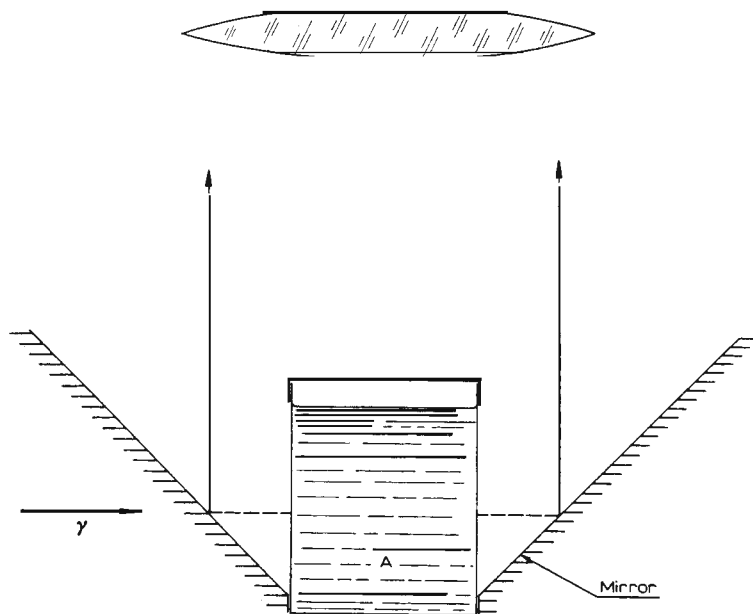


Fig. 2. Diagram of experiment to determine the distribution of intensity according to angle.

The gamma-ray beam falls on a thin-walled vessel filled with fluid (A in Fig. 2). When the radiation arising in this fluid leaves the vessel it falls on a conical mirror and is reflected by this on the objective of a photographic apparatus. The luminescence - since it exhibits no asymmetrical properties - produces a picture in the form of a closed ring.

On the other hand, the radiation of particles with a velocity exceeding that of light does not give a closed ring in the image but two patches with an angle between them equal to  $2\theta$ .

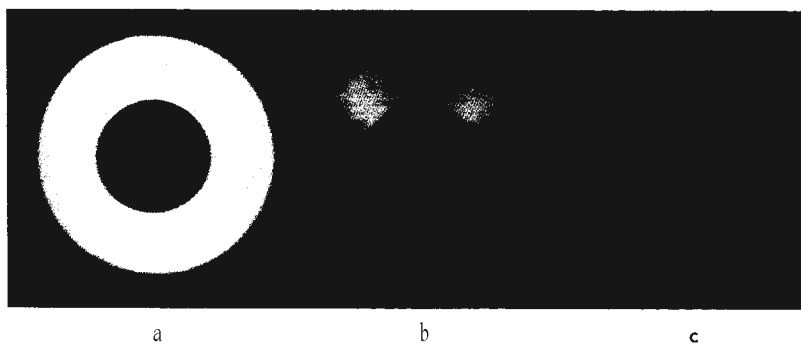


Fig. 3. Photograph of the distribution of intensity according to angle:  
 (a) ordinary luminescence (solution of aesculin in water);  
 (b) light from ethyl cinnamate ( $n = 1.5804$ ); (c) light from water ( $n = 1.3371$ ).

Fig. 3 (c,b) shows examples of such photographs for two pure fluids (water and ethyl cinnamate). For comparison, a photograph is also shown of the luminescence of an aqueous solution of aesculin (Fig. 3a).

The distribution of angles of the radiation intensity (for four fluids) established by measurements from these photographs are set out in Fig. 4. For each of these fluids two curves were plotted corresponding to the excitation of the light by the gamma rays of ThC'' (the upper curves) and by those of Ra (the lower curves).

From Fig. 4 it is easy to determine graphically the angle  $\theta$ . The values of this angle increase with the rise in the refractive index  $n$ , exactly as it should do in accordance with the theory. Results were obtained for one and the same fluid which in experiments with gamma rays of ThC'' gave higher values of  $\theta$  than in experiments using gamma rays of Ra. This difference in measurements in the case of  $\theta_{ThC''}$  and  $\theta_{Ra}$  shows us to use Eq. (I) to determine the <<effective>> velocity ( $\beta_{eff.}$ ) of the Compton electrons which in-



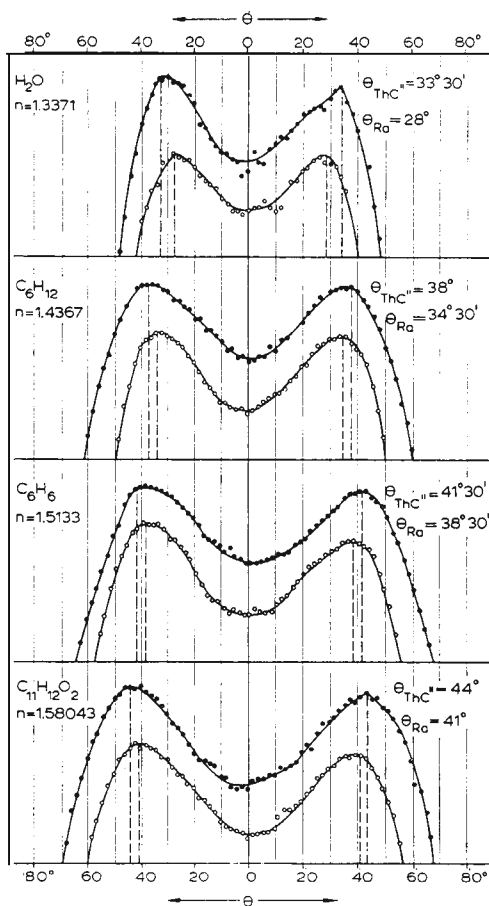


Fig. 4. Distribution of intensity according to angles for fluids with various values for  $n$ , obtained from the photograph in Fig. 3. The curves with dark points (*upper* curves) correspond to the excitation of the light by Compton electrons from the gamma rays of ThC''. For these,  $\beta_{eff} = 0.869$  (cf. Eq. (i)). The *lower* curves correspond to the excitation by Compton electrons of the gamma rays of Ra. In this case  $eff. = 0.847$ .

deed excite the radiation. These velocities amounted to 0.869 and 0.847 respectively. This result is completely in accord with the higher energy of the gamma rays of ThC''.

If we consider the picture not in the plane but spatially, then the radiation must spread out along the surface of a cone whose axis forms the path of an electrically charged particle while the surface line forms with this axis the angle  $\theta$ .

If we place the photographic plate perpendicularly to the beam of the high-speed particles (Fig. 5) we shall obtain, in addition to an image of the track of the beam, also a photograph of the radiation in the form of a ring. This photograph (Fig. 6) was obtained with the aid of a fine beam of protons in the accelerator of the United Institute for Nuclear Research at Dubna.

Up till now, we have in our considerations assumed some fixed frequency. In reality, however, the radiation spectrum is continuous. Since the medium exhibits dispersion, i.e. the refractive index is dependent on the frequency, this means that the light of different wavelengths is propagated at angles which, even with strictly constant velocity of the particles, differ somewhat from one another.

Thus the radiation is broken up as in spectral analysis. The radiation cone will consequently show a definite intensity, and in the case of a medium with normal dispersion the spectral red will lie in the inner part of the cone while the violet is on the outside.

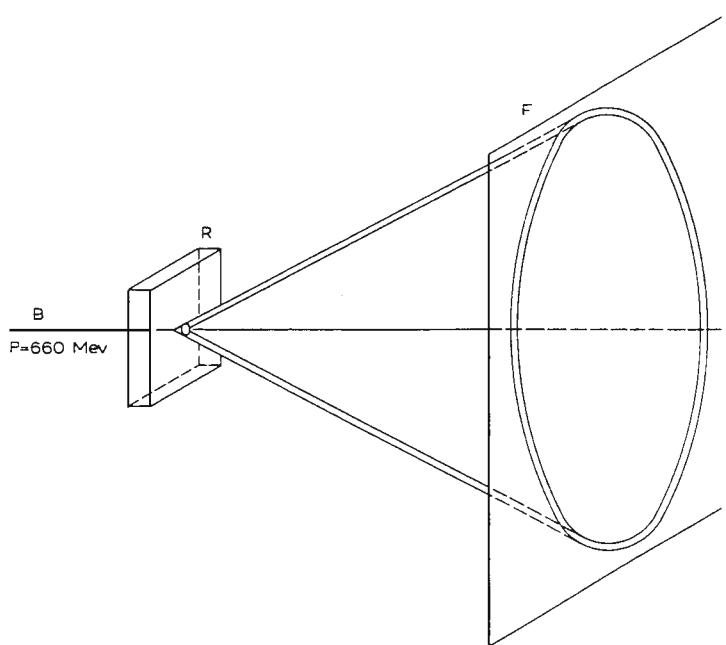


Fig. 5. Diagram of experiment to obtain photographs of the cone section in the plane of the photographic plate.

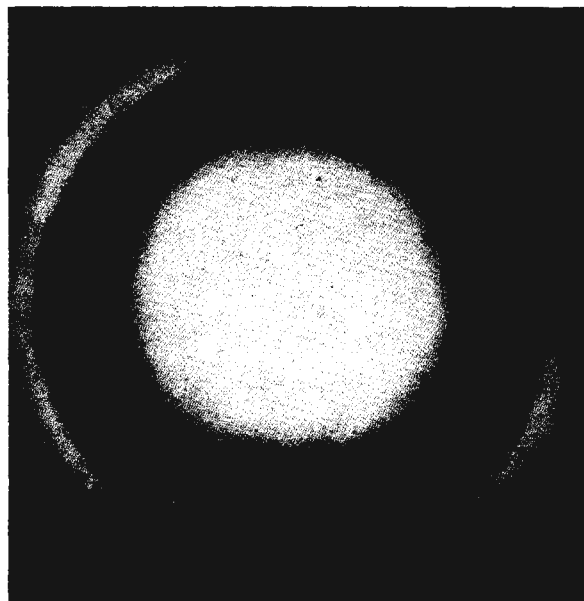


Fig. 6. Photograph of a section of the radiation cone obtained in an experiment of which Fig. 5 is a diagram. The central patch is the track of the proton ray.

[That this is actually so was shown by a photograph showing part of the ring in Fig. 6 taken with a colour plate\*.]

Thus the interpretation of the ray mechanism suggested by Tamm and Frank makes clear, even under qualitative consideration, the especially characteristic properties of this radiation, such as, for example, the asymmetry, the short dying-out period, the presence of an energetic threshold and the universal character of this radiation. Moreover the strict quantitative theory supplies an expression for the energy  $W$  which the electron gives up during this radiation. The formula is expressed as follows:

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

where  $l$  is the length of the path of the electron.

\* Unfortunately the coloured illustration could not be reproduced here. The reader is referred to *Les Prix Nobel en 1958*, opposite page 90.

From this it follows likewise that the energy of the radiation spectrum is proportional  $1/\lambda^3$ , i.e. that it increases powerfully in the direction of the short wavelengths.

In the Röntgen field, however, the radiation must stop because in this field  $n < 1$ .

Finally it follows from the theory that the light must exhibit a polarization, the same in fact as established in the first experiments; the vector of the electric vibrations lies in the plane which contains the ray and the direction of movement of the particles.

This all goes to show that the theory in question covers exhaustively all the properties of the new radiation known up to now. The development of this theory completes a great cycle of research work which covers discovery, all-round experimental investigation, and the development of the theoretical basis of this phenomenon which established a new branch of physics - the optics of rays moving faster than light.

Interest in the new radiation was indeed great, but, in the absence of sufficiently sensitive and convenient measuring devices, only as a matter of principle. Its potentialities for practical use, especially in experimental physics, remained unexploited.

In recent years, however, following the development and production of photomultipliers, the radiation from high-speed electrically charged particles

into the physics of high-energy particles.

Although the intensity of the flash called forth by a single particle is extremely low it can now be measured. Formula (2) shows that when  $\beta \simeq 1$ , the number of photons which an electrically charged particle moving in a medium where  $n \simeq 1.5$  emits, and which fall within the visible part of the spectrum, will amount to 200-300 photons per cm. If we choose the right form and position of the radiator (i.e. the medium in which the electrically charged particle occasioning the radiation moves) an important part of this light can be conducted to the cathode of the photomultiplier. As a result of a multiple intensification at the anode of the multiplier, a current impulse arises which is millions of times stronger than the current we started with. By means of a suitable radiotechnical scheme, this impulse can be maintained and the particle thus observed. A device for this would be a counter which would measure the particles by means of the radiation proceeding directly from them.

This kind of counter is highly reminiscent of the so-called scintillation counter. In this, the measurement of electrically charged particles, which is likewise done with the aid of a photomultiplier, makes use of the luminescence arising from the absorption of energy from the particles in the scintillator. But compared with the scintillation counter, this one has many important advantages :

1. The short duration of dying-away permits the development of counters with a very high resolving power.
2. The presence of an energy threshold makes this type of counter insensitive to the slow particles whose energy lies below the threshold. This property of the counters is especially valuable in those cases where there is a considerable gamma radiation level.
3. The asymmetry of the radiation facilitates with this counter the measurement of those particles which are moving in the radiator in the direction of the cathode of the photomultiplier. Particles moving in the opposite direction are not measured by the counter. In other words, this type of counter has the distinction of focussing on a definite directional effect.

Winckler<sup>14</sup> made use of this characteristic of the counter in determining the « albedo » of the cosmic rays in the upper layers of the atmosphere.

At the present time a large number of counters of this sort is described in the works of Jelley, Marshall, and other authors's, and are distinguished by their original construction.

The practical value of the radiation of high-speed particles does not lie solely in the possibility of using it to detect particles. The full utilization of the peculiar properties of this radiation (often in combination with other methods) considerably enlarges the possibilities of physical experiment in a wide range of cases.

Thus, for example, it is known that one of the most important parameters of a particle - its mass - can be determined on the basis of measurements of its momentum and speed. In the measurement of speeds one usually comes up against experimental difficulties. It is evident without more ado that where the speed of a particle is within a certain range where  $\beta$  (that fulfills the condition  $\beta n > 1$ ) is still sufficiently different from 1, the speed of the particle, on the basis of Eq. (1) and starting from the measured quantity and the known refractive index, can easily be calculated.

When the type of the particle is known, speed measurements enable us

to determine their energy also. This method produces particularly good results in the case of energies in the region of several hundred MeV (see Table 1). These energy measurements are accurate to 0.25%<sup>16</sup>.

We have already noted the fact of the radiation having an energetic threshold renders the counter insensitive to low-energy particles. We thus have the possibility of altering the threshold energy  $E_0$  when we choose a radiator with a suitable quantity  $n$ .

It is clear that two counters set at degrees of threshold energy  $E'_0$  and  $E''$ , and switched on in the proper sequence according to the scheme of anti-coincidence will only measure those particles whose velocity is in the region of  $E'_0$  and  $E''$ .

A procedure of this kind was successfully employed by Serge and his collaborators in their outstanding work which led to the discovery of the antiproton.

Another interesting field of application of the properties of the rays had been found in their use for investigating both showers of cosmic rays. In the investigation of these showers with the aid of devices with ordinary counters, at a certain altitude only those particles are measured which are remotely « descended » from the primary particle. The devices did not measure all the other particles which had emerged during the previous developmental stages of the shower and had already disappeared. But since the shower particles possess gigantic energies they have the power of producing in the air a radiation of the type in question which in practice propagates itself in the same direction. Under favourable conditions this radiation reaches the surface of the earth and can be measured by a photomultiplier. This method procures a more complete picture of the shower and permits valuable knowledge of its developmental process to be obtained.

The distribution in the primary cosmic radiation (outside the atmosphere) of nuclei heavier than hydrogen nuclei is of great importance in cosmology. Investigations into this are at present being carried out via the sputniks. These enquiries are based on the fact that the intensity of the radiation of particles travelling at a velocity greater than that of light is proportional to the square of the charge of the particle. Hence, the impulses coming from particles variously charged, and registered by the counter, differ according to the amplitudes. Analysis of the distribution of amplitudes will allow us to obtain information about the distribution of heavy particles in the cosmic radiation according to their ordinals.

The last subject I would like to mention is the use of the radiation of high-

speed particles for the purpose of measuring their energy, if this energy is fairly high. Here, the measurement of particle energy on the basis of deflection in the magnetic field is no longer possible. But we can attempt to determine it by measuring the total energy which the particle gives up to the radiation of the type mentioned. For this purpose highly transparent, dense radiators must be used which are sufficiently strong, and allow a complete development of the showers.

In this case water proves to be a suitable radiator. In the Institute of Physics in the Academy of Sciences of the U.S.S.R. a device is being constructed for measuring the energy of cosmic particles by this method.

The examples set forth show the great importance which the radiation caused by particles moving at a speed greater than that of light has acquired in experimental physics.

Even so, we have not by a long way exhausted all the possibilities for their practical use. There can be no doubt that the usefulness of this radiation will in the future be rapidly extended.

1. P. A. Čerenkov, *Dokl. Akad. Nauk SSSR*, 2 (1934) 451.
2. S. I. Vavilov, *Dokl. Akad. Nauk SSSR*, 2 (1934) 457.
3. S. I. Vavilov and L. A. Tumermann, *Z. Physik*, 54 (1929) 270.
4. Z. S. Newcomer, *J. Am. Chem. Soc.*, 42 (1920) 1997.
5. Z. Frenzel and Z. Schultes, *Z. Physik. Chem.*, B 27 (1934) 421.
6. Eve Curie, *Madame Curie*, London, 1941.
7. M. L. Mallet, *Compt. Rend.*, 183 (1926) 274; 187 (1928) 222; 188 (1929) 445.
8. E. M. Brumberg and S. I. Vavilov, *Izvest. Akad. Nauk. Omen*, Ser. 7 (1933) 919.
9. P. A. Čerenkov, *Dokl. Akad. Nauk SSSR*, 3 (1936) 413.
10. P. A. Čerenkov, *Dokl. Akad. Nauk SSSR*, 14 (1937) 99.
11. I. E. Tamm and I. M. Frank, *Dokl. Akad. Nauk SSSR*, 14 (1937) 107.
12. Lord Kelvin, Nineteenth Century, Clouds over Dynamical Theory of Heat and Light, *Phil. Mag.*, July (1901).
13. A. Sommerfeld, *Göttingen Nachr.*, 99 (1904) 363 ; (1905) 201.
14. J. Winckler, *Phys. Rev.*, 85 (1952) 1054.
15. J. V. Jelley, *Čerenkov Radiation and its Applications*, Pergamon Press, 1958.
16. R. L. Mather, *Phys. Rev.*, 84 (1951) 181.