SOVIET PHYSICS USPEKHI VOLUME 4, NUMBER 5 MARCH-APRIL 1962

TRANSITION RADIATION AND THE CERENKOV EFFECT

I. M. FRANK

Usp. Fiz. Nauk **75**, 231-240 (October, 1961)

1. INTRODUCTION

THE discovery of the Cerenkov effect and its subsequent theoretical analysis stimulated research into many problems related to this phenomenon. Various aspects of the Cerenkov effect besides those treated in the original theory have been analyzed: for example, the radiation of a fast particle in a plasma in a magnetic field, the Cerenkov effect in crystals, etc. In addition, much work has been published in which phenomena less directly connected with the Cerenkov effect have been treated. A characteristic feature of all this work is the fact that it is almost all theoretical. Many of these predicted effects have now been studied in greater or lesser detail and a large number of them should be amenable to experimental observation.

Except for the development of the Cerenkov counter, which is really an application of the Cerenkov effect, it may be said that in the last twenty years very little on the Cerenkov effect itself has been added to the original results of Cerenkov.

The situation is very much the same for problems related to the Cerenkov effect. Thus, it is only very recently that the phenomenon known as transition radiation has been investigated experimentally. This phenomenon will be considered in detail in the present communication.

Transition radiation is produced when a fast charged particle passes through the interface between two media possessing different optical properties. The theory of transition radiation was published as far back as 1944 by V. L. Ginzburg and the present author. It was at that time that the predicted effect received its now generally accepted name. Various aspects of the theory of transition radiation were considered later in a large number of publications. The number of papers concerned with transition radiation has increased markedly in recent years. However, it has been only recently that the validity of certain of the basic theoretical predictions has been established by experiment.

2. EFFECTS ASSOCIATED WITH THE CERENKOV EFFECT. SIMILARITIES BETWEEN VARIOUS WAVE PHENOMENA

Before considering various aspects of transition radiation it may be appropriate to consider the common features of the family of phenomena whose common bond is the Cerenkov effect. It is of interest in this connection to consider the analogy between Cerenkov radiation and the Mach wave in acoustics. This analogy is usually exploited in popular expositions of the Cerenkov effect and is actually quite useful. Wave phenomena of so completely different nature as acoustic waves and electromagnetic waves possess a number of common basic characteristic features. The delineation of these general features and of the points of departure at which differences develop for a particular kind of wave or for a particular frequency region is important in explaining the mechanisms underlying a number of effects. This approach was widely used, as is well known, by P. N. Lebedev in his study of radiation pressure.

There is little doubt that Lebedev's work influenced Vavilov, who was his student. In this connection we must point out that the formulation of the problem leading to the work in which the Cerenkov effect was discovered was typical of Lebedev's approach. Vavilov was interested in comparing luminescence of uranium-salt solutions when excited by ordinary light, by x rays, and by gamma rays from radioactive materials. However, the discovery of the Cerenkov effect was not directly connected with this formulation of the problem. The actual discovery was made quite accidentally by Cerenkov, who was investigating luminescence produced by gamma rays. Moreover, as became evident later, the Cerenkov effect can be best understood on the basis of Lebedev's ideas, since it is directly related to the concept of radiation pressure.

The important point is that the Cerenkov radiation is generated at the expense of kinetic energy of the particle. Thus, when the radiation is produced the particle is acted upon by a retarding force. This force is nothing more than the recoil communicated to the particle as the result of the fact that momentum is radiated. In other words this force, which performs work equal to the radiated energy, is a direct consequence of radiation pressure. If this approach is used certain basic features of Cerenkov radiation are gotten immediately, namely the existence of a threshold velocity and the directional properties.

It is pertinent to recall Lebedev's interest in the question of radiation pressure on individual particles—atoms and molecules—and his approach to the solution of this problem. Lebedev was interested in this problem in connection with his studies of the formation of comet tails under the effect of radiation pressure. In his own words:[1]

"It is impossible experimentally to investigate the effect of radiation on individual molecules of any body in any direct or simple way; hence I have been concerned with experiments with long (Hertzian) electromagnetic waves, causing them to interact with a simulated "molecule," which possesses a natural period of oscillation—this "molecule" is a resonator suspended on a twisted wire. By changing the period of oscillation of the resonator (this entails no particular difficulty) and causing an electromagnetic wave of a given wavelength to strike it, we can observe the ponderomotive forces that act and establish the way they are affected by resonance phenomena."

Within the framework of classical physics, and since at the time there was no other possibility (the work was carried out in 1894-1897), this model of the molecule should have simulated the expected effect completely. Although the dimensions of a molecule are much smaller than the dimensions of a resonator, it is also true that the wavelengths of light waves are correspondingly shorter than those of the radio waves used. Thus, similitude is preserved and the nature of the wave effects should be the same in both cases. However, Lebedev was not satisfied because the mechanisms by which the light affected molecules was completely unknown. Lebedev's insight as a physicist is indicated by the fact that he did not assume it possible to equate the effect of light on the molecule to the effect of radio waves on the resonator. He also investigated the pressures associated with other kinds of waves, particularly acoustic waves and hydrodynamic waves. He discusses the necessity for these investigations in the following words:[2]

"...by carrying out investigations of waves of different physical nature and establishing the relation between their ponderomotive effects on resonators we can generalize the applicability of the relations which are obtained to cases in which both the wave mechanism and the mechanism by which the wave is absorbed in the resonator are unknown."

On the basis of these investigations Lebedev reached the conclusion that the pressure exerted by waves on a resonator is a general effect for all kinds of waves and that one can invoke radiation pressure on a molecule even though the exact effect of the light radiation on the molecule is unknown.

Lebedev's general approach is still quite useful and one cannot help but agree with Vavilov, who wrote:[3]

"The historian and the physical investigator will regard the work of P. N. Lebedev as a living source for a long time to come."

We can now apply Lebedev's arguments to the Cerenkov effect and exploit the analogy with acoustics. This approach is possible because the phenomenon, as we have seen, is directly related to wave pressure, and because of the general properties of wave phenomena. We also know more than this. If motion occurs in a medium in which waves can propagate, they will, in fact, be excited (even for uniform rectilinear motion) if the velocity associated with the motion exceeds the wave velocity. Examples are the bow wave produced by the motion of a ship and, obviously, the Mach wave associated with supersonic velocities.

Thus it follows that the Cerenkov effect could have been predicted justifiably earlier than it actually was. We know that predictions of this kind were actually made. In 1901 Kelvin noted that electromagnetic radiation should be produced when an atom moves with a velocity greater than the velocity of light. This prediction was based directly on the analogy with experiments carried out by Mach. Kelvin's prediction was completely forgotten and was discovered again almost forty years later by Vavilov who was, as we know, an outstanding student of the history of physics.

Obviously any prediction made by a well-known physicist as Kelvin was not forgotten purely by accident. His prediction contained an important error, which was pointed out very shortly thereafter. This error arose because Kelvin did not carry through his analogy with acoustic waves completely. The point is that elastic waves are possible only in a tangible medium, which must occupy some volume in space. In some definite range of wavelengths, depending on its properties, the medium is assumed to be continuous. The situation is precisely the same for the Cerenkov effect. In this case the electromagnetic waves must propagate in a medium and the theory is formulated on the assumption that the medium is continuous. The medium is characterized by macroscopic parameters (dielectric constant and magnetic permeability) which depend on the frequency of the light and which characterize the velocity of propagation of waves and absorption in the medium.

It is now known that the analogy between the Cerenkov effect for electromagnetic waves and the Mach effect for elastic waves is completely valid. However, in Kelvin's time it was difficult to justify this analogy. Light was believed to propagate in a medium called the ether, which was endowed with rather peculiar elastic properties. It was natural to seek an analogy between ether waves and elastic waves in a medium. There was no reason to analyze the motion of particles in a real tangible medium, the more so since motion of an atom in a tangible medium was not considered physically realizeable.

Later, with the development of the theory of relativity it became obvious that a particle with nonvanishing rest mass could not move with the velocity of light in vacuum. Thus, the case considered by Kelvin was found to be physically unrealizeable and his prediction was forgotten, with some degree of justification. Work carried out by Sommerfeld in 1904—1905, concerning electron motion with supraluminal velocity in vacuum, suffered the same fate and for the same reason. This work, which was known in his time but forgotten later led to results which essentially gave the theory of the Cerenkov effect. In 1937, A. F. Ioffe, another one of our outstanding physicists, pointed out the relation between this work of Sommerfeld and the theory of Cerenkov radiation.

We see that the analogy between the Cerenkov effect and elastic waves holds only when we consider the motion of a radiating particle in a medium. It should be recalled that the velocity of propagation in any medium approaches the velocity of light in vacuum when the frequency is high enough. Hence, for any particle velocity there are always frequencies at which the phase velocity of light (and the group velocity) become greater than the particle velocity. The existence of this limit, which is characteristic of electromagnetic waves, is a particular feature of the Cerenkov effect and is very important.

The fact that the velocity of light in a dense medium is different than in vacuum, and that it depends on frequency, is not only responsible for the Cerenkov effect and its characteristic features, but for many related effects. In radiation phenomena involving light it is always found that the ratio of the particle velocity to the velocity of light is an important parameter. This ratio is different in a medium than in vacuum and is frequency dependent, so that the propagation characteristics have an important effect on a variety of radiation phenomena involving moving particles. The role of the medium is obvious in the optical portion of the spectrum, where the refractive index is appreciably different from unity. It has been discovered in recent years that if the particle is relativistic the effect of the medium also extends into the short-wave region (x rays and gamma rays). This region is extended as the energy of the relativistic particle increases. The methods of electrodynamics of continuous media are found to be applicable as long as the wavelength is much shorter than the distance between atoms. This follows because the radiation of a relativistic particle is concentrated at small angles to its trajectory and is associated with a sizeable segment of path length. As a result the properties of the medium are averaged over rather long distances and, as a first approximation the medium may be regarded as continuous.

3. TRANSITION RADIATION

Cerenkov radiation is generated by a particle moving with a fixed velocity. It is natural to ask whether this effect is unique, i.e., whether it is the only one in which radiation results from uniform rectilinear motion. The answer to this question is a simple one. If the velocity of the particle changes at any point of its trajectory, then bremsstrahlung is generated. This form of radiation results from the modification of the electromagnetic field the particle carries with itself. Similarly, if the particle moves with uniform motion, but passes through an interface between two media with different optical properties, then transition radiation is produced. The origin of this radiation is the same as for bremsstrahlung. When the particle moves into the second medium it is obvious that the field carried by the particle must be modified because of the difference in the velocity of propagation or the absorption properties of the second medium.

Experimentally, the most frequently realized case is the one in which a particle is incident on a metal surface from vacuum. If the particle energy is high enough there is no significant change in its velocity as it penetrates into the metal to a depth greater than the wavelength of visible light. Under these conditions the particle velocity in the surface layer may be assumed constant. In many metals, light is absorbed at certain frequencies in a layer small compared with a wavelength. Hence, as soon as the particle passes through the boundary surface of the metal its field in this frequency region is shielded by the metal. The particle "disappears" in passing through the interface. As a result, in some range of frequency and angle the transition radiation will be almost the same as though the particle had come to a sudden stop at the metal boundary.

Transition radiation should be observable in many situations. It is produced in any accelerator or cathode-ray tube in which a beam of bombarding particles strikes a metal target. In particular, it should always accompany cathode luminescence.

It has been known for a long time that radiation is produced by metals bombarded by charged particles. For some reason, however, the possibility that this effect might be some other form of radiation such as transition radiation, rather than luminescence, has not been considered. All discussion on this subject had been based on various kinds of bremsstrahlung effects. It would appear that the prevailing feeling that a particle must be accelerated or decelerated in order to produce radiation hindered the observation of this effect. The discovery of the Cerenkov effect, however, stimulated new thoughts about the problem. Nevertheless, many years passed between the development of the theory of transition radiation and the time at which the first experimental data on the properties of this radiation were obtained. Experimentally the situation was simpler for transition radiation; when Cerenkov radiation was discovered it was completely unexpected and unpredicted. Furthermore, there was a natural tendency to assume that one of the many forms of luminescence was responsible for the observed effect. To demonstrate that this was a new effect, unrelated to luminescence was a very difficult task. It was a formidable problem and the experimental difficulties were quite severe for the experimental techniques available at that time. These factors emphasize the value of the contribution made by Vavilov and Cerenkov, who indicated the fundamentally new optical features of this effect.

4. EXPERIMENTAL INVESTIGATIONS OF TRANSITION RADIATION

We now describe briefly some of the experimental properties of transition radiation. First, however, we should indicate some of the properties predicted by theory for this radiation.

The radiation intensity should be proportional to the square of the particle charge and (for nonrelativistic energies) the square of the particle velocity. Thus, the intensity should be proportional to the particle energy and inversely proportional to the particle mass (for given charge and energy). Consequently, a 10-kev electron should produce approximately the same transition radiation intensity as an 18-Mev proton.

As the particle velocity increases the conditions for observation of transition radiation become more favorable for two reasons: first, the intensity increases, and second, any possible background is usually reduced. A background effect can be produced by luminescence in the surface layer of the metal; the background intensity depends on the ionization losses of the particle in this layer. For this reason it is reasonable to assume that the background is reduced as the particle velocity increases. This effect is important because the transition radiation intensity is low: the probability that a photon is emitted when a singly charged relativistic particle passes through the boundary is approximately one in a hundred.

A characteristic feature of transition radiation is that the radiation is completely polarized, with the electric vector lying in the plane of the particle velocity and the direction of the ray. It is assumed, obviously, that we can neglect scattering of the particle in the surface layer of the target and depolarization of light, which depends on the target surface; this assumption, however, is not always valid. The theory also predicts the angular distribution of the radiation and the spectral composition, both of which are extremely sensitive to the optical constants of the material being bombarded.

These and other predictions of the theory can be compared with experimental results. Two experimental investigations of transition radiation have been carried out recently. These were preceeded by several earlier experiments. For instance in 1939 Balabanov and Katsaurov of the nuclear physics laboratory of the Physics Institute of the Academy of Sciences observed radiation produced by electrons with energies of approximately 200 kev. This effect was investigated in greater detail in 1935 by Chudakov and Belyaev. However, these two investigations were not followed through completely and the results were not published.

In 1959 a paper by Goldsmith and Jelley appeared in England.[4] These authors observed radiation from gold, silver, and aluminum surfaces bombarded by protons with an energy of approximately 2 Mev. A polarized component was observed in the radiation, with the direction of polarization being that predicted by theory. The existence of a polarized component was used as a criterion for distinguishing the transition radiation from the background, the nature of which was not clarified. However, no convincing proof was given that the polarized components of the radiation were of different nature.

This fact is of great importance because the polarized component represented $\frac{1}{3}$ to $\frac{1}{10}$ of the total radiation intensity. Moreover, the radiation intensity varied greatly from experiment to experiment, apparently as a result of changes in the surface properties of the metals.

Some supporting evidence that the authors actually did observe transition radiation is the fact that the radiation intensity increased in approximately direct proportion to the energy of the bombarding protons. The authors also cite the fact that within the experimental errors the absolute radiation intensities agree with the theoretical values. Unfortunately, however, this result is based on an error.

In determining the radiation intensity, for some reason the authors did not use the formula obtained by Ginzburg and Frank; instead the authors used an approximate analysis in which the metal was assumed to be absolutely conducting. In this case the transition radiation must be identical with the optical portion of the bremsstrahlung spectrum of a particle which is brought to a stop suddenly at the surface of the metal. Because of the dipole nature of the radiation the maximum intensity for a nonrelativistic particle is at right angles to its trajectory. This is probably the reason that the observations of the transition radiation were carried out at approximately 90°. An analysis shows, however, that the assumptions used in deriving the theoretical angular distribution do not apply at angles close to 90°. In any real metal the intensity of the transition radiation must fall to zero as the angle of observation approaches 90°. This result has been pointed out by V. E. Pafomov and has been verified experimentally by Mikhalyak. Thus, the calculated intensity used by Goldsmith and Jelley is too high and can only be used to make qualitative rather than quantitative comparisons with theory.

A considerably more detailed investigation of transition radiation has been carried out by graduate student S. Mikhalyak, working under the direction of A. E. Chudakov.[5] In this investigation the transition radiation was produced by electrons with energies of several tens of kiloelectron volts. It follows from the considerations above that the conditions for observation of transition radiation are much more favorable in this case than when protons are used. In these experiments the polarized radiation component was 90% of the total radiation. Good agreement with theory was found for the dependence of radiation intensity on electron energy, for the absolute intensity (in several metals), and for the angular distribution of the radiation. There is no doubt that the author did, in fact, observe transition radiation and that the predictions of the theory were basically verified. However, our knowledge of transition radiation is still far from complete. Transition radiation may well be more complicated than is now thought. In particular, it was not possible to establish the nature of the unpolarized radiation component in the work carried out by Mikhalyak; thus this unpolarized component still represents an open question in the analysis of transition radiation.

As expected, the experiments carried out by Mikhalyak showed that the properties of the transition radiation are determined by the optical constants of the target. Investigations of transition radiation may therefore turn out to be very useful for studying the optical properties of various materials, particularly metals. An investigation of silver by this technique has essentially already been carried out in recently reported work by Steinmann, and by Brown, Wessel and Trounson, who investigated ultraviolet radiation produced in thin silver foils (thickness of the order of 500 A) bombarded by 25-kev electrons.

It is well known that silver exhibits a narrow transparency band in the ultraviolet portion of the spectrum, near 3300 A. The authors discovered that when bombarded by electrons the surface of the foil radiates a continuous spectrum containing interesting features in the region in which the silver is transparent. A selective radiation peak was observed in this region and the height of this peak was found to be a periodic function of foil thickness. This peak was observed only at small angles with respect to the electron beam. The authors interpreted this effect in terms of a theory of plasma oscillations in a thin metal layer that had been developed by Farrell; this theory predicts radiation of the kind that was observed. The agreement between the observed features of the radiation spectrum near 3300 A and the features predicted by Farrell was taken as verification of his analysis.

The authors of this work were apparently not acquainted with transition radiation. They used electrons with energies of the same order of magnitude as Mikhalyak, who showed that under these conditions the radiation from silver in the visible portion of the spectrum is primarily transition radiation. There is no doubt that the transition radiation spectrum also extends into the ultraviolet. Thus, the ultraviolet radiation lying outside the 3300 A peak, which the authors of these papers call a background, is actually transition radiation. It must be demonstrated therefore that the radiation in the region of the peak is not transition radiation. The features of the transition radiation in a transparent region of the spectrum have not been analyzed before. It may be assumed that reduced absorption means a reduction in transition radiation, i.e., that there will be a radiation minimum in this region rather than a maximum. Recently, V. P. Silin and E. P. Fetisov* have shown that this kind of effect in transition radiation in silver would be very pronouned in the region in which the silver is transparent. As far as one can judge from the communications of Steinmann and of Brown, Wessel and Trounson, it is precisely this effect that was observed.

The fact that the radiation depends on slab thickness indicates only that the radiation produced in the volume of the silver or at the surfaces exhibits a coherent relation with electron motion. This coherence causes interference of the light, resulting in intensification or weakening, depending on slab thickness. It is obvious that this effect can occur only in a region of the spectrum in which the silver is sufficiently transparent. The presence of this coherence effect is evidence that the observed phenomenon is not due to luminescence. On the other hand, interference is a completely natural process for transition radiation. The theory predicts a rather strong transition radiation. The dielectric constant in this region of the spectrum is small compared with unity. Thus, the propagation conditions for electromagnetic waves undergo a marked change in the transition from the vacuum into the silver, and, as already noted, this situation implies the production of transition radiation. The angular distribution should be different than for the region in which the silver is opaque. Transition radiation in a slab has been investigated by V. E. Pafomov.^{7} Good qualitative agreement with the observed angular distribution of the radiation is obtained when the values of the dielectric constant for silver are substituted in the formula obtained by this author. Thus, as pointed out by Silin and Fetisov, the entire silver radiation spectrum can be explained from a single unified point of view.

The following remarks may be of interest: the existence of interference indicates that the radiation is due to an electromagnetic field associated with the moving particle. This field must satisfy Maxwell's equations for the medium when they are written properly for the case at hand. Since transition radiation is a straight-forward consequence of Maxwell's equations, when the experimental conditions are properly introduced the theory should give a complete picture of the observed radiation. It should include any kind of effect based on particular assumptions (obviously aside from luminescence). If a more detailed comparison between experiment and theory reveals discrepancies this would evidently mean that the equations of propagation of light in silver require corrections. In other words, an investigation of this kind is essentially an examination of the optical properties of thin silver layers.

My reason for discussing transition radiation at this Vavilov memorial conference is not only the fact

---

*The author became acquainted with the work of Silin and Fetisov [Phys. Rev.Lett., 7, 374 (1961)] after writing this report. The discussion of the problem of selective radiation in silver was included in the report after it had been prepared for publication.

that it is intimately related to the Cerenkov effect. Transition radiation also touches upon problems of optics and optical radiation mechanisms—subjects with which Vavilov was always very much concerned. It may be of interest to note that just as in the Cerenkov effect, the study of transition radiation, which started as a pure optical effect, has now extended into nuclear physics, more precisely, high-energy physics. This aspect of the subject has become increasingly interesting in recent years.

5. TRANSITION RADIATION OF RELATIVISTIC PARTICLES.

It is well known that at particle velocities very close to the velocity of light the characteristics of the Cerenkov radiation in a dense medium no longer depend on particle energy. It is then natural to ask whether transition radiation can be used for the detection of relativistic particles and measurement of their energies. It is not yet possible to give a final answer to this question; there is no doubt, however, that transition radiation of relativistic particles exhibits a number of new properties that merit special attention.

It has been pointed out by the author of the present paper that there is no loss of intensity of transition radiation of relativistic particles when the metal is replaced by a transparent dielectric. Thus, transition radiation produced at different surfaces can be added; this is important because the intensity of transition radiation is very small. It was later found that as the particle energy increases the deviation from unity of the refractive index needed for obtaining full radiation is smaller. Thus, the transition radiation spectrum of an ultrarelativistic particle extends into the short-wave region (x rays and gamma rays). These features were pointed out by Garibyan,[8] who showed that the total energy associated with the transition radiation is proportional to the total particle energy. The increased radiation energy results because the limit of the transition radiation spectrum moves towards higher frequencies as the particle energy increases, i.e., the radiated spectrum expands.

The short-wave region of the transition radiation has been studied in several papers. Many of the known features of relativistic particle radiation have been found to be related to transition radiation. Ter-Mikaelyan[9] has shown that the presence of a medium reduces the intensity in a definite portion of the bremsstrahlung spectrum. This so-called density effect was one of the first observed effects of a medium on the radiation of hard photons. Using the simple example of transition radiation in a metal we have already indicated the analogy between bremsstrahlung and transition radiation. The theories of these effects are intimately related and a knowledge of the radiation spectrum that is produced when a particle comes to a sudden stop (or disappears) can be used to compute the transition radiation. As a result, the features of short-wave transition radiation can be easily obtained from the density effect. It is found that transition radiation should be produced in precisely that region of the spectrum where the density effect depresses the bremsstrahlung.

Other characteristic features of transition radiation of ultrarelativistic particles have also been explained. If there is to be no reduction in the intensity of the transition radiation the particle must travel long distances before and after passing through the interface. In certain cases this path must be enormous. Thus, to produce optical transition radiation an electron with an energy of 10^{11} ev must travel a path of the order of 2 km in vacuum before or after passing through the interface.* Thus, it would certainly not be a simple task to observe visible transition radiation. However, the required path length is proportional to the radiation wavelength, and is correspondingly shorter for short-wave radiation. Hence, it should be easier to produce short-wave radiation.

Similar features are well known in radiation effects which play a role in high-energy physics. Many of these effects have been analyzed by E. L. Feĭnberg.[10] It is now relevant to include transition radiation in the catalog of these effects.

Because the path the particle travels before intersecting the boundary is of importance it is necessary to consider the role of multiple scattering, which can effect the rectilinearity of the particle trajectory. L. D. Landau and I. Ya. Pomeranchuk[11] were the first to show that multiple scattering has an important effect on bremsstrahlung energy. Multiple scattering must also be taken into account in the analysis of transition radiation of ultrarelativistic electrons. Both transition radiation and bremsstrahlung are produced when an ultrarelativistic electron moves from vacuum into a medium. In certain cases it is impossible to distinguish one from the other and they must be considered in terms of a single effect.

Thus, as the theory of transition radiation of relativistic particles continues to unfold, it appears to play an ever-increasing role in the family of effects assoiated with short-wave radiation of high-energy particles.

It is to be hoped that applications of transition radiation in optical investigations and in high energy physics will undergo further development in future years.

[1] P. N. Lebedev, Experimental Investigations of the Ponderomotive Effect of Waves on Resonators. Selected Works, Gostekhizdat, Moscow, 1949, p. 87.

[2] P. N. Lebedev, ibid., p. 88.

---

*Particles with this energy are observed in cosmic rays. Energies of this magnitude are also almost obtained with modern accelerators.

[3] S. I. Vavilov, In Memory of P. N. Lebedev. Collected Works, AN SSSR, Moscow, Vol. III, p. 167.

[4] P. Goldsmith and J. V. Jelley, Phil. Mag. **4**, 837 (1959).

[5] S. Mikhalyak, Dissertation, Moscow State University, 1961.

[6] W. Steinmann, Phys. Rev. Letters **5**, 470 (1960); Brown, Wessel, and Trounson, Phys. Rev. Letters **5**, 472 (1960).

[7] V. W. Pafomov, JETP **33**, 1074 (1957), Soviet Phys. JETP **6**, 829 (1958).

[8] G. M. Garibyan, JETP **37**, 527 (1959), Soviet Phys. JETP **10**, 372 (1960).

[9] M. L. Ter-Mikaelyan, DAN SSSR **94**, 1033 (1954).

[10] E. L. Feĭnberg, UFN **58**, 193 (1956).

[11] L. D. Landau and I. Ya. Pomeranchuk, DAN SSSR **92**, 535 (1953).

Translated by H. Lashinsky

Translator's Comments:

The interpretation of the experimental results of Steinmann and Brown, Wessel and Trounson, referred to in this paper by Frank, has been discussed in greater detail in recent papers by Silin and Fetisov[1] and Stern.[2] Silin and Fetisov present an analysis of these experiments in terms of transition radiation while Stern points out that Ferrell's[3] calculation and the transition radiation calculation give equivalent results for the radiation peak. Stern's note gives a good summary of the present status of the subject and it may be pertinent to quote his concluding remarks:

"In conclusion, it has been shown that Ferrell's calculation of a peak of radiation at the plasma frequency from thin films can also be obtained from a calculation of transition radiation, and in fact they are two different ways to consider the same phenomenon. Since the transition radiation calculation includes all radiation from the film, it is more general. Ferrell's method only calculates the peak though it does so correctly and shows the physical mechanism causing the peak. . . . "

---

[1] V. P. Silin and E. P. Fetisov, Phys. Rev. Letters 7, 374 (1961).

[2] E. A. Stern, Phys. Rev. Letters **8**, 7 (1962).

[3] R. A. Farrell, Phys. Rev. 111, 1214 (1958).