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BIBLIOGRAPHY

J. V. JELLEY, CERENKOV RADIATION AND ITS APPLICATIONS,

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A book called Cerenkov Radiation and its Applications, by J. V. Jelley, was published at the end of last year by the English publisher Pergamon Press.

Cerenkov radiation is the radiation emitted by charged particles which move in a transparent medium with a velocity which exceeds the phase velocity of light in this medium. This radiation was first studied in detail by P. A. Cerenkov, working under the direction of S. I. Vavilov. The first theoretical analysis of Cerenkov radiation was published by I. E. Tamm and I. M. Frank, in 1937.

During the twelve or fifteen years immediately following its discovery, Cerenkov radiation was more or less of academic interest to physicists. In the main it was only the properties of the radiation itself which were investigated theoretically and experimentally, and little thought was given to its practical utilization. The first proposals for possible applications of Cerenkov radiation were made in 1947. At this time V. L. Ginzburg considered the possibility of generating extremely short radio waves by means of Cerenkov radiation and I. A. Getting proposed a simple optical system for the detection of single charged particles by means of the Cerenkov radiation emitted by these particles. This radiation is extremely weak. The number of photons emitted by a fast charged particle in uniform motion in a refractive medium is less than several hundred per centimeter of path and the maximum-energy photons lie in the ultraviolet. The human eye is not capable of distinguishing such weak radiation. Hence, to detect particles by means of Cerenkov radiation it is necessary to have an instrument which can detect weak light pulses. Such an instrument is the photomultiplier; suitable photomultipliers were adequately developed after the second World War.

In 1947 Getting proposed the use of photomultipliers for recording the weak Cerenkov light pulses produced by the passage of an individual charged particle through a transparent radiator.

The first successful experiments with Cerenkov counters were performed in 1951, when papers were published almost simultaneously by Mather, Marshall, and Jelley. Mather and Marshall built Cerenkov counters for the direct measurement of the velocity of beams of high-energy charged particles obtained from accelerators while Jelley constructed a Cerenkov counter with which it was possible to detect with high efficiency single charged particles.

Since 1951 the number of designs and applications of Cerenkov counters have increased rapidly. Today the Cerenkov counter has become an everyday tool in high-energy particle physics. There is little doubt that the role of Cerenkov counters in high-energy research will be an ever-increasing one.

The development of the Cerenkov-detector technique was one of the reasons for the awarding of the Nobel Prize in Physics for 1958 to three Soviet scientists, P. A. Cerenkov, I. E. Tamm and I. M. Frank.

The theory of the Cerenkov effect was developed simultaneously with the experimental work. There has been a curious division of labor in the work on the Cerenkov effect during the years following its discovery and analysis. The overwhelming majority of experimental papers on the construction and application of Cerenkov counters have appeared abroad: in America, Great Britain and Italy, while the majority of theoretical papers concerning the properties and possible applications of Cerenkov radiation have appeared in the Soviet Union. Detailed studies have been made of the features of Cerenkov radiation in anisotropic and gyrotropic media (V. L. Ginzburg, A. A. Kolomenskiĭ, A. G. Sitenko, V. E. Pafomov, M. I. Kaganov, etc.). Detailed studies have also been made of problems involving the radiation of charged particles in the presence of boundaries. These include radiation of a particle in a channel in a refractive medium (V. L. Ginzburg and I. M. Frank, A. G. Sitenko, etc.), radiation of a particle moving in vacuum above a plane dielectric (M. Danos, V. E. Pafomov, etc.), Cerenkov radiation in waveguides (A. I. Akhiezer and G. L. Lyubarskiĭ, Ya. B. Faĭnberg, M. I. Kaganov and L. S. Bogdankevich, etc.) and a number of other problems. This does not mean that the theoretical work has been carried out in isolation from practical problems. For example, the theory of Cerenkov radiation in a gyrotropic crystal applies directly to the ionosphere because the ionized gas (plasma) in the magnetic field of the earth is an anisotropic and gyrotropic medium. In recent years the theory of the Cerenkov effect in gyrotropic media has been of interest in connection with the problem of a controlled thermonuclear reaction since all known methods of containing hot plasma are based on the use of magnetic fields, and a plasma in a magnetic field, as has been indicated, behaves like a gyrotropic crystal. Investigations of boundary-value problems in the theory of Cerenkov radiation are also motivated by practical problems, one of which is the generation of radio waves by means of this radiation.

This rather long introduction has been given to summarize the present status of the theory and application of Cerenkov radiation. At the present time Cerenkov radiation is being used more and more in the detection of fast charged particles and the determination of many of their important characteristics. There are also other important fields of application for this effect. Although practical progress in these fields is still not noteworthy, the problems investigated are important and, in our opinion, the efforts being made toward their solution will increase sharply in the near future.

The book by Jelley is concerned basically with the technology of Cerenkov counters. Numerous papers in this field are scattered in many physics journals and this situation makes it difficult to become acquainted with the state of the art or to apply the results of accumulated work. Hence the appearance of this book, written by one of the most qualified workers in the field, is most timely.

The book is much more than a mere systematic presentation of the principles of design and application of Cerenkov counters. Approximately one third of the book -- about one hundred of its three hundred pages -- is devoted to the theory of Cerenkov radiation. For this reason Jelley's book is also very useful for those who wish to become acquainted with the theory of Cerenkov radiation and related effects (transition radiation, Doppler effect in refractive media, and so on).

We now consider the book itself. The first chapter, which serves as an introduction, contains a presentation of the history and "prehistory" of the discovery of the Cerenkov effect. It is interesting to note that the effect had actually been observed long before it attracted the attention of Cerenkov. As far back as 1910 Mme. Curie had noted that flasks with concentrated solutions of radium salts emitted a weak pale-blue radiation. This was twenty-four years before the appearance of Cerenkov's first paper and twenty-seven years before the explanation of the effect by Frank and Tamm. Indeed, at that time (1910) the theory of macroscopic electrodynamics of material media had already been developed and the explanation of this effect could have been made many years earlier than was actually the case. However, this did not happen, apparently because the new effect was masked by a number of complicated processes which take place in luminescent liquids and solids under the effect of different kinds of radiation. It was in 1934 that S. I. Vavilov first indicated that the effect observed by Cerenkov could not be luminescence and that the suggestions as to its nature were made.

The author describes briefly the observation of L. Mallet who, several years before Cerenkov, observed radiation in pure liquids irradiated by gamma rays, but did not appreciate the fact that this was a completely new effect and not ordinary luminescence. The author then gives a detailed description of Cerenkov's work and his results.

The first chapter also contains several pages devoted to a qualitative description of the Cerenkov effect. Here we find the well-known construction used to show the formation of the Cerenkov cone by means of Huygens principle. The author also describes the effect from the microscopic point of view. However, this treatment is not entirely accurate. Specifically, polarization of a medium by virtue of the passage of a charged particle, with the consequent loss of energy, is a phenomenon which is not necessarily restricted to particle velocities comparable with the velocity of light in the medium (p. 4). A moving charge loses energy by polarization at lower velocities as well.* If, however, the velocity of the charge is greater than the phase velocity of light in the medium, in addition to the polarization loss there is an additional loss--the loss due to Cerenkov radiation.

The second chapter treats the radiation of a charged particle in an isotropic refractive medium. The first paper by Frank and Tamm is considered in detail and the nature of the dispersion in a real medium is discussed. In this connection the statement is made (p. 15) that dispersion was not considered in the first paper by Frank and Tamm. Actually, however, dispersion was considered by Frank and Tamm: to verify this, one need not even consult the original work by Frank and Tamm; examination of the following page in Jelley's book is sufficient.

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*Cf., for example, reference 1, where this effect is also treated.

The author also presents the basic results obtained by Tamm in his later paper (1939).

Among the topics treated in this paper are the duration of the Cerenkov light flash, radiation in a dispersionless medium, and the inverse Cerenkov effect (the Cerenkov effect in a moving medium).

At the end of the second chapter there is a quantum-mechanical analysis of the Cerenkov effect (based on results obtained by Ginzburg) and the radiation produced by a particle with spin. While the basic work by Tamm and Frank is presented by the author in adequate detail, all the later investigations are treated rather briefly. As, a rule, only the results are given, but the methods by which these results are obtained are not described. However, in each case all, or almost all, of the relevant work on a given problem is mentioned, thus facilitating further reading for those who are interested.

The treatment of Cerenkov radiation theory is continued in the third chapter. In the beginning of the chapter radiation from dipoles, multipoles, and oscillators in unbounded refractive media is considered. This problem was first treated by Frank. In discussing the work of Frank the author indicates in a footnote that in a private communication N. L. Balazs has pointed out, firstly, that the expressions obtained by Frank for the Cerenkov radiation from moving electric and magnetic dipoles is twice as large as it should be, and, secondly, that the expressions for the energy loss of electric and magnetic dipoles perpendicular to the velocity vector are incompatible.

Both of these remarks by Balazs are in error. The "extra" factor of 2 in the expressions obtained by Frank arises because Frank has considered the motion of a dipole in the time interval between -T and T. Hence, the radiated energy is proportional to 2T, the radiation time. To obtain an expression for the energy radiated per unit the formulas obtained by Frank must be divided by 2T (not by T), in which case the "extra" factor of 2 vanishes. The second part of the communication by Balazs raises a very interesting question concerning the transformation properties of magnetic and electric dipoles moving in refractive media. As is well known, a particle that has only an electric dipole moment in the coordinate system in which it is at rest exhibits a magnetic moment when in motion; the same applies for a magnetic dipole. The formulas for the transformation of the moments are well known for the case in which the particles move in free space. These are the formulas used by Frank in his first paper, in which he obtained the expression for the radiation of a moving magnetic moment whose validity has been questioned by Balazs. In his second paper Frank showed that this result follows from the formula applied by him for the transformation for dipole moments in free space. He also found the form of the transformations for which the radiation expressions for electric and magnetic moments are compatible, that is to say, expressions of similar form. In this case it turns out that the dielectric constant of the medium appears in the transformation formulas (if we assume that $\mu = 1$ and neglect the magnetic properties of the medium). The reason for this inconsistency has been pointed out in a paper by Ginzburg and in a recent paper by Ginzburg and Éĭdman.[2] In his second paper Frank considers the magnetic dipole as a combination of two point magnetic charges. In this case the medium in the space between the two charges is polarized and in order to determine the field in the medium one must consider not only the moments of the particles, but also the polarization of the medium due to the particles. Taking account of this polarization is a complicated problem which has not yet been solved successfully. However, if the moment is localized in a region whose dimensions are smaller than interatomic distances, the polarization of the medium need not be considered and one obtains the radiation expression whose validity Balazs has questioned without justification.

In passing we may note that the formula for the radiation of an electric dipole perpendicular to the velocity vector given in the book contains a misprint [Eq. (3.2), p. 33]; the expression should be multiplied by v^2/c^2.

There is a brief treatment of the radiation from higher multipoles and the description of the Doppler effect in refractive media is confined to ten lines.

An analysis of radiation from dipoles and multipoles is essentially an analysis of interference of the Cerenkov radiation emitted by a system of charged particles. As is well known, the radiation from a point charge can also be regarded as resulting from the interference of waves emitted by the charge at each point along its path. If the path of the charge is long compared with the radiated wavelength the interference leads to the formation of a radiation cone. In this case, obviously the velocity of the charge must exceed the phase velocity of the wave which is radiated. However, if the path length of the charge in the medium is comparable with the length of the radiated wave, radiation can also be produced if the velocity of the charge is smaller than the phase velocity of light. In his book Jelley discusses this "sub-threshold" radiation, using an analysis given in a paper by Lawson.

There is one related effect which is not treated in the book. Cerenkov radiation can be produced by sources other than a charged particle or a system of charged particles. A current that is displaced as a whole with high velocity can also radiate. A typical example is the pinch in a gaseous discharge. Cerenkov radiation from current beams has been considered by A. I. Morozov.[6] The possible utilization of the properties of this radiation in controlled thermonuclear reactions has been discussed by Morozov and L. S. Solov'ev.[8]

In discussing radiation in isotropic ferrites the author writes that the expression for the radiation of a charge in an isotropic ferrite was first obtained by A. G. Sitenko. However, Jauch and Watson obtained this expression five years before Sitenko.

The Cerenkov radiation in uniaxial crystals and in optically active media are considered in detail. The treatment of radiation in a gyrotropic medium is based on a paper published by A. A. Kolomenskiĭ in 1953. In this paper the general theory of the Cerenkov effect in gyrotropic media is given and a concrete example is considered--a medium with the tensor dielectric constant

$$\varepsilon=\begin{pmatrix} \varepsilon & -ig & 0 \\ ig & \varepsilon & 0 \\ 0 & 0 & \varepsilon \end{pmatrix}. \tag{1}$$

This form of the dielectric tensor was chosen by Kolomenskiĭ only to illustrate the application of the theory; he was not concerned with the existence of an actual medium with such a dielectric tensor. It is much more meaningful to consider radiation in an optically active medium, in which case the dielectric constant tensor is of the form:

$$\varepsilon=\begin{pmatrix} \varepsilon_1 & -ig & 0 \\ ig & \varepsilon_1 & 0 \\ 0 & 0 & \varepsilon_2 \end{pmatrix}. \tag{2}$$

An electron plasma in a magnetic field is a medium of this kind. In our opinion, the Cerenkov radiation analysis should be used for a dielectric tensor of this form. Such an analysis has been carried out by Sitenko and Kolomenskiĭ. The example of radiation in a gyrotropic medium considered by the author relates to the Cerenkov radiation in a plasma in a magnetic field, i. e., in a medium described by a tensor such as that in Eq. (2).

We wish to consider problems associated with the radiation of a charge which passes through a plasma in some detail. In the book only the radiation from a plasma in an applied magnetic field is considered. A specialized kind of "Cerenkov effect" is also found in an electron plasma which is not in a magnetic field. We refer here to the excitation of longitudinal plasma waves by a moving charge. Consider a charged particle moving through an electron plasma with velocity **v**. The radiation field of such a particle must move with the velocity of the charge, i. e., the function giving the field of the particle depends on the argument **x–vt**. Suppose that the charge radiates a wave

$$e^{i\mathbf{k}(\mathbf{x}-\mathbf{v}t)} \tag{3}$$

The wave vector for this wave is **k** and the frequency **kv** = cos ϑ, where ϑ is the angle between the velocity vector of the particle and the wave vector of the radiated wave.

In a plasma the wave vector and the frequency are related by the dispersion equation (long waves)

$$\mathbf{kv}^2=\omega_0{}^2+\frac{3\varkappa T}{m}k^2, \tag{4}$$

where $\varkappa$ is the Boltzmann constant, T is the plasma temperature, m is the mass of massive electron, and ω_0 is the plasma frequency. From this equation we find the angle between **k** and **v**

$$\cos\vartheta=\frac{v}{V_{ph}}, \tag{5}$$

where $V_{ph}=\frac{\mathbf{kv}}{k}=\frac{\omega}{k}$ – is the phase velocity of the radiated wave and v is the velocity of the charge. It will be apparent from Eq. (5) that a longitudinal wave is radiated only if its phase velocity is smaller than the velocity of the radiating particle. Thus, there is a complete analogy with the transverse Cerenkov effect.

The Cerenkov effect in an electron plasma is also interesting because it is responsible for the damping of longitudinal electromagnetic waves in the plasma. We consider a rarefied plasma in which collisions between particles can be neglected. As has been shown by Landau, the electromagnetic waves in a plasma of this kind are damped and the damping factor γ for long waves is the exponentially small quantity

$$\gamma=\frac{1}{2}\sqrt{\frac{T}{2}}\frac{1}{(kD)^3}e^{-\frac{1}{2(kD)^2}}, \tag{6}$$

where k is the wave vector of the wave, D is the Debye radius, and all the expressions are to be taken for kD<<1.

One may ask: what is the damping mechanism in a plasma in which there are no collisions between particles? The answer to this problem was given by Bohm and Gross in 1948.[3] The problem has also been considered recently by Shafranov.[4] It turns out that the absorption of the wave in the plasma is due to particles for which the condition in Eq. (5) is satisfied. These particles move in phase with the electric wave for extended periods of time and energy is transferred from the wave to the particles. This effect is the so-called inverse Cerenkov effect. The number of particles which satisfy this condition can be estimated on the basis of a Maxwellian distribution by substituting for the particle velocity the phase velocity of the wave ω/k. We find that the number of particles in the plasma with velocities ω/k is proportional to

$$e^{-\frac{m}{2\varkappa T}\left(\frac{\omega}{k}\right)^2}. \tag{7}$$

Since we are considering long waves ($kD \ll 1$) is follows from Eq. (4) that $\omega \approx \omega_0$. Substituting this relation in Eq. (7) and using the relation we obtain the exponential factor in Eq. (6).* Thus, the absorption of long waves in a rarefied plasma is due to the inverse Cerenkov effect.

In discussing research on the Cerenkov effect plasmas, we should also mention the work of Morozov,[5] who has considered the Cerenkov radiation in a plasma in a magnetic field, taking account of the compressibility of the plasma. When the compressibility of the plasma is taken into account it is found that the excited waves are not purely electromagnetic, but magnetoacoustic; the velocity of these waves is determined by the acoustic velocity in the plasma in the absence of the external field and the velocity of light in an incompressible conducting medium with an imposed magnetic field.

This same chapter in the book contains an analysis of boundary-value problems in the theory of Cerenkov radiation. These include the motion of a charge in a vacuum parallel to a plane dielectric, the radiation of charges in slow-wave systems (waveguides filled with dielectric and waveguides with irises, etc.). Here it should be pointed out that the possibility of obtaining a discrete Cerenkov spectrum was not first indicated by Abele, as is stated in the book, but two years earlier by Akhiezer, Lyubarskiĭ, and Faĭnberg. These authors also developed a general theory for Cerenkov radiation and the Doppler effect in slow-wave systems.

The section on transition radiation contains a note in which it is reported that the author, together with Elliott and Goldsmith, has been conducting experiments (January 1958) to establish the existence of transition radiation and apparently observed this radiation. Transition radiation, which is produced in the motion of a charge from one medium to another, was predicted by Ginzburg and Frank in 1945.

After the publication of Jelley's book an interesting paper devoted to the theory of transition radiation was written by Garibyan.[9] Consider two media with different dielectric constants, with a plane interface. Suppose that a charged particle passes from one medium into the other, moving normally to the boundary. In passing through the interface, the particle produces the so-called transition radiation. Ginzburg and Frank computed the energy of the transition radiation emitted in the backward direction (in the medium in which the particle moved before reaching the boundary) and showed this energy to be small and a weak function (logarithmic) of the energy. Garibyan has recently computed the energy of the transition radiation in the forward direction, and has found that in the relativistic case this energy is a linear function of energy and can be quite large.

In considering the motion of a charge parallel to a plane dielectric the author gives two expressions for the radiation energy loss. One of these has been obtained by Linhart for the motion of the charge in a vacuum, and the other was obtained by Pafomov for the case in which the charge moves in a dielectric with a dielectric constant ϵ_1 parallel to the interface with a dielectric characterized by ϵ_2. However, with $\epsilon_1 = 1$ the Pafomov formula does not yield the result obtained by Linhart, even with the simplifying assumptions used by Linhart in his calculations. This discrepancy arises because the Linhart formula is incorrect. It is more appropriate to use the expression for the energy loss obtained by Danos, who considered the same problem as Linhart but obtained the correct results. The formula obtained by Danos is in agreement with the results obtained when the Pafomov formula is applied to the limiting case.

We may make one further remark concerning the Cerenkov radiation in an empty channel in a dielectric. As has been shown by Ginzburg and Frank, the radiation of a point charge moving along the axis of such a channel is the same as the radiation in a continuous medium so long as the radius of the channel is smaller than the length of the radiated wave. However, if a more complicated electrical system, say an electric dipole, moves along the axis of the channel the presence of the channel has an important effect on the radiation, no matter how small the radius of the channel. This result has recently been pointed out by Ginzburg and Éĭdman,[2] and also by

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* The point to be emphasized is that the damping factor γ is not proportional to the distribution function, but to its derivative with respect to velocity. In the case considered here this relation does not change the magnitude of the exponential factor.

Bogdankevich,[7] for the case of a dipole at right angles to the axis of the channel.

In this book Jelley devotes a rather large amount of space to a discussion of the difference between Cerenkov radiation and bremsstralung. This problem is important in connection with the detection of particles by means of Cerenkov radiation.

We have touched on almost all the questions which appear in the two theoretical chapters of Jelley's book, Cerenkov Radiation and Its Applications. The book contains one other chapter, a significant part of which is devoted to theoretical problems. This is the last (eleventh) chapter, called "Miscellaneous Ideas and Applications." Various ideas relating to Cerenkov radiation, which have been proposed in recent years, are discussed in this chapter. Although some of these proposals and ideas are open to question, the author has included them in the book, hoping thereby to acquaint a large number of readers with these problems and thus to facilitate the evaluation of the proposed solutions. We list some of the topics in this chapter: Cerenkov standard-light sources, Cerenkov radiation in linear accelerators, pulsed radio waves associated with cosmic-ray avalanches, Cerenkov radiation in water-moderated nuclear reactors, the inverse Cerenkov effect and a method of coherent acceleration based on this effect, and the detection of decay products in reactors.

Because of its unique properties (short response time, directivity, and velocity threshold) Cerenkov radiation has been used widely as a means of detecting particles. However the light emitted by an individual particle can be detected only by means of modern photomultipliers. For this reason one of the chapters of the book (fifth) is devoted to photomultipliers, which are most important in the design and construction of Cerenkov counters.

In the introductory part of this chapter the author points out the high sensitivity of photomultipliers as detectors of electromagnetic radiation; in this respect these devices are surpassed only by radio receivers. The weak intensity of Cerenkov radiation forces the experimenter to use the best available photomultipliers, with cathodes of high quantum efficiency and appropriate spectral sensitivity, and of low noise level. In a number of cases it is very valuable to have the possibility of obtaining from the photomultiplier a pulse that does not require further amplification. Thus, photomultipliers with high gain are required. Furthermore, it is desirable that the photomultiplier have good time characteristics, so that it be usable for short light pulses if necessary. In general, a Cerenkov counter requires a photomultiplier with a combination of characteristics which is still not available. Hence the choice of the photomultiplier in a particular case must represent a compromise because, for example, good time characteristics may be accompanied by low gain or a high amplitude spread, and so on.

The author considers three factors which he feels demand the primary attention when the photomultiplier is used in a Cerenkov counter. These are the dark current, the signal-to-noise ratio, and the fluctuations in the amplitude of photomultiplier pulses. The basic formulas and data required to make the necessary estimates of these factors are given. In addition, descriptions are given of procedures for calibrating the threshold of a discriminator directly in terms of the number of photoelectrons emitted from the cathode of the photomultiplier. One of these consists of the measurement of the half-width of the pulse height distribution obtained by irradiating an NaI(Tl) crystal with γ rays. By using the half-width and the data on secondary emission coefficients for the dynodes we can compute the number of photoelectrons. However, this procedure may not give the proper number of photoelectrons, since the broadening measured experimentally must necessarily include fluctuations in the magnitude of the light flashes from the crystal. This spread is usually due to the non-uniform activation of the crystal and causes the calculated number of photoelectrons to be too low. Other features of photomultiplier operation are mentioned: the different forms of feedback, which lead to the appearance of satellite pulses; the finite transit time of the electrons, the spread of which limits the "speed" of Cerenkov counters; saturation, which causes a non-linear dependence of output amplitude on light intensity and which is the factor that limits the maximum gain of the device. The electronic circuitry used in conjunction with Cerenkov counters is not considered in the book although the gain in signal-to-noise ratio which can be realized by means of coincidence techniques is pointed out.

Certain practical comments concerning operation of photomultipliers are collected in a special section. In our opinion, a number of these comments are of value only when applied to certain specific kinds of photomultipliers.

In this same chapter a method is given for calculating the absolute efficiency of photomultiplier cathodes for Cerenkov radiation. These calculations make it possible to estimate the number of photoelectrons emitted from the cathode of a photomultiplier in a detector of a given kind and to thus obtain some idea as to the characteristics of this instrument.

Inasmuch as the absolute intensity and spectral distribution of the Cerenkov radiation are well known, to compute the number of photoelectrons it is necessary to know the quantum efficiency and the spectral sensitivity of the photocathode (and in some cases the spectral transmission of the radiator). Unfortunately, the photocathode characteristics cited above are frequently unknown for the photomultipliers available to the experimenter. The quantum efficiency can be only roughly estimated from the sensitivity as given in the photomultiplier specifications, which is measured with a standard light source. An appropriate procedure is described in the book. However, the reliability of this procedure is, in our opinion, extremely doubtful because the calculation makes use of the spectral sensitivity of the photocathode and this is generally known only in general terms, from the average characteristics of photomultipliers of a given type. Thus, in any case the reliability of an estimate of the number of photoelectrons depends on the accuracy with which one knows the quantum efficiency and spectral sensitivity.

In the concluding section of this chapter there is a summary of the characteristics of various photomultipliers, including the English EMI tube, the American RCA and Dumont, the Swiss AFIF, and French AVP, and the Soviet FEU-12 and certain photoelectric cells. The author states that he has included only the characteristics of photomultipliers suitable for use in Cerenkov counters. As far as Soviet photomultipliers are concerned, however, in addition to the FEU-12, domestic industry provides a number of other photomultipliers which can be used, and are used, in Cerenkov counters, namely the FEU-24, the FEU-33, the FEU-S, the FEU-B, the FEU-V (the last three FEU types are supplied with the quantum efficiency of the cathode stated for a given wavelength.)

In our opinion, an extremely small part of this chapter is devoted to the time characteristics of photomultipliers. The question of fluctuations in pulse amplitude in the photomultiplier should also be treated in considerably greater detail.

Information concerning the characteristics and applications of Cerenkov counters are given in Chapters 6, 7, 8, and 10. Usually Cerenkov counters are classified as focusing or non-focusing. In focusing counters a special optical system is used to concentrate the light on the detector. Both focusing and non-focusing counters (the first, always, and the second, sometimes) exploit some characteristic feature of the Cerenkov radiation. Cerenkov counters can also be classified in terms of application, in which case the basic characteristics of these detectors and their advantages and disadvantages as compared with other types become more apparent. The author lists eleven general application groups: The first includes Cerenkov counters (focusing and non-focusing) used as the "fastest" detectors of charged particles. The second, focusing counters as used for direct measurement of the velocity of particles in a limited region above the threshold for Cerenkov emission. The third classification refers to detectors in which the threshold is used in order to distinguish particles by mass (for the same momentum or range) or to distinguish particles with high energy from background particles of low energy (or, conversely, by use of anti-coincidence arrangements to separate slow particles from high-energy particles.) This group includes focusing and non-focusing counters. The fourth classification group comprises velocity selectors, i. e., detectors that record particles whose velocities lie within certain definite limits. Velocity selection can be carried out with a focusing counter or with a combination of threshold detectors. The fifth group refers to detectors which have the "anti-directional property," i. e., the ability to distinguish between particles that move in opposite directions. The sixth classification refers to counters that can be used to measure the charge of a particle. There are also total-absorption spectrometers, i. e., counters in which all the energy of a photon of high-energy electron is absorbed; large-area counters; particle-flux recorders; directional selectors, which use focusing counters, and finally, neutron detectors. A number of these applications are unique to the Cerenkov counter. These include velocity and directional selectors and threshold detectors. In other cases, other detectors, for example scintillation counters, can compete with the Cerenkov counter. Even in these cases, however, there are a number of factors which dictate a preference for Cerenkov counters. For example, Cerenkov total-absorption spectrometers, in contrast with scintillation total-absorption spectrometers, are insensitive to a background of slow heavy particles.

The two classification schemes cited above are used as the basis of the presentation in the two following chapters, which are devoted to the optical properties and to the design of Cerenkov counters. However, these classification schemes are not exhaustive and do not encompass all the specific features of Cerenkov counters. Hence, special consideration is given to three specialized types: "thin," "deep," and total-internal-reflection counters. Cerenkov counters are called "thin" if they produce a minimum disturbance of the incident particle. The "thinness" criterion varies, depending on the specific application of the thin counter. Thus, for fast counting, the radiator must not cause strong scattering of the particles. A basic difficulty associated with the operation of such detectors is the small amount of light and the relatively large fluctuations in pulse amplitude at the photomultiplier. No focusing is used in thin counters and greatest attention is directed toward increasing the efficiency with which the light is collected at the cathode of the photomultiplier.

Although the amount of light produced in a thin scintillator is tens of times greater than that of the Cerenkov flash, there is a very important reason which, in a number of cases, makes it preferable to use the Cerenkov detector. In thin layers of matter the ionization energy losses, and consequently the amount of energy transformed into light in the scintillator, fluctuates widely. Thus the spread in pulse amplitude in a thin scintillation counter may be greater than the spread in a Cerenkov counter.

In a total-absorption spectrometer (deep counters) one makes use of the fact that a photon or high-energy electron gives rise to a shower or electromagnetic avalanche in matter. The characteristics of such a detector are determined first of all by what fraction of the total energy of the incident particle is absorbed in the radiator. Since the range of the cascade electrons which emit Cerenkov radiation is proportional to the energy of the primary particle, from the intensity of the light flash it is possible to get an idea of the energy of the particle which initiates the avalanche. Jelley asserts that in order for the light yield to be proportional to the energy of the particle the emission threshold must be small compared with the critical energy of the material, although this is not necessary. It is convenient to use a material with a high atomic number and density since the dimensions of the detector can be very small in this case. This consideration indicates the advantage of the Cerenkov radiator as compared with the luminescent radiator since the materials of high Z tend to reduce the efficiency of a scintillator. Unfortunately the book contains only a small amount of data which can be used for designing total-absorption spectrometers.

Great interest attaches to total-internal-reflection counters since these combine good directional selectivity with a large working surface. A detector of this kind has a radiator in the form of a rectangular parallelopided. If the particle is in normal incidence to one (usually the largest) of the edges, the light cannot emerge from the radiator so long as the index of refraction satisfies the condition $n > \sqrt{2}$. The book presents curves which give the fraction of the light reflected in the radiator for diagonal incidence of particles with different velocities on one of the edges of the radiator. These curves characterize the threshold properties and directional selectivity of total-internal-reflection counters.

The sixth chapter ends with a section devoted to the choice of radiator materials and also contains numerous data necessary for the design of Cerenkov counters.

In the construction of Cerenkov counters ("thin" counters, focusing counters, etc.) it is desirable to have a material with a high index of refraction (this provides a high light yield), low light absorption, low density and low atomic number (to minimize scattering and energy losses), and low dispersion. However these requirements are not always compatible. Furthermore, it is necessary that the material be easily available, machineable, and non-fluorescent. The most widely used materials are plastics, such as the polymethyl mythacrylate resin known to us as Plexiglas (Perspex in England and Lucite in the U. S. A.). There are voluminous tables and curves showing the properties of different materials which are important for use in Cerenkov counters. These data include the index of refraction at different wave lengths for plastics, natural crystals, synthetic crystals, different kinds of glass, liquids and liquified gases and information on the spectral transparency of plastics and glasses. There is an extensive list of materials suitable for use in total-absorption spectrometers (heavy glasses, solutions of heavy salts, etc.), useful data on the reflection characteristics of different metallic surfaces used as reflectors, and data on other reflectors.

The seventh chapter is devoted to an analysis of the optical problems related to the construction of focusing and non-focusing counters. Focusing counters are considered first. Most focusing counters are fixed-focus devices. In these counters the focusing conditions are satisfied only at one value of the Cerenkov angle. In most of these counters, by an appropriate choice of radiator geometry the Cerenkov light is transformed into a parallel optical beam which is then focused by means of a lens. The focusing can also be accomplished by reflection or refraction, for example by means of a parabolic mirror. The first model proposed by Getting is shown together with a number of modified versions. The principles of operation of the achromatic counter, which has been analyzed by Frank, are also described.

More modern counters are variable-focus devices, with which it is possible to detect radiation emitted at different angles. In these devices spherical lenses or cylindrical mirrors are used in the optical system. Counters of this type were first suggested and studied by Marshall. The basic parameters of a focusing counter are the time resolution and the energy resolution. As is well known, the duration of the light flash at the cathode of the photomultiplier may be quite different from the duration of the emission flash itself because of the difference in transit time for light rays which travel over different paths. These problems are considered in detail only in connection with the use of achromatic counters.

The energy resolution of focusing counters depends on the properties of the beam (beam width, angular and energy spread of the particles) and the properties of the radiator (defraction, multiple scattering, dispersion or chromatic aberration, spherical aberration and slowing down of the particles).

The Cerenkov light emitted by a beam of particles of finite width cannot be focused to a point; the dimensions of the image can be computed on the basis of Abbe's sine law. The effect of defration and scattering is given in the third chapter. In this chapter there are simple formulas which can be used to estimate the effects on energy resolution due to scattering and dispersion. Methods which allow for compensation of the change in the emission angle as a result of slowing down of the particles are also considered.

The discussion of non-focusing counters is based on the work of Mando. Detectors of this type can be classified in three groups: those having specular reflecting walls, those having diffusing walls, and those which rely partly on specular reflection and partly on diffusion. Counters with specular reflection are very fast and have the "anti-directional property," i.e.,. they can distinguish between particles moving in opposite directions. However these advantages are accompanied by highly non-uniform light collection and low efficiency. Diffuse reflection counters, on the other hand, have high efficiency and good uniformity, but their time-resolution characteristics are poor and they do not have the anti-directional property.

The book considers only the diffuse reflection counter. The basic characteristic of this detector is the ratio of the intensity of the light collected at the photocathode to the intensity of the emitted light. This quantity is frequently called the optical efficiency of the detector. The dependence of optical efficiency on time determines the length of the light flash at the cathode of the photomultiplier. The formula given in the book for optical efficiency is obtained for a number of assumptions for the case of an integrating sphere. Nonetheless, the formula can be used to make estimates for a large number of practical cases.

Frequently so-called light pipes are used to transmit light from a radiator to the cathode of the photomultiplier. The use of the light pipes requires care since the low intensity of the Cerenkov radiation makes it necessary to use light pipes which have the maximum transmission coefficient. An important factor in the design of a light pipe may be the directivity of Cerenkov radiation. A number of materials used for light pipes in scintillation counters, for example, polystyrene, are weak scintillators. Light pipes for Cerenkov counters must therefore be made from quartz or plexiglas or must be hollow. Jelley points out the factors which must be considered is estimating the transmission efficiency of a light pipe. This efficiency is determined primarily by the fraction of the light flux which is "captured" in the light pipe, i. e. the flux that remains in the light pipe after the first reflection. This quantity can be easily estimated for the case in which the intensity is isotropic. The fraction of the light transmitted to the far end of the light pipe is estimated by a formula obtained by R. L. Garwin.

The concluding part of this chapter is devoted to the possibility of increasing the light yield of Cerenkov detectors in the visible region of the spectrum. For this purpose one can use fluorescent materials that absorb radiation in the ultraviolet part of the Cerenkov spectrum and emit in the region in which the photomultiplier is sensitive. Suitable materials, including POPOP (diphenylhexatriene) which have been widely used as scintillators, can be used in Cerenkov counters with liquid radiators. It is obvious that with the addition of such a "spectrum shifter" the detector loses the advantages associated with the directional characteristics of the Cerenkov emission.

The eighth chapter in Jelley's book is devoted to descriptions of various counters. In this section the author classifies the counters by applications.

Counters designed for accurate measurement of particle velocities are considered first. Mather has developed a photographic instrument for measurement of energies of protons in the external beam of the synchrocyclotron at Berkeley. This author has analyzed a number of the factors which enter into the resolving power of the instrument and has given methods for choosing the detector parameters (index of refraction and radiator thickness) to obtain high resolving power. When the instrument is used with a polystyrene shifter it can measure the energy of 340-Mev protons with an error of about 0.2% with a parallel beam. A disadvantage of this detector is the low sensitivity.

There is a description of a counter used by Marshall for recording charged π mesons. The resolution of the instrument (line width at half height) is approximately 13% at a π meson energy of 145 Mev.

There is also a description of a very simple detector used at the Carnegie Institute for studying proton-proton scattering. The resolution is approximately 8% at an energy of 435 Mev.

In the next section there is a description of a threshold detector used by Duerden and Hyams. As an example of a velocity selector there is a detector constructed by Chamberlain and Wiegand. This device was used in the experiments in which the antiproton was first detected. The operating range in these experiments was $0.75 < v/c < 0.78$. In the section devoted to total-absorption spectrometers most of the instruments of this kind which have been built in various laboratories are mentioned. These include a counter with a radiator made from lead glass, a thallous chloride single crystal, and carbon tetrachloride. The latter was saturated with a POPOP solution to enhance the light yield and to improve the resolution. With this counter it was possible to obtain a resolution (line width at half height) of 22% at an electron energy of 217 Mev. Apparently the most popular spectrometers use lead glass as a radiator although the resolution here is worse than the resolution of a CCl_4 counter. These instruments have been used to measure the Panofsky ratio (Cassels and Marshall), the Compton effect on protons (Yamagata), in research on antiproton interactions (Brabant), and other work.

The thin counter which is described was used by Linsley and Horwitz to determine the charge of cosmic ray particles and to measure the flux of α particles in the primary radiation.

Counters having the antidirectional property are illustrated by the instrument used by Winckler intended for measuring the cosmic-ray albedo at high altitudes. In the section on directional selectors there is a rather detailed description of the design and characteristics of the detector used by Mather and Martinelli. This instrument has been used for studying the production of π mesons in proton-proton collisions.

In the concluding section of this chapter there are data on high-energy neutron detectors.

Cerenkov counters in which gas is used as a radiator are considered in the tenth chapter, which is rather short. Up to this time gas counters have not been as widely explored as other kinds. It is to be expected, however, that when some of the large accelerators now under construction are put into operation gas counters may find wide application. The advantage of these counters is the fact that the refractive index can be varied over wide limits. Thus the emission threshold can be changed, and these counters can be used over a wide energy range. However, the intensity of the Cerenkov radiation in a gas is extremely small. For example, a relativistic electron in helium emits one photon per 37 cm of path under normal conditions. In this chapter there is a description of several gas counters which have been used to measure the intensity of bremsstrahlung with a maximum energy of 500 Mev, the detection of π mesons with energies of 3 Mev and others.

Cerenkov radiation in the atmosphere is considered in the ninth chapter of the book. This chapter is somewhat specialized as compared with most of the material in the book. A considerable part of this chapter is devoted to a presentation of the results of observations of Cerenkov radiation of cosmic-ray particles in the atmosphere. The work of the author occupies an important place in this research.

Our review of the book by Jelley has been rather long, to enable us to discuss a number of problems which are not considered in the book, but are related to it. It is hoped that the mention of these problems will give the reader a more complete understanding of the various questions related to Cerenkov radiation.

In our opinion, the basic value of the book lies in the fact that it represents the first systematic collection of the enormous amount of material on Cerenkov radiation which has been accumulated in recent years. This material is presented clearly and with consideration for its physical significance; moreover, the presentation features a number of good examples. The book contains a fairly exhaustive bibliography and the reader can consult the original literature for details, if so desired.

The difficult job which Jelley has undertaken--the responsible, and not always rewarding, problem of evaluating the work of a large number of workers in a rapidly developing field of physics--is deserving of the greatest recognition. A Russian translation of this book would be most desirable.

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