# ČERENKOV RADIATION

## And Its Applications

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*by*

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# ČERENKOV RADIATION AND ITS APPLICATIONS

# AUTHOR'S PREFACE

THE vast and rapid development of high energy nuclear physics in recent years has provided a great stimulus to research on new types of radiation detectors. But for this, and the advent of the photomultiplier, the subject of Čerenkov radiation might well have remained only of academic interest. The field itself occupies only a very restricted niche in modern physics; nevertheless it impinges on a wide range of topics, including not only nuclear physics but also optics, high frequency radio techniques, astrophysics and cosmic rays.

The development of the Čerenkov detector has followed closely on that of the scintillation counter, both being remarkable for their simplicity and sensitivity. Although the Čerenkov detector does not possess the versatility and precision of the scintillation counter, its unique properties have led to the development of an extremely useful instrument in the fields of high energy machine physics and cosmic-ray research.

As far as the author is aware, this is at the present time the only monograph devoted exclusively to the subject of Čerenkov radiation and its applications. In view of this the aim has been to present as complete an account of the whole field as is possible in a volume of this size.

On the theoretical side, the classical treatment of the normal Čerenkov effect in isotropic media is presented in detail, together with an account of the underlying physical basis of the phenomenon. For the many and varied special cases, for example anisotropic media and ferromagnetics, only the results however are presented; the mathematical treatments are often very lengthy and their inclusion would serve very little purpose.

The book has been written primarily for the experimentalist, but technical details of specific types of Čerenkov counters have purposely been restricted, since developments are rapidly taking place all the time, and present designs may well become obsolete within a few years. Emphasis has therefore been laid on the general properties and applications of counters of various types, with inclusion of sufficient technical data to allow the design to be worked out for an instrument for any particular purpose.

Special attention has been paid to the assembly of a complete bibliography on all aspects of the subject; this includes, in particular, most of the references to the considerable amount of theoretical work carried out in the U.S.S.R., and the very extensive developments and applications of the techniques to high energy problems centred around the large accelerators in the U.S.A.

The author would like to express his thanks to innumerable colleagues at Harwell with whom the individual chapters have been discussed, and he is grateful to Professor W. E. Burcham, F.R.S., of Birmingham University who has had the difficult task of reading the manuscript.

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CHAPTER 1

# INTRODUCTION

## 1.1 Historical

The very faint emissión of a bluish-white light from transparent substances, in the neighbourhood of strong radioactive sources, had been observed by many workers in the field of radioactivity prior to an understanding of its origin. Those who have read the life of Mme Curie (1941), may recall the account of how she found bottles of concentrated radium solutions aglow with this uncanny pale blue light. Her preoccupation with the much more significant discoveries in radioactivity no doubt stifled an investigation of the causes and nature of this luminescence. This was in 1910, twenty-four years before Frank and Tamm produced the correct explanation for the origin of this radiation. The early observations of Čerenkov radiation were made at a time when the electromagnetic theory of light had been well established and the study of optics and luminescence featured large in the field of physics. Thus, in principle, the theoretical interpretation of the effect might have appeared many years earlier than it did. The delay in the study of the phenomenon was due to a number of causes. For instance, at the time of these early observations, much work was going on in the systematic study of the fluorescence and phosphorescence of materials irradiated by ultra-violet light, x-rays and the newly discovered radiations from the radioactive elements. The diverse and relatively complicated phenomena associated with these forms of luminescence only helped to postpone the discovery of Čerenkov radiation; the latter in any case was so weak that it was frequently masked by the presence of these other effects. Nevertheless, it was through studies of fluorescence and phosphorescence that the work on Čerenkov radiation finally developed. The absence of really sensitive light detectors also contributed to the delay in the discovery of Čerenkov radiation; the early work had to be carried out either by visual observation or by photographic recording with long exposure.

The first deliberate attempt to study the phenomenon was made by Mallet (1926, 1928 and 1929) whose work has unjustly been either forgotten or ignored. He found that the light emitted from a wide variety of transparent bodies placed close to a radioactive source always had the same bluish-white quality, and that the spectrum was continuous, not possessing the line or band structure characteristic of fluorescence. He was the first to appreciate the generality of the effect and to notice that in a number of other respects also, it was very different from fluorescence and other known forms of luminescence. Unfortunately Mallet did not pursue the work, nor did he attempt to offer an explanation for the origin of the light. The subject then lay dormant until, in 1934, Čerenkov commenced an exhaustive series of experiments which he continued until 1938. These experiments were remarkable for their simplicity and for the excellent agreement between their results and the theory, which had in the meantime been proposed by Frank and Tamm, in 1937. Čerenkov appears to have been unaware of the earlier work of Mallet, though he too met the problem accidentally, through studies of fluorescence; his experiments covered a wider range than did those of Mallet. The next contribution was due to Ginsburg who in 1940 produced a quantum theory of the phenomenon which was henceforward known as Čerenkov radiation.

The war years caused a further lapse in research in the field, though at the same time they heralded the development of the photomultiplier. The advent of this remarkable instrument, the most sensitive light detector known, gave a great impetus to the subject, which has since been growing at an ever increasing rate. It was the development of this same instrument that allowed Curran and Baker in 1944 to devise the first form of the modern scintillation counter. The latter has proved to be an extremely versatile tool in studies of nuclear and cosmic-ray physics; the Čerenkov counter, having less numerous applications, has developed more slowly but is becoming increasingly important, for its most significant applications lie in the high energy field, where so much progress is now being made. The development of ever larger accelerating machines places an increasing demand on instruments for the measurement of beams of particles of very high energies and intensities.

Returning to the historical survey, the first proposal to use a photomultiplier and a simple optical system for detecting single particles by the Čerenkov effect, was made by Getting (1947). After an unsuccessful attempt by Dicke (1947) to detect cosmic-rays by this means, and some experiments of Weisz and Anderson (1947) who observed small effects with light-sensitive Geiger counters, it was Jelley (1951) who first detected single fast charged particles with high efficiency, using distilled water and a photomultiplier. Almost immediately, Mather (1951) and Marshall (1951) published accounts of the first Čerenkov detectors to be used for the direct measurement of particle velocities, in beams from high energy accelerators. Since 1951 there has been a steady increase in the number of practical applications of the Čerenkov counter to nuclear and cosmic-ray physics. These are now too numerous for individual mention in this introductory review, but perhaps special reference should be made here to the first detection of Čerenkov radiation in a gas by Ascoli in 1953, the observation of light pulses from the night sky by Galbraith and Jelley, also in 1953, and, more recently, the vital rôle of the Čerenkov detector in the discovery of the anti-proton by Chamberlain *et al.* in 1955.

On the theoretical side considerable interest has been shown by Fermi and others (1940) in the effects on the specific ionization produced by fast particles in dense media, produced by the local polarization associated with the Čerenkov effect. Čerenkov radiation was suggested by Ginsburg (1947) as a possible source of microwaves, and its relationship with other physical processes has also been widely discussed. Other problems investigated include studies of Čerenkov radiation in anisotropic media and in ferromagnetics, the radiation produced by electric and magnetic dipoles, and modifications introduced by the quantum theory. The ultimate resolution of the focusing type of counter has been worked out in terms of the effects produced by scattering, diffraction and dispersion.

### 1.2 Descriptive account of the Čerenkov effect

While the complete mathematical theory is presented in Chapter 2, it is nevertheless appropriate at this point to explain the basic principles of the effect in a qualitative manner. This should enable the reader to appreciate more fully the interpretation of the early experiments which are described in the next sections.

Suppose an electron to be moving relatively slowly through a piece of glass or other transparent medium. Fig. 1.1(a) shows a section of the glass in the vicinity of the track *AB* of this electron, the circles representing the individual atoms composing the glass. Normally these will be roughly spherical in shape, and undistorted. However, in the region close to the passing electron, which at a particular instant in time is for instance at the point *P*, the electric field of the particle distorts the atoms so that the negative charges of the electrons are displaced to one side of the heavier positive charges of the nuclei of these atoms. The medium thus becomes polarized about the point $P$. When now the electron moves on to another point, say $P'$, the elongated atoms around $P$ return to their normal shape. While the atoms are distorted they behave like elementary dipoles, with the negative poles pointing away from the track if the passing particle is a negative electron, or vice versa for a positron or proton. Thus, as the particle passes through the medium, each elemental region of the glass along the track will in turn receive a very brief electromagnetic pulse. Owing to the complete symmetry of

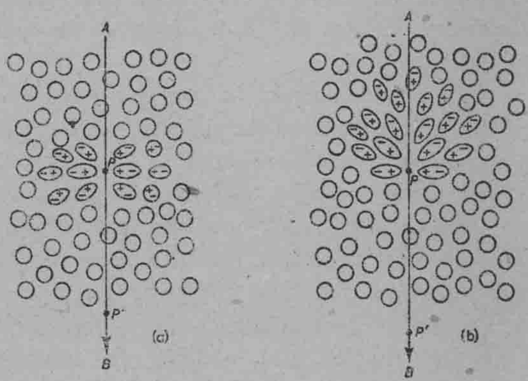


FIG. 1.1. The polarization set up in a dielectric by the passage of a charged particle. (a) At low velocity. (b) At high velocity.

the polarization field surrounding the electron, there will be no resultant field at large distances and therefore no radiation. There is symmetry both in azimuth and along the axis, in this case.

If however the electron is moving fast, that is at a speed comparable to that of light in the medium, the picture is quite different (see Fig. 1.1b). In this case the polarization field is no longer completely symmetrical. In the azimuthal plane, symmetry is preserved, but along the axis there is a resultant dipole field which will be apparent even at large distances from the track of the electron. Such a field will be momentarily set up by the electron at each element along the track in turn, each element then radiating a brief electromagnetic pulse. The radiation will be spread over a band of frequencies corresponding to the various Fourier components of this pulse.

In the general case, the radiated wavelets from all parts of the track interfere destructively so that, at a distant point, the resultant field intensity is still zero. However, if the velocity of the particle is higher than the phase velocity of the light in the medium, it is possible for the wavelets from all portions of the track to be in phase with one another so that, at a distant point of observation, there is now a resultant field. It will be understood from the Huygens construction shown in Fig. 1.2 that this radiation is only observed at a particular angle $\theta$ with

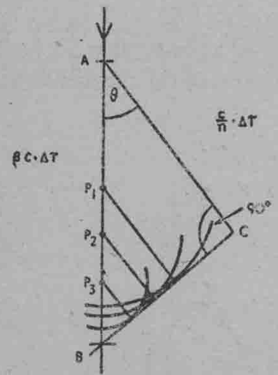


FIG. 1.2. Huygens construction to illustrate coherence.

respect to the track of the particle, namely that angle at which the wavelets from arbitrary points such as $P_1$, $P_2$ and $P_3$ on the track $AB$ are coherent and combine to form a plane wave front $BC$. This coherence takes place when the particle traverses $AB$ in the same time that the light travels from $A$ to $C$. If the velocity of the particle is $\beta c$ where $c$ is the velocity of light *in vacuo* and $n$ the refractive index of the medium, in a time $\Delta\tau$ the particle will travel a distance $AB = \beta c \cdot \Delta\tau$, and the light a distance $AC = \Delta\tau \cdot (c/n)$. From this we obtain:

$$\boxed{\cos\theta = \frac{1}{\beta n}} \tag{1.1}$$

which is known as the "Čerenkov relation".

It is seen that:

(i) For a medium of given refractive index $n$, there is a threshold velocity $\beta_{\min} = (1/n)$, below which no radiation takes place.

At this critical velocity the direction of radiation coincides with that of the particle.

(ii) For an ultra-relativistic particle, for which $\beta = 1$, there is a maximum angle of emission, given by $\theta_{max} = \cos^{-1}(1/n)$.

(iii) The radiation occurs mainly in the visible and near-visible regions of the spectrum, for which $n > 1$. Emission in the X-ray region is impossible for $n$ is then less than unity and (1.1) cannot be satisfied.

Figure 1.2 has been drawn in one plane only. There is of course complete symmetry about the axis of the particle. The light originating from

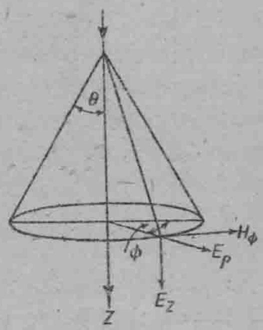


**Fig. 1.3. The formation of the Čerenkov cone, and the polarization vectors.**

each element of track is propagated along the surface of a cone whose apex is at this element, whose axis coincides with the track, and whose semi-vertical angle is the angle $\theta$ (see Fig. 1.3). The distribution in $\theta$ of the light intensity approximates to a $\delta$-function, and the polarization is such that the electric vector $E$ is everywhere perpendicular to the surface of the cone, and the magnetic vector $H$ tangential to this surface.

From what has already been said, it will be seen that the phenomenon is in some ways analogous to the V-shaped shock wave observed in acoustics when a projectile travels through the air at a velocity in excess of the speed of sound, the quantity $\beta n$ taking the place of the Mach number in aerodynamics. A more familiar case is that of the formation of a bow wave from a ship moving through water when its speed is greater than that of surface waves on the water.

Returning to the optical case, it will be realized that there are two further conditions to be fulfilled to achieve coherence, in addition to that stated in (i). First, the length $l$ of the track of the particle in the medium shall be large compared with the wavelength $\lambda$ of the radiation in question, otherwise diffraction effects will become dominant and the light distributed over an angle $\delta\theta \sim \lambda/l \sin\theta$, instead of appearing at only one angle $\theta$ as in (1.1). Secondly, the velocity of the particle must be constant during its passage through the medium, or, to be more specific, the differences in the times for the particle to traverse successive distances $\lambda$ shall be small compared with the period $(\lambda/c)$ of the emitted wave.

In anticipation of section 3.10 in Chapter 3, it is appropriate here to emphasize that this radiation phenomenon should not be confused with either recombination or excitation radiation associated with ionization caused by the particle. Neither should it be confused with Bremsstrahlung, which is an acceleration radiation produced if the particle enters the sphere of influence of the electrostatic field of an atomic nucleus.

### 1.3 The early observations of Mallet

Mallet describes his first observations in a paper in 1926 entitled "Luminescence de l'eau et des substances organiques soumises au rayonnement $\gamma$". In his first experiment he immersed a 30 mg radium source of $\gamma$-rays in distilled water which was placed in a wooden container to eliminate possible luminescence of the latter. He found that the light was bluish-white and that its total intensity increased as the depth of water was raised to 10 cm, suggesting that there was little or no self absorption of the light. The same effect occurred if the $\gamma$-ray source was outside the water, and running water was found to behave in the same way as still water. He then succeeded in taking a photograph of the light with the source 15 cm away, obtaining an intense blackening after 17 hr exposure, while the darkening from the direct action of the $\gamma$-radiation was five or six times weaker. It was also shown that 1 mm glass was more absorbing to the radiation than 5 mm quartz or 5 mm of albumen. The significance of this experiment was that most of the radiation was evidently of short wavelength.

In his second paper, in 1928, Mallet described his first attempt to analyse the spectrum of the radiation, to see if it had a line or band structure like that associated with fluorescence. His spectrograph, designed by Fabry, consisted of a collimator having an aperture of 54 mm at f/2·0 and two 30° flint glass prisms. Using two radium sources each of strength 250 mg, he obtained spectra from water and carbon disulphide after exposures lasting for between two and four days. He was the first to find that the spectrum was continuous and extended to 3700 Å, the cut-off imposed by the apparatus. He continued the spectrographic work and published a third paper in 1929. With a new spectrograph having quartz lenses and two hollow quartz prisms, each of angle 45° and filled with water, he obtained spectra with a dispersion of 22 mm on the plate, between wavelength limits of 2400–4360 Å. In these last experiments he used a 250 mg RaE source, and required between four to eight days to obtain adequate exposures for the light from water and carbon disulphide.

Mallet did not observe the asymmetry in the angular distribution of the light with respect to the exciting radiation, discussed in section 1.2, and made no attempt to study its polarization.

### 1.4 Čerenkov's original experiments

In 1934 Čerenkov first noticed a very weak visible radiation from pure liquids under the influence of $\gamma$-rays. A study of a variety of liquids led him to the conclusion, unaware as he was of Mallet's earlier work, that this was a phenomenon of a different nature from that of fluorescence. Since most of his early experiments were carried out visually, he had to use $\gamma$-ray sources of a strength which, on present standards of tolerance dosage, was very high. Since the accounts of the early experiments are not easily accessible to many readers, they will be described in some detail.

In his first experiment Čerenkov used the very simple apparatus shown in Fig. 1.4. A small phial containing 104 mg of radium was inserted at position $R_1$ in a wooden block $B$ in which stood a platinum crucible $A$. The liquid under investigation was placed in $A$ above the radium source. By means of the optical system consisting of the collimator $L_1$, reflecting prism $P$ and telescope $L_2L_3$, it was possible to observe at $E$ the faint glow in the liquid near the source. The field of view was defined by the diaphragm $D$; other elements of the optical system were a graded wedge $W$, used to measure relative intensities, filters $F$ of different colours, for crude spectral analysis, and a Nicol prism $N$ used for investigating the polarization of the radiation. With the eye accommo-