CERENKOV RADIATION

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At the International Conference in Geneva last summer on the Peaceful Uses of Atomic Energy, one of the exhibits which attracted most interest was the so-called “swimming-pool” reactor, on show from the United States. When this reactor was working, even at quite low power levels, one could see the water in which the reactor was immersed was continuously emitting an intense bluish-white light. This light, which is known as Cerenkov radiation, arises through the passage of fast moving electrons from the core of the reactor (or pile) through a dielectric medium, in this case water. It is perhaps as a result of this exhibit that many people have for the first time met the phenomenon of Cerenkov radiation. All radioactive sources emitting fast electrons or γ-rays produce this radiation in transparent media, though in most cases the light is far too weak to be seen with the unaided eye. However, in the case of a reactor containing water, which itself serves to screen the observer from the dangerous activities of the pile, the level of radiation is so high that the accompanying light is bright enough to see. Although the amount of light may be new to most readers, it has been known to physicists since the beginning of the century. Its interpretation, however, came not until many years later, in 1937. Let us now trace historically how the effect was first observed and how physicists arrived at a satisfactory explanation of its origin.

Those who have read the life of Madame Curie may remember the great excitement she and her husband experienced when they entered their laboratory in the dark at night, noticing that their bottles of concentrated radium solutions were always aglow with an uncanny blue light. Their preoccupation with the much more important discoveries in radioactivity probably prevented their investigating the causes and nature of this luminescence. No doubt many other workers in the field of radioactivity in the early days had also noticed this curious glow of transparent solids and liquids in the proximity of strong radioactive sources. It began to be realised that the phenomenon was of a nature different from that of the true fluorescence, which is known to occur, for example, when certain crystalline materials such as zinc sulphide, calcium tungstate, and various salts of uranium are irradiated by the “rays” emitted from radioactive bodies. A Frenchman by the name of Mallet appears to have been the first to investigate the new phenomenon carefully, concentrating on studies of the spectrum of the radiation. Mallet, whose work was carried out between 1926 and 1929, found that the light emitted from a wide variety of transparent bodies close to a radioactive source always had the same bluish-white characteristic of fluorescence. He used such diverse media as ice, water (both still and flowing), alcohol, carbon disulphide, oils, and albumen, among others. Unfortunately Mallet did not pursue the work, neither did he attempt to offer an explanation for the origin of the light.

CERENKOV’S INVESTIGATIONS

It was five years later, in 1934, that the Russian physicist Cerenkov, at the Physical Institute of the Academy of Sciences in Moscow, started an exhaustive study of the phenomenon. He continued the work for a period of about four years. Cerenkov appears to have been unaware of the earlier work of Mallet, though it is true that he met the problem accidentally, through studies of fluorescence. Cerenkov’s experiments covered a wider range than Mallet’s; first he measured the relative intensities of the light from different pure liquids, confirming that the spectra had no colour bands. Moreover, he then found that, unlike normal fluorescence, the intensity did not depend on the temperature nor could the light be quenched by adding impurities to the medium. Cerenkov’s more significant discoveries, however, were that the light had unique polarisation properties and, most important of all, that its emission was markedly directional. The light travelled out along the surface of a cone, the axis of which coincided with the direction of the radiation, while the angle of the cone appeared to depend on the energy of the exciting particles. Cerenkov offered no explanation of this strange light, a process quite new in the field of optics. wavilow proposed the theory that perhaps it was a form of radiation associated with the slowing down of the electrons from the radioactive source, akin to the production of the continuous x-ray spectrum when fast electrons impinge on the target of an x-ray tube. There were, however, several objections to this theory, and it was not until 1937 that the Russian theoreticians Frank and Tamm, also at the Institute in Moscow, worked out the correct interpretation of the effect in terms of the classical electromagnetic theory of light.

It is convenient at this stage to state in simple terms precisely what Cerenkov radiation is and when it occurs. In Frank and Tamm’s own words, “an electron moving in a medium radiates light if it is moving uniformly, provided that its velocity is greater than the velocity of light in the medium”. The effect is then a direct optical analogue of the supersonic bang from an aircraft moving faster than the velocity of sound in air.

HOW THE PHENOMENON ArISES

How does the phenomenon arise? Let us suppose we have an electron moving swiftly through a piece of glass (or any other transparent medium). Fig. 1 shows a highly magnified section of the glass in the vicinity of the track AB of the electron, where the circles represent the individual atoms composing the glass. In general they 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
wave transmitting aerial. In this case, however, frequencies of the oscillations correspond to waves in the optical region of the spectrum.

This is not, however, the complete story, for we have considered only the radiation from a single element of the track. At a point far away compared with the spacing of the atoms, it is the radiation from the whole track that has to be considered, since the wavelets from all the separate elements will interfere with each other depending on their relative phases. In the general case when the particle is not fast enough, the radiation from each element of track is in fact cancelled by that of some neighbouring element. However, if the particle is moving fast enough, the wavelets all add up in phase (called coherence in optics) and the track radiates as a whole, along a wavefront inclined at one particular angle with respect to the track.

The condition for this coherence is quite similar to that arrived at by reference to Fig. 2(a). Suppose an electron traverses a thin slab of glass from A to B at a velocity \( \beta c \), where \( c \) is the velocity of light in free space and \( \beta \) is the ratio of the velocity of the particle to that of light and is always less than unity. It is easily seen that if \( \theta \) is only one angle \( \theta \) at which the light can be emitted, namely that for which the wavelets from individual elements of track, such as \( P_1, P_2, P_n \), are in phase. This will occur when it takes the same time \( \Delta t \) for the particle to go from A to B as it takes the light to go from A to C. For the particle, \( \Delta t = \beta \Delta x / AB \), and for light \( \Delta t = (c/n) \times AC \) since the velocity of light is \( (c/n) \) in the glass, where \( n \) is its refractive index. From the conditions, it is seen that there is a very simple relation between the angle \( \theta \), the speed of the particle \( \beta \), and the refractive index. This relation, known as the "Cerenkov relation", is:

\[
\cos \theta = \frac{AC}{AB} = \frac{1}{\beta n}
\]

From this simple equation are derived two general conditions, imposed by the fact that \( \cos \theta \) can only vary between the value 0 and 1. There is a threshold condition such that when \( \theta = 0 \), \( \beta \sin \theta = 1/n \) so that electron going more slowly than \( (c/n) \) will produce no light at all. There is also a condition for the maximum angle of light emission, when the speed of the particle is very close to that of light; i.e. when \( \beta \rightarrow 1 \), the angle \( \beta \cos \theta \rightarrow \sin \theta \).

Fig. 2(a) was only drawn in one plane. In practice the light is emitted on the surface of a cone as shown. Fig. 2(b), the angle \( \theta \) now being the semi-apex angle of the cone. The light is polarised in such a way that the electric vector \( E \) is everywhere perpendicular to the surface of the cone and the magnetic vector \( H \) tangent to the surface. The light, which has a spectral distribution inversely proportional to the cube of the wavelength, is thus much more intense in the blue, near wavelengths, than in the red, long wavelengths. The intensity of the radiation is extremely weak, amounting to only about \( 4 \times 10^{-19} \) erg for an ultra-fast electron plunging through a depth of 1 centimetre of water. The figure for the light intensity is based on a spectral region...
In this case, however, the waves correspond to wavelengths in the ultraviolet spectrum.

The complete story, for a single electron, is as follows. The radiation from the wavelets is polarized, since the wavelets are emitted in phase. In the general case, the radiation from a particle is in fact cancelled by that from virtual particles. However, if the particle is sufficiently fast, and the wavelets all add up in phase (Fig. 2(b)) and the track radiates in a plane inclined at one particle lifetime, the coherence is quite simple. Fig. 2(a). Suppose an electron moves from A to B at a velocity of light in free space which is much less than the velocity of the particle to that of light. It is easily seen that the effective wave length which the light can be emitted is the same as the wave length of the light from individual wavelets. The sum of the waves from individual wavelets, if taken at the same time for the particle and the light, takes the light to go faster, and the sum of the waves from individual wavelets is in phase, and the velocity of light is the refractive index. From the velocity of light, there is a very simple relation between the speed of the particle and the speed of light. This relation, known as the Euler relation, is

\[
\frac{AC}{AB} = \frac{1}{\beta n}
\]

in the case of two parallel planes. There is no threshold condition, and the angle is always 1/n, so that electrons with energy \( (k/n) \) will produce no light. The maximum angle is fixed, but the speed of the particle is not. When \( \beta \to 1 \), the light is not produced.

The Cerenkov radiation is produced by charged particles moving in uniform magnetic fields. It is emitted in a cone with an apex angle related to the velocity of the particle. The radiation is intense in the blue, and is not produced when \( \beta \to 1 \).
In this case, however, the wavelets do not correspond to wavelengths in the usual sense.

For an electron moving with velocity "v" at right angles to the radiation from the wavelets, since the wavelets from all points of the radiation will still interfere with each other in phases. In the general case, however, if the particle velocity is not large enough, the radiation from the wavelets all add up in phase and the track radiates as if it were inclined at an angle of 90°.

Coherence is quite simple. Suppose an electron moves from A to B at a velocity of light in free space while the particle to that of light in glass. It is easily seen that the wavelets from individual points of the particle to that of light in glass. At the same time, the velocity of light is (c/n) in the medium. From the relation known as Snell's law,

\[ \frac{AC}{AB} = \frac{1}{\beta n} \]

there are derived two speeds at which the light can be propagated in one plane. In practice, the surface of a cone as shown in the diagram being the semi-apex angle of the cone is formed in such a way that it is everywhere perpendicular to the magnetic field. The magnetic vector H tangent to the cone which has a spectral distribution to the cube of the wave number is intense in the blue, shorter, long wavelengths. This is extremely weak, amounting for an ultra-fast electron to a few electrons per 1 centimetre of water: this is based on a spectral region at a critical angle of 90°.

Cerenkov Radiation as seen in the U.S. Swimming-pool reactor. The radiation shows as a ghostly blue light, and does not resemble fluorescence. (Reproduced by kind permission of the U.S.A.E.C.)
from violet to orange, that is, from 4000 to 6000 Ångstroms wavelength. For those familiar with the concept of quanta it amounts to about 100 photons/cm. of track. In water, for example, for which the refractive index is 1.33, the threshold energy for electrons is 260 keV. If the electrons have an energy of 500 keV, the light is emitted at an angle of $\theta = 31^\circ$ and the radiation output is about $3.8 \times 10^{-10}$ ergs (or 95 photons) per cm. path. At very much higher energies, for which we get $4 \times 10^{-10}$ ergs/cm., the cone angle increases to its maximum value of $\theta_{\text{max.}} = 41^\circ$.

It should be emphasised that in terms of energy loss, the amount going into the form of Cerenkov light is only a very small fraction of the energy lost by ionisation, in fact about 0.5%. It is also important to realise that the distortion of the atoms is really very small, quite inadequate to excite or ionise them: the light, therefore, is not to be confused with that which may also be associated with the ionisation itself. In most pure solids and liquids, however, the light associated with ionisation is quite negligible compared with the Cerenkov radiation, as it also is in the case of air at atmospheric pressure. The light of the Aurora is, however, an example of light produced by ionisation. The Aurora is excited by slow protons from the sun. Their low velocity, combined with the extremely small refractive index of air at great altitudes, precludes Cerenkov radiation from taking place; the low air pressure at these altitudes is, at the same time, favourable for the generation of light by ionisation.

**APPLICATIONS OF THE RADIATION**

Having discussed at some length the underlying principles of Cerenkov radiation we will now turn to some of its diverse and very useful applications, particularly in the fields of nuclear physics and cosmic-rays. Cerenkov radiation has been used as the basis for new types of detectors and counters for fast particles, and it is these applications that have brought its study to the fore in the last few years. Radiation detectors based on the Cerenkov effect usually employ photomultipliers to detect the very weak pulses of light, though occasionally used with sufficiently intense beams of particles, photographic recording of the light is possible. It was the rapid development of the photomultiplier tube that gave the new impetus to work on Cerenkov radiation, as indeed it also gave to the development of the Scintillation counter. The photomultiplier is by far the most sensitive light detector known and can detect single photons with an efficiency approaching 20% for some tubes. In order to appreciate the range of possible applications, let us see what properties Cerenkov detectors will possess, from the simple description of the process outlined above.

Cerenkov counters can be used as threshold detectors that is, detectors which will record only those particles passing through them for which the velocity, and therefore energy, exceed a certain critical value, as already mentioned. Thus it is possible to count single fast particles against a very intense background of much slower particles. A corollary to this property is the ability to select particles of a given mass, provided their energy is known, since the latter is given by $\frac{1}{2}mv^2$ where $m$ and $v$ are the mass and velocity of the particles. An example of the use of such a detector as a threshold counter is that selecting the few cosmic-ray protons in a sea-level against the high background of mesons and electrons, the protons moving too slowly to produce Cerenkov light. Dr. Duerden and Dr. Hyams at Manchester University first carried out such experiments with a simple water detector, selecting those particles known to have passed through the detector but which did not give a pulse from it. Cerenkov detectors special design played an important role in the recent exciting discovery of the negative proton at Berkeley, California, the threshold feature of the instrument serving to select particles of the right mass since the velocity was measured by other means. The essential features of these great discoveries have already been discussed in an article in these pages by Prof. O. R. Frisch of the Cavendish Laboratory, Cambridge (Discoveries December 1955, p. 498).
The formation of the wavefront in Cerenkov light can illustrate the formation of light, and the disposition of the factors of the electromagnetic wave.

![Diagram of Cerenkov effect](image)

The photographic Cerenkov detector of Mather's, used to measure the energies of protons from a large synchrocyclotron in California.

We have so far only mentioned applications for which it is required to know that the velocity of the particle is above or below the threshold value; however, it is possible to measure accurately the velocity of the particles in certain cases, in an energy region in which $\theta$ is varying rapidly with $\beta$. Dr Mather, at the University of California Radiation Laboratory, used a very simple but elegant photographic instrument to measure the energy of the external beam of protons from the synchrocyclotron there. The essential features of this instrument are shown in Fig. 3. The Cerenkov radiation is produced in a thin sheet of glass, 0.67 millimetre thick, tilted at such an angle that a very small portion of the cone of light strikes the back of the glass at normal incidence; this light is then reflected back through the glass, since its rear surface is aluminised, and enters a Leica camera via a small prism. After fairly long exposures, of the order of minutes, a small arc-shaped image appears on the recording film. The purpose of the prism is to cancel dispersion inherent in Cerenkov radiation. Proton energies can thus be measured to an accuracy of about $\pm 1\%$ with this instrument.

Many versions of Cerenkov counter have been made for measuring the velocities of protons and $\pi$-mesons produced by the large nuclear physics machines; most of these use photomultipliers rather than photographic recording. Dr J. Marshall of the University of Chicago was one of the first to develop suitable forms of counter for this purpose.

Another use of Cerenkov counters depends on the directional property of the light. It was through this that the author first detected in 1951 single cosmic-ray particles by the Cerenkov effect. He used a detector of the simplest type, consisting of a cylindrical container 20 centimetres long, filled with distilled water, mounted above a photomultiplier. It worked on cosmic-ray $\mu$-mesons which come downwards from the atmosphere and produce a few counts per minute. When the whole apparatus was turned upside down the counts almost disappeared, since the light cone could no longer reach the photomultiplier. Counters of this type have been flown with balloons by Winckler in America to heights of over 100,000 feet, to measure the cosmic-ray "albedo", that is, the proportion of fast particles at high altitudes travelling upwards to those travelling downwards.

Recently some experiments of quite a different nature have been carried out by Dr Galbraith and the writer at the Atomic Energy Research Establishment at Harwell, in which they have studied light flashes from the night-sky associated with showers of high-energy cosmic-ray electrons in the atmosphere. In this application of Cerenkov radiation, no special counters are used since the atmosphere itself is the light producing medium. That faint light should be produced at night in this way was predicted by Prof. Blackett in 1948, but it was not until 1952 that these light flashes were first discovered by us. For this work which can only be carried out on clear, moonless nights, we used a simple reflecting telescope consisting of a parabolic mirror 10 inches in diameter at the focus of which was placed the photosensitive surface of a photomultiplier, see Fig. 4. The first apparatus was mounted in a domestic dustbin which
acted as a light screen. The light pulses are extremely short, of duration probably of the order of $10^{-8}$ seconds, and arrive at a rate of few per minute. The electron showers with which the light is associated, are detected by Geiger counters placed on the ground around the light receiver. We continued this work at the Pic du Midi Observatory in France in 1953, where we were aided by the much greater clarity of the atmosphere.

To summarise, we have seen that Čerenkov radiation, though a small aspect of physics, has unique features whereby it has become a powerful tool of the nuclear and cosmic-ray physicists.

**READING LIST**

For further general reading see, for example, the review article by the writer, in "Progress in Nuclear Physics", 1953.

**UNIVERSITY COURSE ON SPACE TRAVEL**

The Extra-Mural Department of Manchester University has been enterprise enough to organise what is probably the first University Course on Space Travel. This University Extension Course of seven lectures took place from January 16 to February 27. J. Ring, Lecturer in Physics, spoke on "Space Travel in Fact and Fiction"; and F. G. Kahn, Lecturer in Astronomy, followed with a lecture entitled "Beyond the Earth's Atmosphere", designed to give a picture of the Universe, the extent of space, the nearest bodies in our own galaxy, and the possible objectives of space travel from the Earth. The third lecture was by J. H. Gerard, Lecturer in Mechanics of Fluids, on "Aerodynamics and the Possibilities of Flights through Outer Space"; and the fourth, again by J. Ring, was on the "Necessity for Artificial Satellites and the Problem of Interstellar Navigation", including a discussion of fuel, food, water, and other needs. Lecture 5, by Z. Kopal, Professor of Astronomy, and lecture 6, by J. G. Blower, Lecturer in Zoology, were on "Physical Considerations of Space Travel", and described the conditions which might be expected on our neighbouring planets, our ability to exist there, the effect of radiation on cells, and the effect of cosmic radiation as known on the Earth's surface, together with a discussion on what might be the effect on the human body when travelling in outer space without the protection of the atmosphere. J. Ring concluded the series with a general discussion of the objects and purposes of space travel and its possible benefits to the human race, under the general heading, "What do we do when we get there?"

The following books were recommended for the course: Burger, "Rockets and Space Flight"; Brown, "Frontier to Space"; Boyd and Sarnoff, "Rocket Explorations of the Upper Atmosphere"; Newell, "High Altitude Rocket Research"; G. F. Weigley, "Between the Planets"; Eddington, "The Expanding Universe"; Oosterhoff, "High-Speed Flight"; White, "The Earth, Moon, and Planets"; Russell, "The Solar System and the Origin of the Earth"; Jones, "Life on other Worlds"; Kalin, "Genetics" (Pelican Science News No. 2 (Pelican)) and "Between the Planets"; and, of course, the enthusiasm was such that questions continued well after the formal scheduled for the end of the lecture.