The Discovery of Cherenkov Radiation

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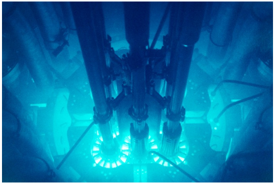


Cherenkov's Scientific Beginnings

- Pavel Alekseevich Cherenkov began postgraduate studies at the Institute for Physics and Mathematics in Leningrad in 1930, and began working under direct supervision of Sergei Ivanovich Vavilov in 1932
  - This institute was transformed into the Lebedev Institute in Moscow in 1934, with Vavilov as director
- Cherenkov chose to study the luminescence of uranyl salt solutions under the gamma-ray radiation of radium

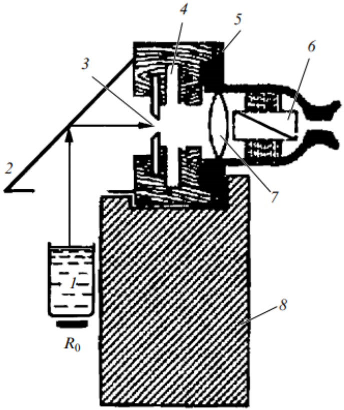
Fig. 1. Vavilov (left); Cherenkov, 1931 (right).

Investigating Luminescence

- Lumniscence is a weak glow caused when molecules are excited by some external source and then release light when decaying back to their ground state after some finite time
- This glow is weak, close to the human visibility threshold, and photomultipliers had not yet been developed
- Vavilov and Brumberg had developed the optical wedge method to quantify this glow, featuring the human eye has the measuring instrument

The Experimental Setup

- Vessel 1 contains the salt solutions under study, with slots for radium samples to be inserted below and to the side
- A Glan prism at 6 is used to measure polarization
- An optical wedge (opaque on one side and transparent on the other) is inserted into 4, moving perpendicular to this figure's plane, to absorb some portion of the light



The Experimental Procedure

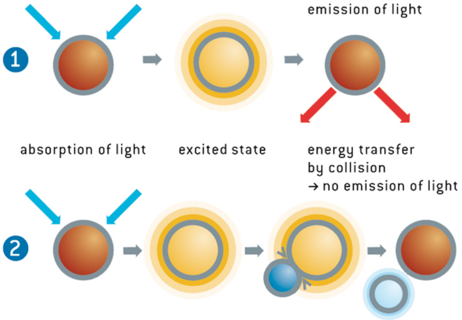
- The observer (Cherenkov) prepares by sitting in the completely dark room for 1-1.5 hours to attain maximum eye sensitivity
- The intensity of the glow is measured by moving the optical wedge until the light is no longer visible
  - The position of the wedge (corresponding to the amount of light it absorbs) is used as the measurement
  - The observer must be very consistent with their eye's sensitivity!
- An assistant maneuvers the wedge to avoid experimenter bias

A Strange Finding

- In 1933, Cherenkov happened to do a test with a pure solvent in the vessel, sulfuric acid
- He observed a glow of comparable intensity to the uranyl salt solution in the same sulfuric acid
- Vavilov suggested investigating other solvents as well, to see if this background was due to some contamination
- Cherenkov observed the same glow intensity for every solvent he tried, including thrice-distilled water

Investigating More

- Vavilov suggested using some standard techniques for luminescence investigation he had helped develop
- Adding quenchers and varying the temperature of a solution can suppress luminescence, as the excited state energy can be lost through collisions before it decays back to ground state



Investigating More

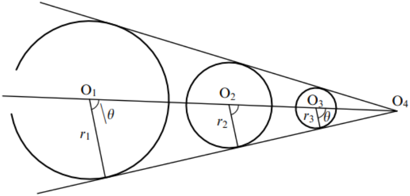
- Temperature variation and addition of large amounts of quenchers both had no notable effect on the observed glow in pure solvents
  - ⇒ The glow must be a prompt emission compared to normal luminescence time scales
- The light was mostly polarized parallel to the gamma-ray direction
- Measurements with color filters showed the light was mostly blue
- These results were published in 1934, with Vavilov postulating the glow was due to bremsstrahlung of electrons

Beginnings of the Theory

- Further experiments with a β source confirmed the effect was caused by the electrons
- A measurement with the vessel under a magnetic field showed the light's polarization direction and intensity both changed with the magnetic field
  - ⇒ The light is highly directional, related somehow to the electrons' motion
- Ilya Frank, who had assisted Cherenkov with some of the measurements, mentioned this directionality to Igor Tamm

The Theory

- Tamm immediately remarked that there must be coherent emission over the electron path comparable to the wavelength of the light wave
  - The angular spread of radiation has order of magnitude given by $\Delta\phi = \frac{\lambda}{L}$
- This inspired Frank's development of a qualitative model using the Huygens principle
  - This explained the directionality of the light by predicting a conical emission given by $\cos\theta = \frac{c}{nv}$



Developing the Theory

- Tamm and Frank fully developed this theory using Maxwell's Equations and submitted the paper in early 1937
- Direction of the radiation given by

$$\cos\theta = \frac{c}{n(\omega)v}$$

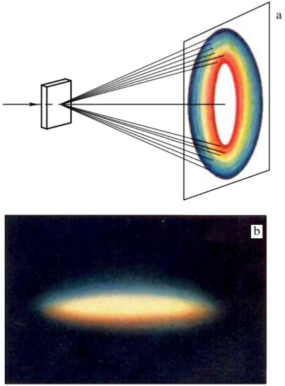
- Intensity given by

$$I(\omega)d\omega = v\frac{e^2}{c^2}[1 - \frac{c^2}{v^2 n^2(\omega)}\omega d\omega]$$

- These relations give rise to the condition that the radiation only occurs for $v > \frac{c}{n(\omega)}$

Cherenkov Radiation's Angular Spread

- An aside: later on, in the 1950s V P Zrelov did a clean demonstration of the $\cos\theta = \frac{c}{n(\omega)v}$ relation using a proton beam and photographic film



Confirming the Theory

- In 1937 Cherenkov performed additional measurements that matched the Frank-Tamm theory's predictions
- These results were submitted to *Nature* and rejected, but were published in *Physical Review*
- The existence of Cherenkov radiation was confirmed a year later by American physicists Collins and Reiling, using accelerator electrons, although they seemed to reject Frank and Tamm's theory
  - They wrote "Electrons constantly lose energy as they pass through a medium. The resultant acceleration is responsible for Cherenkov's radiation."
  - Collins and Reiling also established the term "Cherenkov Radiation", though some in Russia call it "Vavilov-Cherenkov Radiation"

Afterword

- Despite the difficulty of human eye-based measurements, none of Cherenkov's work was found to be in error by any later measurements
- Vavilov, Cherenkov, Frank, and Tamm all received the Stalin Prize of First Degree in 1946 for this work
- Tamm, Frank, and Cherenkov were awarded the Nobel Prize in 1958 "for the discovery and the interpretation of the Cherenkov effect"

Prior Work

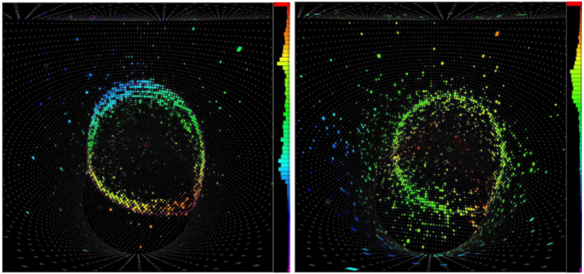
- On the experimental side: in 1910 Marie Curie noticed blue glows from vials with concentrated radium, but paid no special attention to them
- In 1926-1929 the French physicist Mallet measured this glow had a continuous spectrum, but he was unable to determine its nature and abandoned the investigation
- Vavilov's particular expertise allowed him to guide Cherenkov's experiments that determined the manner in which Cherenkov radiation was distinct from luminescence

Prior Work

- On the theoretical side: in 1904 Sommerfeld calculated that a charged particle moving faster than light would radiate directional EM waves
  - But special relativity was developed shortly after, and this work was forgotten
- In 1889, Heaviside calculated a charged particle moving faster than the speed of light in a medium would radiate EM waves, even getting the angle of the radiation correct
  - But he did not take dispersion into account, and so did not have the correct total radiation loss
  - More importantly, no charged particles had even been discovered at the time, and near-light-speed movement seemed inconceivable

Cherenkov Radiation Today

- Cherenkov radiation's universality and directionality have made it a very useful tool in detectors since the development of photomultipliers
- Famously was key to the discovery of neutrino oscillations in Super-Kamiokande



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