Observation of Čerenkov radiation with a photon energy of 284 eV

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Čerenkov radiation by relativistic electrons has been observed in amorphous carbon near its K absorption edge. The real part of the dielectric constant of carbon is confirmed to be greater than unity near 284 eV.

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Čerenkov radiation is emitted by a charged particle at the frequency ω when the particle's velocity v in a homogeneous medium exceeds the phase velocity of electromagnetic waves in this medium, $c/\epsilon'(\omega)$, where $\epsilon'(\omega)$ is the real part of the dielectric constant of the medium (see, for example, Ref. 1).

The dependence of ϵ' on the frequency ω near the edges for photoabsorption by electrons from various atomic shells of a medium was calculated back in 1933 by Hönl,[2] who used the Coulomb approximation for the probability amplitude for the photoelectric effect. Hönl's calculations predicted that in any medium there would be a frequency interval near the photoabsorption edges in which the condition $\epsilon'(\omega)>1$ would hold, so that Čerenkov radiation would be possible. Since then, several workers[3–5] have taken up the theory of Čerenkov radiation in these absorption-frequency intervals and have also calculated the contribution of Čerenkov radiation to the ionizational energy loss of electrons in a medium.

A more rigorous calculation[6] of the dielectric constant near the photoabsorption edges, however, has led to slightly different results. This calculation was based on the Kramers–Kronig dispersion relation and the detailed dependence of the photoabsorption cross section; the fine structure of the photoabsorption edges was taken into account. It turns out that there are only a limited number of media and a limited number of electron shells for which $\epsilon'(\omega)$ can exceed unity, and then only in comparatively narrow frequency intervals around the frequencies of the electron motion of the corresponding shells. The calculation of Ref. 6 also shows that the theory of Refs. 3–5 ignores the effect of the relatively large distance over which x-ray Čerenkov radiation is formed by a relativistic particle, so that the more rigorous theory of Ref. 6 must be used in calculating the radiation spectra.

One of the materials in which there may be comparatively hard Čerenkov radiation is carbon. Figure 1a, taken from the preprint in Ref. 6, shows the frequency dependence $\epsilon'(\omega)$ near the K absorption edge of carbon (curve 1). The imaginary part of the dielectric constant, $\epsilon''(\omega)$, is shown by curve 2. Figure 1b shows the results calculated in the preprint in Ref. 6 for the spectral energy density of Čerenkov radiation from a rather thin film of carbon [the film thickness is $T \gg l_c(\omega)$, where $l_c(\omega)$ is the photon absorption length]. Here the electron energy was assumed to be 1.2 GeV, which is well above the threshold energy $E_{th} = mc^2/[\epsilon'(\omega) - 1]^{1/2}$ for all frequencies for which $\epsilon'(\omega) > 1$.

In the present letter we are reporting an experimental study of the Čerenkov

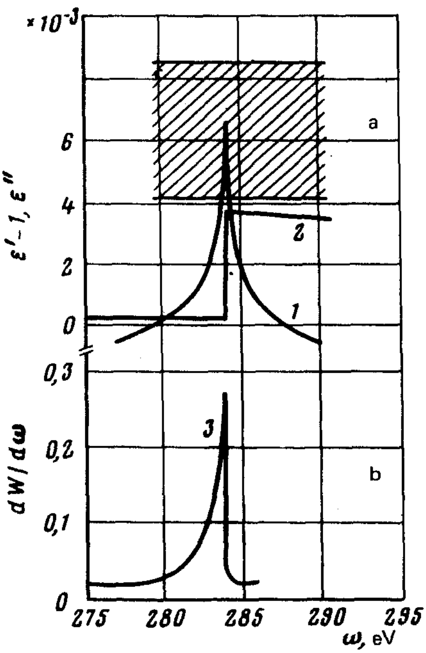

FIG. 1. 1, 2–Frequency dependence of the dielectric constant; 3–frequency dependence of the spectral intensity of the radiation by electrons for carbon with a density of 1 g/cm³.

radiation from electrons in amorphous carbon.

The experiments were carried out on the LUÉ-2 electron accelerator of the Khar'kov Physicotechnical Institute. The apparatus consisted of a special vacuum x-ray monochromator, which was built into one section of the electron tube of the accelerator; the target assembly; and the detector, which was placed inside a lead shield on the floor of the room. The thickness of this shield on the side of the entrance window of the detector was ~40 cm. The detector consisted of a proportional counter filled with 90% Ar + 10% CH_4 at a pressure of 0.10–0.15 atm. Its entrance was a film of Lavsan (similar to Dacron) with a thickness of 0.6 μm, supported by a nickel grid with an effective transmission of 50%. A sliding metal gate ~1 mm thick in front of the entrance window was used to measure the background of hard electromagnetic radiation.

The target consisted of a sheet of amorphous carbon with a thickness of 200 μm, transverse dimensions of 20 × 56 mm, and a density of 1.75 g/cm^3. Sheets of polyethylene film with a thickness of 50 μm were applied to the different sides of the carbon sheet in such a manner that one part of the target was a carbon-plus-polyethylene target, while the other part was a polyethylene-plus-carbon target, in the order as encountered by the electron beam. Since the radiation emitted from the target was actually taken from a final surface layer with a thickness of the order of the absorption length (a few microns), it was thus possible to study the radiation from carbon, with a density of 1.75 g/cm^3, and from polyethylene, with an equivalent carbon density ~0.83 g/cm^3, while holding the amount of material in the path of the electron beam constant.

The grazing-incidence monochromator used a plane diffraction grating with 1200 lines/mm. The glancing angle at which the radiation was incident on the grating was varied from 6° to 90° in experiments in negative diffraction orders.

In order to reduce the size of the monochromator, while keeping the detector as far as possible from the electron beam, we inserted an auxiliary mirror in the monochromator. The total length of the monochromator turned out to be about 7.6 m. The energy resolution of the monochromator was about 1 eV for photons with ~300 eV, but in the present experiments the instability of the electron beam degraded the energy resolution to ~50 eV. The entrance axis of the monochromator made an angle $\theta_M = 8.42 \times 10^{-2}$ rad with the axis of the electron beam. The 1.2-GeV electron beam had transverse dimensions ≈5 mm. In the course of the experiments, the electron beam underwent excursions of up to 10 mm from its central position. Since a 1-cm excursion of the radiation point shifted the detection region in the photon energy spectrum by ≈50 eV, there was no point in adjusting the monochromator for a higher energy resolution. The monochromator monitored a solid angle ~10^{-6} sr.

The LUÉ-2 accelerator produced electron pulses with a length of 1.2 μs and a repetition frequency of 50 Hz. The electron current was chosen in such a way that background pulses were coincident with no more than 20% of the accelerator pulses when the counter window was shut. The optimum value of the average current was ~10^{-7} A.

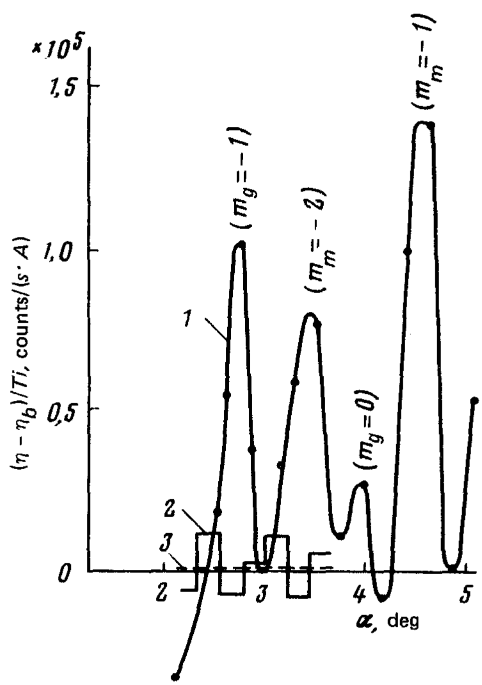

FIG. 2. Count rate of the x-ray photons, plotted as a function of the orientation of the diffraction grating (the angle α). 1–Various diffraction orders of the Čerenkov photons (m_g is the diffraction order for the case in which the electron beam meets the target, the diffraction grating, and the detector in that order; m_m is the diffraction order for the case in which the electron beam meets the target, the diffraction grating, the mirror, and the detector in that order); 2–radiation spectrum from a polyethylene target; 3–average radiation spectrum from a polyethylene target. Here n-n_b is the difference between the detector count rates with the entrance window of the counter open and closed, expressed in counts per second per ampere of the beam current.

We measured the spectrum of the radiation emitted by electrons from a carbon target with a density of 1.75 g/cm^3. The measurements were taken in brief runs in order to reduce the effects of the instability of the electron-beam position. We measured the difference between the detector count rates with the counter window open and closed for various orientations of the diffraction grating; in other words, we carried out a scan over the spectrum. The effect amounted to 5-7% of the background level. The results are shown in Fig. 2. The several intensity peaks in the spectrum correspond to different diffraction orders of photons with an energy of 284 eV. Since the energy resolution was not good enough for a precise determination of the photon energy, we could not be absolutely sure that we were observing the 284-eV Čerenkov line, rather than the 277-eV characteristic line of carbon $C_{K\alpha}$ excited by electrons. We accordingly carried out a control experiment with a target in which the last material in the path of the electron beam was polyethylene instead of carbon. In this case the calculated vertex angle of the Čerenkov cone is less than the angle θ_M, so that the detector should not have detected Čerenkov photons from the polyethylene. Our estimates show that the characteristic radiation is the same from the two targets, since in this case it should not be very sensitive to the density. On the other hand, in the case of the polyethylene target we did not observe the peaks in the intensity spectra (histogram 2), while in the case of the carbon target these peaks were clearly defined. This fact by itself–aside from the measurements of the absolute intensity–can be explained only in terms of Čerenkov radiation, which is highly directional, in contrast with the characteristic radiation.

From the measurements of the Čerenkov radiation angle we can calculate the maximum value of the real part of the dielectric constant near the K photoabsorption edge of carbon. According to Ref. 1, the Čerenkov radiation angle is related to the difference $\epsilon' - 1$ by

$$\theta = [\epsilon'(\omega) - 1 - (mc^2)^2/E^2].$$

Since the Čerenkov radiation from carbon, with a density of $\rho = 1.75$ g/cm^3, does reach the monochromator oriented at $\theta_M = 8.42 \times 10^{-2}$ with respect to the axis of the electron beam, while the Čerenkov radiation from polyethylene does not reach the monochromator in this case, we can set limits on the maximum Čerenkov-radiation angle in carbon:

$$\theta_{CH_2} < \theta_M \lesssim \theta_C .$$

For carbon with a reduced density $\rho = 1.0$ g/cm^3 we thus find the estimate

$$4.05 \times 10^{-3} \lesssim (\epsilon' - 1)_{max} < 8.54 \times 10^{-3}$$

(see the hatched region in Fig. 1). The calculated value of $(\epsilon' - 1)_{max}$ is[6] 6.77×10^{-3}, and it lies within this hatched region.

In summary, these experiments confirm the prediction of Ref. 6 of Čerenkov radiation in the x-ray region. The maximum amount by which $\epsilon'(\omega)$ exceeds unity has been measured.

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