AN EXPERIMENTAL INVESTIGATION OF TRANSITION RADIATION AND ITS POSSIBLE APPLICATION TO MEASURE THE ENERGIES OF FAST PARTICLES

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Transition radiation at optical frequencies from 20–50-MeV electrons is investigated experimentally. It is shown that the intensity of the radiation registered in a narrow cone around the direction of motion of the particles depends strongly on the particle energy, and that this effect can be utilized to measure the energy of the particles.

1. INTRODUCTION

TRANSITION radiation, which is produced when a charged particle crosses the interface between two media having different dielectric constants, was predicted theoretically in 1946 by Frank and Ginzburg.[1] For the ultrarelativistic case Garibyan[2] (see also the review article[3]) later obtained formulas giving the total intensity of the transition radiation emitted in the forward direction and also the spectral distribution. A technique was proposed and achieved for detecting transition radiation in the x-ray region.[4,5] The most remarkable aspect of the detection of x-ray transition radiation was the possibility that it could be utilized to determine the energies of ultrafast particles, for which it is not practicable to use Cerenkov radiation.[6,7] Alikhanyan[8] as well as Amatuni and Garibyan[9] considered the possibility of using optical transition radiation to determine the energies of ultrarelativistic particles, and derived the conditions under which the optical intensity can depend sensitively on the primary particle energy. This possibility exists in principle when the dielectric constant of the medium is near unity (as in the case of x-ray frequencies) and implies the selection of a narrow frequency interval in the region where the medium is transparent. Yuan et al.[10] have attempted to utilize these considerations experimentally in the registration of transition radiation from relativistic pions and protons traversing a layered medium. A weak, logarithmic, energy dependence of the transition radiation intensity was observed, in agreement with the theory. This result was associated with the fact that a very wide interval of transition radiation frequencies was registered.

In[11], on the other hand, it was shown theoretically, using a formula of[2], that when detection of the transition radiation is confined to a relatively narrow cone around the direction of the primary particle, the intensity will depend strongly on the particle energy. In the present experimental work we have investigated the aforementioned energy dependence and the spectral distribution of transition radiation from 20–50 MeV electrons in a single glass plate and also in several stacked plates.

The intensity of forward-emitted transition radiation in a frequency interval $d\omega$ and in a solid angle $d\Omega$ is expressed by the following formula in the case of a single interface:[2]

$$\frac{d^2w}{dwd\Omega}=\frac{e^2\beta^2\sin^2\theta\cos^2\theta}{\pi^2c(1-\beta^2\cos^2\theta)^2}\cdot$$
$$\times\left|\frac{(\varepsilon-1)(1-\beta^2-\beta\sqrt{\varepsilon-\sin^2\theta})}{(\varepsilon\cos\theta+\sqrt{\varepsilon-\sin^2\theta})(1-\beta\sqrt{\varepsilon-\sin^2\theta})}\right|^2, \quad (1)$$

where ϵ is the dielectric constant of the medium and θ is the angle of emission.

It can be shown that for $\theta \ll \pi/2$, $\epsilon > 1$ (which occurs at optical frequencies), and $\beta \sim 1$ the square of the modulus in Eq. (1) equals unity. Then, integrating (1) over the azimuthal angle, we obtain in the approximation of small angles θ,

$$\frac{dw}{d\omega}\approx\int\frac{2e^2\theta^3\,d\theta}{\pi c[(mc^2/E)^2+\theta^2]^2}. \quad (2)$$

It follows from (2) that the emission maximum is observed at $\theta = \sqrt{3}mc^2/E$; with increasing energy the peak becomes narrower and is shifted in the direction of smaller angles θ. The spectral distribution of the transition radiation then has the form $d\omega/\omega$.

The integration of (2) over θ yields

$$\frac{dw}{d\omega}\approx\frac{e^2}{\pi c}\left\{-\left[\left(\frac{mc^2}{\theta E}\right)^2+1\right]^{-1}+\ln\left[\left(\frac{\theta E}{mc^2}\right)^2+1\right]\right\}. \quad (3)$$

For $\theta \ll mc^2/E$ it follows from (3) that

$$\frac{dw}{d\omega}\approx\frac{e^2}{2\pi c}\theta^4\left(\frac{E}{mc^2}\right)^4, \quad (4)$$

while for $\theta \gg mc^2/E$ we have

$$\frac{dw}{d\omega}\approx\frac{e^2}{\pi c}\left[\ln\left(\frac{\theta E}{mc^2}\right)^2-1\right]. \quad (5)$$

It therefore follows from (3)–(5) that in the angular interval 0–θ the intensity increases with energy as $\sim E^4$ when $\theta \ll mc^2/E$. As θ increases, this form of dependence is gradually weakened and becomes logarithmic when $\theta \gg mc^2/E$.

In the case of a layer of matter that is much thicker than the zone in which radiation is generated the intensity is twice as great as in the case of a single interface. However, the intensity of the transition radiation remains quite low, and can be amplified by a layered medium consisting of many laminae. In this case, if the radiation production zone in the medium and in a vacuum is much thinner than the thicknesses of the laminae and their separations, respectively, we obtain simply the sum of the transition radiation intensities from all the layers.

In[11] we have presented the angular distribution curves for different values of $\gamma = E/mc^2$ and the dependence of the transition radiation intensity in a single layer on the particle energy for different angular intervals $0-\theta$. These curves indicate that for experimental apparatus which registers photons emitted at angles from 0 to a given value of θ the particle registration efficiency will depend on the particle energy. For the present experimental work we used the technique suggested in[11].

2. EXPERIMENT

The experimental work was performed on the linear accelerator (injector) of the Erevan electron synchrotron (ARUS). The scheme of the apparatus is shown in Fig. 1.

A beam of electrons with the energy spread $\Delta E/E \approx 1\%$ in the linear accelerator LA was deflected by the magnet M and entered the experimental apparatus through the collimator C; the diameters of the utilized collimator apertures were 3.5 or 8 mm. The electron beam entered the vacuum chamber through an aluminum foil ($\sim 50\ \mu$ thick) window, traversed one of the glass plates P_1, P_2, or P_3 (125, 220, and 450 μ thick, respectively) passed through the mirror R and through the aluminum exit window, and was registered by a Faraday cylinder. The average current, depending on the electron energy and the degree of beam collimation, was in the range $5 \times 10^{-9}-5 \times 10^{-7}$ A. The angular spread of the beam, depending on the degree of collimation and the energy of the particles, and determined from the size of a spot on photographic paper placed at the location of the Faraday cylinder, was in the range $(1-3) \times 10^{-2}$. The plates P_1, P_2, and P_3 in which the radiation was produced, were fastened to a disk B and were positioned in the path of the beam by remote control without disturbing the vacuum. The mirror R was prepared by vacuum deposition of aluminum on a 120-μ glass plate.

Radiation at optical frequencies, which was produced in the glass plate, was deflected 90° by the mirror and passed through the quartz window of the vacuum chamber into the registering section of the apparatus. A lens L (f = 51 cm), diaphragm D, and FÉU-29 photomultiplier were positioned in the path of the photons. Various different optical filters were placed between the diaphragm and the photomultiplier for the purpose of studying the spectral distribution.

Photons that were emitted at a given angle θ were formed by the lens L into a ring of radius $R = f \tan \theta$, independently of the distance between the electron trajectory and the instrumental axis, in the manner of the lenses used in gas Cerenkov counters. The diaphragm D, positioned in the focal plane of the lens, permitted registration of photons emitted in a given angular range $0-\theta$, depending on the diameter of the aperture. All the apparatus was carefully shielded from background radiation by means of lead, iron, and paraffin blocks. At each separate measurement of the dark current of the photomultiplier and the current produced by background particles and by radiation originating in different parts of the apparatus were compensated by a special bridge circuit at the position P_4 of the disk B, when the beam did not encounter a glass plate.

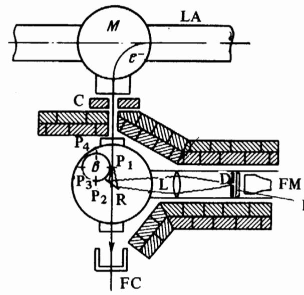

FIG. 1. Diagram of experimental apparatus. LA – linear accelerator; M – magnet; C – collimator; B – rotatable disk; P_1, P_2, and P_3 – glass plates; P_4 – position of disk B for measurement of background current; FC – Faraday cylinder; R – mirror; L – lens; D – diaphragm; F – optical filter; FM – photomultipler.

In addition to the investigated optical transition radiation produced in a glass plate, the electrons can produce Cerenkov radiation and bremsstrahlung in the glass plate and also in other parts of the apparatus inside the chamber (the aluminum windows, gas, mirror etc.) The background radiation from all parts of the apparatus except the glass target was compensated, as already mentioned. Nevertheless, several steps were taken to reduce this background. Thus the $\sim 10^{-2}$-mm Hg vacuum in the chamber excluded the production of Cerenkov radiation in the gas. Also, all internal surfaces of the chamber were blackened with Aquadag.

We estimated that the bremsstrahlung and Cerenkov radiation produced in the glass plate itself made no important contribution to the registered radiation. Our estimate of the bremsstrahlung intensity in the region of photomultiplier sensitivity, even without allowing for the influence of the medium, was lower than the anticipated transition radiation intensity. Cerenkov radiation is generated at large angles in a glass plate, and although its intensity exceeds the transition radiation intensity, it undergoes total internal reflection and is not registered at the small angles accepted by the diaphragm D. However, the contribution from both forms of radiation was determined experimentally as follows. Since the transition radiation in a plate that is much thicker than the "radiation formation zone" in the medium does not depend on the plate thickness, while Cerenkov radiation and bremsstrahlung both depend on this thickness, we obtained measurements in three plates P_1, P_2, and P_3 of different thicknesses. The observed intensities were afterwards extrapolated to zero thickness, which corresponds to the transition radiation intensity.

3. RESULTS AND DISCUSSION

Figure 2 shows how the ratio between the photomultiplier current and the Faraday cylinder current varies with the target thickness when radiation is registered in the angular interval $0-\theta = 8 \times 10^{-2}$ for different electron energies E. As the glass plate thickness increases the radiation intensity exhibits little increase. Thus, as was expected, the Cerenkov radiation and bremsstrahlung make only a quite small contribution to the meas-

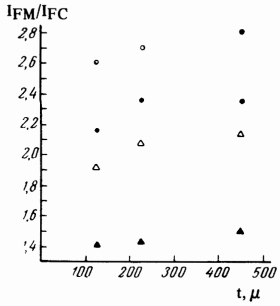

FIG. 2. Ratio of the photomultiplier current to the Faraday cylinder current (I_{FM}/I_{FC}) vs. glass plate thickness (t). ○ – E = 45 MeV, ● – 39.8 MeV, Δ – 32.2 MeV, ▲ – 21.8 MeV; $\theta \leqslant 8 \times 10^{-2}$.

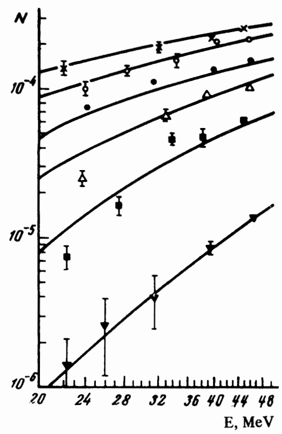

FIG. 3. Number of photoelectrons vs. electron energy. X – $\theta \leqslant 8 \times 10^{-2}$, ○ – $\theta \leqslant 6 \times 10^{-2}$, ● – $\theta \leqslant 4 \times 10^{-2}$, Δ – $\theta \leqslant 3 \times 10^{-2}$, □ – $\theta \leqslant 2 \times 10^{-2}$, ▼ – $\theta \leqslant 10^{-2}$. N is the number of photoelectrons per single primary electron.

ured intensity. Similar results were obtained for other angular intervals and also in spectral measurements.

Figure 3 shows the experimental and theoretical dependences of the number of photoelectrons produced in the photocathode by transition-radiation photons at wavelengths corresponding to the photomultiplier sensitive region, as functions of the electron energy in different angular intervals 0–θ. The experimental values obtained for different plate thicknesses were extrapolated to zero thickness, which, as indicated in the foregoing discussion, corresponds to the transition radiation. The values obtained in this manner were divided by the photomultiplier amplification; we thus obtained the number of photoelectrons. The theoretical curves calculated from (1) took into account the losses arising as the generated light passed through the entire optical system and also the frequency response of the photocathode. The loss factor in the optical system and the photomultiplier amplification were determined experimentally, while for the frequency response of the photocathode we used the manufacturer's certification.

Figure 3 shows that the transition radiation intensity is strongly dependent on the electron energy. In the investigated energy region this dependence becomes more pronounced as the angular interval is narrowed. Thus for $\theta \leq 10^{-2}$ the dependence is of the form $\sim E^3$, while for $\theta \leq 8 \times 10^{-2}$ we have $\sim E$. Satisfactory agreement between experiment and the shapes of the theoretical curves is also observed. However, the measured absolute intensities lie above the theoretical curves by an average factor 1.45. The same ratio of difference is observed in the measurements of the spectral distribution and of radiation in a layered medium. This experimental excess over theory can evidently be attributed either to inexact knowledge of some quantities used in determining the efficiency of the registering systems or to a thin film of vacuum oil that was formed on the glass plates and became an additional source of transition radiation. The theoretical values in Fig. 3 have been multiplied by the factor 1.45.

We also measured the transition radiation in layered media consisting of n = 5 and n = 9 plates; these results are shown in Fig. 4. Amplified intensity was observed, with energy dependence that is similar to the case of a single plate. The investigated spectral distribution of the transition radiation is of independent interest because of the previous absence of experimental data at relativistic particle energies. In the present experiment we used optical filters having transmission coefficients that began to differ from zero at a certain wavelength λ and then increased steeply to almost 100%, at which level they remained into the far infrared. Accordingly, the theoretical and experimental values shown in Fig. 5 represent, in each case, the number of transition radiation photons integrated from λ_1, the wavelength at which the filter transmission reaches 50%, to the maximum wavelength of photomultiplier sensitivity. In contrast with the previous figures, the experimental values are here reduced by the factor 1.45. Figure 5 shows that for $\theta \leq 8 \times 10^{-2}$ and E = 50 MeV or 30 MeV our experimental results are well fitted by the theoretical curves. Similar results were obtained with 20- and 40-MeV electrons.

Our experimental data show the following:

1. The behavior of the experimental intensity of transition radiation in a plate and in a layered medium as a function of energy, and also that of the spectral intensity distribution, are in good agreement with the corresponding theoretical curves. The experimental absolute values exceed the theoretical values by the factor 1.45.

2. When $mc^2/E > \theta$ a quite pronounced dependence of the transition radiation intensity on the charged particle energy is observed.

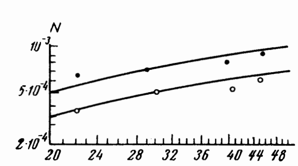

FIG. 4.

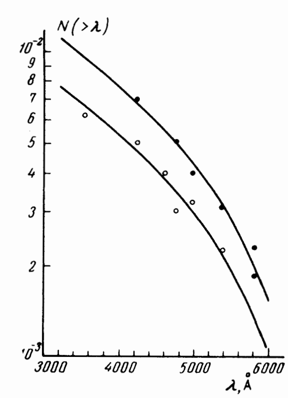

FIG. 5.

FIG. 4. Number of photoelectrons vs. electron energy in a layered medium having n layers. ● – n = 9, ● – n = 5. N is the number of photoelectrons per single primary electron.

FIG. 5. Number of transition radiation photons in the wavelength interval from a given λ to 6200 Å vs. electron energy E. $\theta \leqslant 8 \times 10^{-2}$; ○ – E = 50 MeV; ● – E = 30 MeV. N is the number of photons per primary electron.

3. At optical frequencies the intensity of transition radiation is enhanced when a single plate is replaced by a layered medium.

The following conclusions are based on the foregoing. Transition radiation in a single plate subject to the condition $mc^2/E \gtrsim 0$ can serve as a simple method of measuring particle energy in a beam of known intensity. It is of great interest to measure the energy of a single high-energy particle because the other available methods either become extremely complicated at very high energies or are unsuitable in principle. By using transition radiation in a medium consisting of many layers we would be able to measure the energy of a particle in the interval $\gamma = E/mc^2 \approx 10-1000$, which corresponds to the momentum ranges ~5—500 MeV/c, 1.3—130 GeV/c, 5—500 GeV/c, and 10—1000 GeV/c for electrons, pions, kaons, and protons, respectively. The upper limit of measurable energies is bounded by the technologically feasible intervals of included angles θ and by the angular spread of the charged particles. It must be remembered that this measurement technique involves practically no loss of particle energy. We note also that to permit a reduction in the number of layers in the medium we can use coated glass plates and a photomultiplier having better spectral properties.

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206