Effect of angular discrimination of x-ray transition radiation on particle separation efficiency

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Results are presented of measurements of the angular distributions of x-ray transition radiation generated in foam plastic by 2, 3, 4, and 4.6 GeV electrons. The results are compared with the theory. It is shown that angular discrimination results in a significant improvement of separation of ultrarelativistic particles.

The real possibility of creating particle detectors based on x-ray transition radiation has led in recent years to an intense study of various characteristics of this radiation.[1-17] In particular, Yuan and Wang[4] investigated the angular distributions of x-ray transition radiation, and Alikhanyan et al.[5] discussed the question of angular discrimination of the photons, showing that in this case the dependence of the intensity of the transition radiation on the primary-particle energy is enhanced. In both cases a layered radiator was used to obtain the transition radiation.

No less interest is presented by the angular dependence of x-ray transition radiation produced in porous radiators, particularly in foam plastic, as a result of the possibility of using these materials as efficient radiators. In addition to the independent interest, a knowledge of the widths of the angular distributions is necessary in performance of future experiments with chambers using x-ray transition radiation, in which observation is carried out simultaneously of different particles, each of which is accompanied by its own transition radiation.[18] It is understandable that in this case an overlap of the angular distributions of the photons from the different particles is not permissible, since it would then be impossible to identify them.

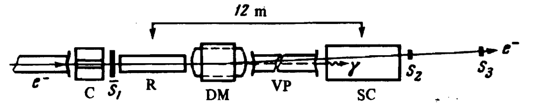

FIG. 1. Diagram of experimental apparatus: C—collimator, R—radiator, DM—deflecting magnet with helium bag, VP—vacuum pipe, SC—streamer chamber, $\bar{S}_1$—anticoincidence counter, $S_{2,3}$—aperture counters.

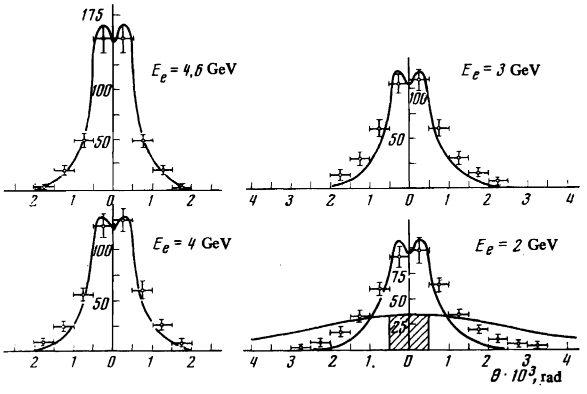

FIG. 2. Angular distributions of x-ray transition radiation for various electron energies.

The present experiment, whose arrangement is shown in Fig. 1, investigated the angular distribution of x-ray transition radiation arising on passage of electrons with energy E_e = 2, 3, 4, and 4.6 GeV through a porous plastic foam radiator[2, 10, 12] with a density ρ = 0.04 g/cm³ and length 160 cm. The quanta produced here, together with the primary particle, are detected in a streamer chamber with a length of 80 cm and filled with the mixture Ne (87%), Xe (13%). Use of the small deflecting magnet DM, which deflects the primary electron upward by several centimeters, facilitates analysis of the experimental results, increasing their reliability. We note also that a scintillation counter S_1 with a central opening was connected in anticoincidence with the aperture counters S_2 and S_3, which have dimensions 0.5 × 0.5 × 0.5 cm. Because of the absorption in the radiator, in the windows, and in the air gaps, the spectrum of x-ray transition radiation in the chamber has a maximum in the region ~15 keV. The detection efficiency for photons of this energy with the Xe concentration used is ~90%.

The analysis of the experimental data consisted of measuring the distances of the center of the luminous clusters (photoelectrons) from the primary-particle track. The distributions obtained are shown by the points in Fig. 2, where the ordinate is the number of photoelectrons (the corresponding errors are statistical), and the abscissa are the angles, conversion to which was accomplished for the known distance of the streamer chamber from the radiator. The errors in determination of the angles are due to the finite size of the luminous clusters and the uncertainty of the point of origin of the photon in the radiator.

The contribution of the experimental background, which was measured by replacement of the radiator by its equivalent of the same thickness in g/cm², for all values of E_e did not exceed 5% of the magnitude of the x-ray transition radiation. At the same time the theoretical background due to bremsstrahlung does not exceed 0.2%. Thus, the main part of the background is due to transition radiation formed in the windows of the vacuum pipes and helium bags, and also to the general room background.

All distributions measured have close to zero asymmetry, but a rather large positive excess. The latter is understandable if we take into account that the experimental points reflect the projections of the lateral distributions on a plane parallel to the primary track, and in this case the probability density in the central part of the distributions increases. We note immediately that the beam divergence does not introduce distortions in the angular distributions, since in each case we usually observe both the electron track and the photoelectron tracks.

The effect of Compton scattering in the radiator material also can be neglected, since the expected number of photons scattered at the angle of interest here does not exceed 2×10^{-5}, while the average number of photons detected is ~3. In addition, it is necessary to take into account the fact that the experimental values of the widths of the angular distributions of x-ray transition radiation may be exaggerated as the result of the contribution due to the electron multiple-scattering angle in the radiator material. Generally speaking, this contribution can be significant, as can be seen from Fig. 2, where we have shown the projection of the electron multiple-scattering angular distribution[19] for $E_e = 2$ GeV for the present radiator. However, it is evident that the experimental distribution is substantially narrower, and this is explained by the fact that collection of the electrons was carried out in a narrow angle θ_a determined by the aperture counters ($\theta_a \approx \pm 5 \times 10^{-4}$ rad). The hatching in Fig. 2 corresponds to the region of detection of electrons, this distribution being considered uniform and positive, $\Delta\theta_a = \theta_a/\sqrt{3}$. The mean-square deviations of the experimental distributions $\Delta\theta$ and the transition-radiation distributions $\Delta\theta_{tr}$ corresponding to Fig. 2 are as follows:

E_e, GeV:	4.6	4	3	2
$\Delta\theta \cdot 10^3$, rad:	0.64	0.73	0.94	1.17
$\Delta\theta_{tr} \cdot 10^3$, rad:	0.56	0.66	0.89	1.13

The data in the last line are obtained from the condition

$$\Delta\theta^2 = \Delta\theta_{tr}^2 + \Delta\theta_a^2.$$

It is evident that $\Delta\theta$and $\Delta\theta_{tr}$ differ by no more than 15%.

For a comparison of the results obtained and the theory, we calculated the corresponding projections of the angular distributions. The calculation was carried out with inclusion of photon absorption and in the approximation of average energies over the particle spectrum, with the formula given below, which was obtained from Eq. (14) of ref. 20 for media which are close to porous:

$$\left\langle \frac{d^2N_{ph}}{d\omega\, dx} \right\rangle = \frac{2}{137\pi^2\omega} \left[\left(\frac{\omega_0}{\omega} \right)^4 + \left(\frac{c\mu(\omega)}{\omega} \right)^2 \right] \int_x^{\theta_m} \frac{I(\omega, y)\, y^3\, dy}{(y^2 - x^2)^{1/2} (y^2 + 1 - \beta^2)^2}$$
$$\times \left[\left(y^2 + 1 - \beta^2 + \frac{\omega_0^2}{\omega^2} \right)^2 + \left(\frac{c\mu(\omega)}{\omega} \right)^2 \right]^{-1}. \qquad (1)$$

Here $\mu(\omega)$ is the absorption coefficient for field intensity, ω_0 is the plasma frequency, $x = \theta_{tr}$, and θ_m is the maximum angle of radiation. The quantity $I(\omega, y)$ is defined by Eq. (19) of ref. 20. The theoretical angular distributions are shown in Fig. 2 in the form of solid curves; the two-humped nature is explained by the absence of radiation at the angle $\theta = 0$ in space.

Let us consider the question of the effect of angular discrimination of x-ray transition radiation on the dependence of the average number of photons $\bar{n}$ on E_e. In the calculation we will take only those photons which have been recorded in the angular interval 0 ± 10^{-3} rad (Fig. 2). In this case we obtain dependence b in Fig. 3 with $d\bar{n}/dE_e = 0.71$. Curve a is shown for the case of no angular discrimination, and $d\bar{n}/dE_e = 0.51$. It can be seen that the steepness of the characteristic $\bar{n}(E_e)$ in the case of angular discrimination increased by a factor 1.4, while $\bar{n}$ for $E_e = 4.6$ GeV decreased by less than 10%.

Having obtained the dependences shown in Fig. 3, we will analyze the conditions for separation of electrons with energies 1.3 and 4.6 GeV (for curve b the value of $\bar{n}$ at the point 1.3 GeV will be found by extrapolation). This analysis will be completely applicable also to separation of π and K mesons with energy $E = 1.3 \times 10^3$ GeV. Since the number of photons fluctuates according to a Poisson distribution,[21] it can be shown that the fraction of the discriminated component $1 - R$, where R is the rejection factor, is

$$1 - R = \frac{J_1\eta_1}{J_2\eta_2}, \quad \eta_{1,2} = \sum_{n=n'}^{\infty} \frac{(\bar{n}_{1,2})^n}{n!} \exp(-\bar{n}_{1,2}). \qquad (2)$$

Here $J_{1,2}$ are the intensities of the components, $\eta_{1,2}$ are the efficiencies for detection of the components by transition radiation, $\bar{n}_{1,2}$ is the average number of photons, and n' is the level of discrimination in the number of photons detected.

For $J_1 = J_2$ we obtain the conditions for separation of electrons with energies $E_e = 4.6$ GeV and $E_e = 1.3$ GeV (π and K mesons with energy 1.3×10^3 GeV), which are shown in the table, from which we can readily see the effect due to angular discrimination in combination with discrimination in the number of photons assumed in the calculation. The ratio of the Lorentz factors of the particles in our case is ~3.5. The angular discrimination effect will be more significant in the case of π mesons and protons ($\gamma_\pi/\gamma_p \approx 6.7$), which substantially improves the conditions for separation of these particles.

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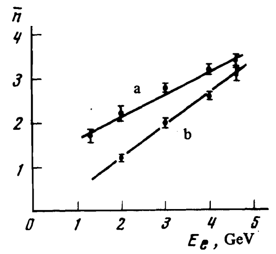

FIG. 3. Average number of x-ray transition-radiation photons detected, as a function of electron energy: a—in the absence of angular discrimination, b—in the presence of angular discrimination.

n'	η_1, %	η_2, %	R, %	n'	η_1, %	η_2, %	R, %
Dependence a				Dependence b			
3	30	70	57	2	15	80	81
4	13	50	74	3	3	58	95
				4	0.5	35	99

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