ion penetration in solids.[9]

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DETECTION OF X-RAY TRANSITION RADIATION BY MEANS OF A SPARK CHAMBER*†

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A new method for x-ray transition radiation detection by a streamer spark chamber is suggested. The use of the chamber secures a separate observation of both the radiation and the particle. It is shown that the mean number of the transition quanta linearly increases in the electron energy range 1.2 to 2.46 GeV. When plastic foam was used instead of a layered medium the efficiency of electron detection by transition radiation was 86%.

The advancement of superhigh-energy physics has called for new methods of measuring particle energies. The Cherenkov radiation commonly used makes it possible to measure only $\beta = v/c$ (v is the particle velocity, c is the velocity of light) which gives rise to considerable difficulties when using it in an ultrarelativistic region. Transition radiation[1] has recently attracted more and more attention due to the fact that the total intensity in the direction of the ultrarelativistic particle motion depends linearly on $\gamma = E/\mu c^2$.[2] In addition, it was shown by Garibian[2] and Barsukov[3] that the main fraction of this radiation is in the x-ray frequency region. In Ispirian and Oganessian and Alikhanian et al.[4] the conditions were found and experimentally supported where, in the optical region as well, the transition-radiation intensity increases strongly with γ.

Nevertheless, a small number of photons and small emission angles with respect to the direction of the particle motion cause considerable difficulties both in investigation and in the use of x-ray radiation.

The first attempts to this effect were made by Arutunian, Ispirian, and Oganessian, Arutunian et al., and Alikhanian,[5] where the idea of detecting transition quanta, suggested by Alikhanian et al.,[6] was put into effect by the use of characteristic radiation.

The x-ray transition radiation in a layered medium has recently been studied on an electron beam of energy from 1 to 4 GeV from the Yerevan electron accelerator. The x-ray transition radiation was detected by means of a CsI scintillation counter with a hole in its central portion for free passage of primary electrons. The efficiency of electron detection, i.e., the fraction of cases where at least one of the transition-radiation quanta is detected by the counter, proved to be 10% for electron energies of 3-4 GeV. In Yuan, Wang, and Prunster[7] charged particles were deflected from the propagation direction of transition quanta by a magnetic field and later the quanta were detected by a germanium solid-state detector. The efficiency of detection of positrons of 2-GeV energy in this work was 27%.

However, a preliminary spatial separation of a particle from the accompanying radiation usually gives rise to a decrease in the instrument's transmission, and the detection of radiation quanta by means of scintillation or semiconductor counters makes it difficult to calculate their quantity. But the successful application of transition radiation to measuring energies of individual particles depends not only on the presence of a great quantity of transition quanta emitted from a layered medium, but on the efficiency of detecting them with a simultaneous possibility

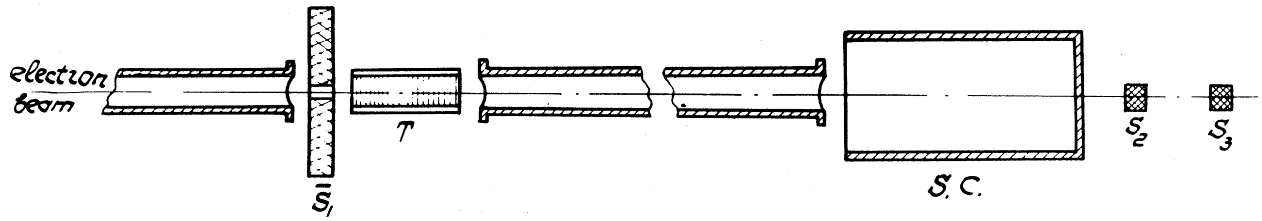

FIG. 1. General arrangement.

of counting. If this possibility is lacking, the device in question can be used as threshold detector.

In the present study a streamer spark chamber with Xe addition was used to detect transition radiation quanta. The chamber was filled with a mixture of 30% He and 70% Ne at atmospheric pressure. The Xe addition accounted for 10% and 15% of the mixture. For proper functioning some iodine vapor was passed into the chamber at a pressure of 10^{-2} Torr.

The advantage of this method lies in the fact that one and the same device detects separately both radiation and particles. Due to the presence of Xe, the chamber is highly efficient in detecting photons. Such conditions for steamer chamber functioning can, in principle, be chosen that one and the same chamber can, with 100% efficiency, detect photons over a wide energy range. A high spatial and angular resolution of the chamber allows counting with good accuracy the number of electrons produced by transition photons over any range of angles. It is evident that in this case the problem of the intrument's transmission is solved in an optimal manner as well, which in fact is of great significance for the experiment.

The arrangement is schematically shown in Fig. 1. Electrons of a given momentum ($\Delta p/p \sim 1\,\%$) pass through a target T which is a layered medium and, along with transition quanta produced in the medium, are detected in the spark chamber SC. The selection of electrons passing through the center of the layered medium and the spark chamber is effected by means of the scincillation counters S_1, S_2, and S_3. The counter S_1 has in its center a hole 0.5 cm in diameter and is set for anticoincidence with S_2 and S_3. The distance between the layered medium and the chamber is 11 m. The chamber is 80 cm long (along the track), 10 cm wide, and 20 cm high. To reduce the bremsstrahlung and absorption of photons in the air, tubes 10 cm in diameter evacuated down to 10^{-2} Torr are placed throughout the electron path. The windows in the tubes and the outlet window of the spark chamber are made of Mylar 15 μm thick. The pictures of the tracks in the spark chamber are taken in the direction of the electric field by means of two stereoscopic cameras.

The measurements in each case were made in two series with a target of a layered substance and with a continuous target of the same material and equivalent thickness. Since in the latter case no transition quanta were produced, the measurements gave rise to a background due to the bremsstrahlung in the target and δ electrons produced in the chamber gas. The geometry of the arrangement made it possible to detect in the spark chamber quanta of maximum radiation angle equal to 4×10^{-3} rad. The measurements were made using a layered medium of polyethylene films of thickness $a = 45$ μm, the average distance between them being $b = 500$ μm, the number of films $N = 500$ and $N = 1000$. In addition, a target of plastic foam 2 g/cm^2 thick was used.

Those pictures were selected and processed where a primary passing particle was observed, regardless of whether any photoelectrons were present in the picture or not. Figure 2 shows a typical event of detection of a primary particle and two photons by photoelectrons, denoted by arrows. The measurement results are shown in Table I. The first column is for the targets and the amount of Xe. The second column shows the

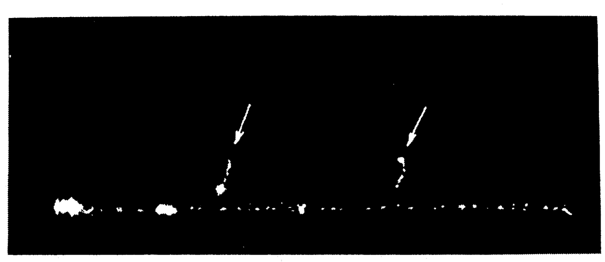

FIG. 2. Typical case of detecting primary particle and two transition quanta by photoelectrons indicated by arrows.

Table I. Results of experimental measurements of photoelectrons generated by transition quanta.

Target & Xe concentration	Momentum GeV	W	$\bar{N}$	N_{theor}	N_δ	N_{brems}
Polyethylene N=1000 10% Xe	I.2	0.37±0.1	0.56±0.136	1.5	0.48±0.07	0.16±0.04
Polyethylene N = 1000 10% Xe	2.0	0.67±0.13	1.06±0.15	4.3	0.40±0.06	0.174±0.041
Polyethylene N=500 10% Xe	2.46	0.62±0.13	0.93±0.136	3.8	0.37±0.06	0.07±0026
Polyethylene N = 1000 15% Xe	2.0	0.67±0.13	1-21±0.14	4.9	0.31±0.055	0.20±0.045
Plastic foam 2 g/cm^2 10% Xe	2.0	0.86±0.13	1.05±0.13	—	0.4±0.06	0.085±0.027

momentum of primary electrons. The third column gives the efficiency of detection of these particles by means of transition radiation. The fourth column represents the ratio between the total number of photoelectrons and that of events; that is, the average number of transition quanta per primary particle. These data take account of the background. The fifth column includes the calculated value of this number. The sixth and seventh columns list the average values of the number of δ electrons and bremsstrahlung quanta, respectively, obtained from background measurements. About 120 processed pictures were used for each group of measurements.

It is evident from the table that the dependence of efficiency of detection W and the average number of quanta $\bar{N}$ on the particle energy may be thought of as linear. A more accurate determination of the course of these dependences is restricted to the range of experimental error. As far as the value N_δ within the range of experimental error is concerned, it does not depend on the electron energy and the type of target, while $N_{\rm brems}$ depends on the target thickness and does not depend on the electron energy, which is only natural.

An analysis of the experimental results shows that in the background measurements the number of pictures with two or more secondary electrons is small. These results are easy to interpret, if one takes into account the fact that the total length of the target was 0.1 radiation length; that is, the probability of simultaneous radiation of two bremsstrahlung quanta is insignificant, while the number of films in a stack was chosen such that the average number of transition quanta should be close to unity.

The following is the theoretical analysis of the results obtained. The average number of transition radiation quanta produced in one plate of a stack made of N plates is expressed by the formula[8]

$$\frac{d\bar{N}_1}{d\omega}=\frac{1}{N}\frac{dN}{d\omega}=\frac{4}{137\pi}\frac{\omega_p''^2}{\omega^3}\sum_{k=0}^{\infty}\frac{(k+d)\sin^2[\pi(a/p)(k+d+\omega_p''/\omega+\omega/\omega_p')]}{(k+d+\omega_p''/\omega+\omega/\omega_p')^2(k+d+\omega/\omega_p')^2},$$

where

$$\omega_p'=\frac{4\pi v}{p(1-\beta^2)},\quad \omega_{a,p}''=\frac{(a,p)\sigma}{4\pi v},\quad \sigma=\frac{4\pi ne^2}{m},\quad d=\left[\frac{\omega_a''}{\omega}+\frac{\omega}{\omega_p'}\right]-\left(\frac{\omega_a''}{\omega}+\frac{\omega}{\omega_p'}\right);$$

the square brackets in the last expression denote the largest integer contained in the bracketed quantity. By virtue of Ref. 8, the average number of transition-radiation quanta is found from the above formula, if $\omega_p{}'/\omega \ll N \ll 4\omega^2/\sigma$. It is readily seen that in the case in question these conditions are satisfied. It should also be noted that the series member denoted by k stands for the number of quanta emitted at an angle $\theta_k = [(4\pi v/p\omega)(k+d)]^{1/2}$. In the case of polyethylene $\sigma = 10^{33}$ sec^{-2}, $a = 4.5 \times 10^{-3}$ cm, $p = a+b = 5.45\times 10^{-2}$ cm. For electrons of energies $E = 1.2$, 2.0, and 2.4 GeV, the curves calculated by the above formula and shown in Fig. 3 are obtained for the angles of photon radiation over the range $(0\text{-}4)\times 10^{-3}$ rad.

When calculating the number of quanta emitted from an N-plate stack, one should also take account of their being absorbed in the stack where they are produced. This condition implies that the spectral distribution of the number of transition quanta produced in one plate is to be multiplied not by the number of plates N but by $N(\omega) = [1-e^{-aN\mu(\omega)}]/[1-e^{-a\mu(\omega)}]$, where $\mu(\omega)$ is the absorption coefficient of the quanta in the film substance expressed in cm^{-1}.

In order to obtain the number of the photons (photoelectrons) observed, the spectrum of the quanta emitted from a layered medium should be multiplied by the curve of their absorption in Xe.

On summing each of the spectra of the detected quanta thus calculated over all the frequencies, values are obtained for the number of photoelectrons which are shown in the fifth column of the table. It is readily seen from comparison with the fourth column that the experimental values are 3-4 times lower than the theoretical ones. This discrepancy is most probably due to the fact that either some of the photoelectron tracks produced in the spark chamber might be overlooked because of a short path, or the absorption of transition-radiation quanta was not taken account of with sufficient accuracy.

Of great interest are the results of measurements with a plastic foam target. This target is not of an ordered structure and it consists of randomly spaced pores with different thicknesses of the pore walls and dimensions of the pores themselves. The production of transition radiation in this case as well testifies to the fact that for the radiation to be generated the structure need not be periodic, but the presence of the interface of the media is sufficient. This condition greatly simplifies the problem of designing transition-radiation generators.

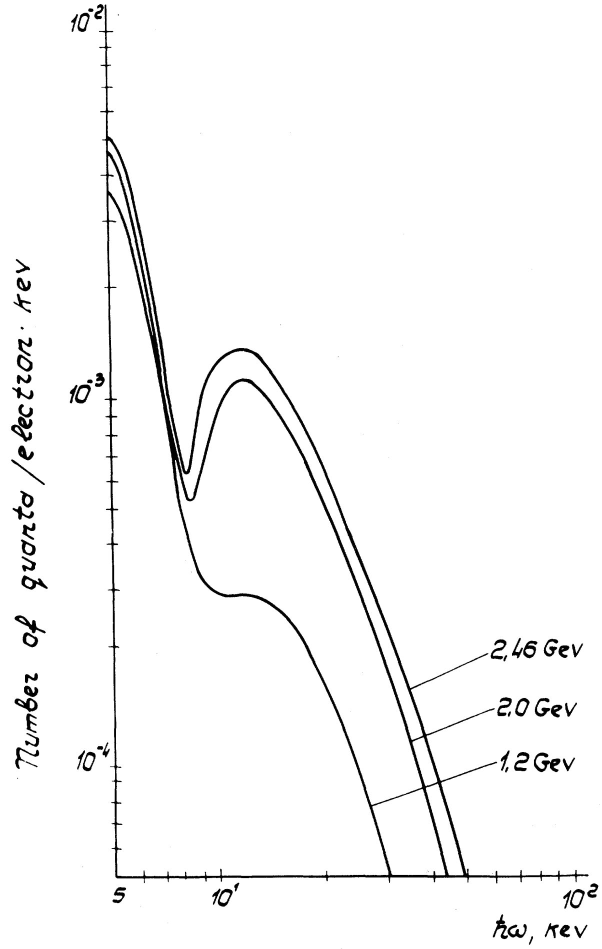

FIG. 3. Calculated curves for average number of transition quanta.

The results in question permit the design of a system of a layered medium and a spark chamber where the particle tracks with large values of $\gamma = E/\mu c^2$ will differ from other particle tracks with smaller γ because of the former being specifically accompanied by photoelectron tracks. With a known particle momentum (for example, when the spark chamber is in a magnetic field) the values p and γ allow a determination of the particle nature. We believe that the method described here can be rather useful at particle energies up to hundreds of GeV.

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PERTURBATION OF MAGNETIC SURFACES IN A ROTATING HIGH-β TOROIDAL PLASMA

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In a toroidal resistive plasma in the presence of a radial electric field one can obtain large perturbations of magnetic surfaces when the frequency of the azimuthal plasma rotation approaches the Alfvèn frequency.

Recent work has considered the effect on diffusion of azimuthal rotation due to radial electric fields in toroidal resistive plasmas. Stringer[1] first included toroidal variation of the electrostatic potential and pointed out a possible resonance between angular frequency of rotation and natural electrostatic plasma modes: The response of the plasma to the charge separation rotating at frequency $-v_0/r$ (v_0 being the electric drift) has in fact to be inversely proportional to the electrostatic dielectric constant. Further work[2,3] has made this physical effect quantitatively precise.

In the present work it is pointed out that the inclusion of nonpotential perturbations for the same model of a resistive toroidal plasma in the presence of a radial electric field $E_0(r)$ can bring new resonant effects when the frequency of the azimuthal plasma rotation approaches the frequency of some natural electromagnetic wave in the plasma. It is in fact explicitly shown that, for not too small β [$\beta_p = p/(B_\theta^2/8\pi) > 1$, where $p = nT$ is the plasma pressure and B_θ the poloidal magnetic field], at $v_0^2 \sim \theta^2 v_A$ (where $\theta = B_\theta/B_0 \ll 1$, B_0 being the toroidal magnetic field, and $v_A^2 = B_0^2/nM$ the Alfvèn velocity), very large modifications of the toroidal equilibrium can occur.

The basic equations of our calculation are

$$-\nabla\varphi + \vec{v}\times\vec{B} = -(T_e/en)\nabla n + \vec{j}\times\vec{B}/en, \tag{1}$$

$$nM(\vec{v}\cdot\nabla)\vec{v} = -T_e\nabla n + \vec{j}\times\vec{B}, \tag{2}$$

$$\nabla\cdot(n\vec{v}) = 0, \tag{3}$$

$$\nabla\cdot\vec{j} = 0, \tag{4}$$

$$\nabla\times\vec{B} = \vec{j}. \tag{5}$$

For simplicity, $T_i = 0$.

Equations (1)-(5) are applied to an axisymmetric system of large aspect ratio ($\epsilon = r/R \ll 1$). In the usual toroidal coordinates $ds^2 = dr^2 + r^2 d\theta^2 + (1+\epsilon\cos\theta)^2 dz^2$ the magnetic field is given by $\vec{B} \equiv (0, B_\theta(r), B_0/(1+\epsilon\cos\theta))$ and the exact magnetic surfaces are given by $r =$ constant. All quantities are now expanded in ϵ, namely $n = n_0 + \epsilon n_1(r,\theta)$, $\varphi = \varphi_0(r) + \epsilon\varphi_1(r,\theta)$, etc., where all the zeroth-order quantities refer to a straight cylinder of plasma. The magnetic field is also perturbed so that $\vec{B} = \vec{B}_0 + \epsilon\vec{B}_1$, where $\vec{B}_0 \equiv (0, B_\theta, B_0)$ and $\vec{B}_1 \equiv (B_{1r}, B_{1\theta}, -B_0\cos\theta)$.

From Eqs. (1) and (2) one can write $\vec{v}_\perp$ as

$$\vec{v}_\perp = (\vec{B}\times\nabla\varphi)/B^2, \tag{6}$$