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# RESONANCE RADIATION OF ELECTRONS OF ENERGY UP TO 600 MeV IN A LAYERED MEDIUM

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The theory of the radiation produced when a relativistic charged particle passes through a periodic layered medium (resonance radiation) was developed in the papers of Ter-Mikaelyan [1,2]. The possibilities of using resonance radiation to detect high-energy particles were analyzed by Alikhanyan et al. [3] This radiation was observed by us experimentally by passing muons of ultrahigh energy through a layered medium [4-6].

In this paper we present experimental results on the characteristics of the radiation produced in different layered media by passage of high-energy electrons.

The experiment was performed with the electron synchrotron of the Physics Institute of the USSR Academy of Sciences (maximum energy 680 MeV). The number of electrons in a pulse streched out to 0.5 sec was $\sim 10^2 - 10^4$, depending on the electron energy, which was varied between 250 and 600 MeV with $\Delta E/E \lesssim 5\%$.

Different layered media were used. Each consisted of n sheets of paper of definite thickness $l_1$, placed in air at an equal distance $\alpha l_1$ from one another. $\alpha$ was varied from 3 to 19.8 and n was varied from 10 to 300 for $l_1 = 2.43 \times 10^{-2}$ cm, $\alpha = 5.84 - 28.9$ and $n = 130 - 780$ for $l_1 = 9.3 \times 10^{-3}$ cm, and $\alpha = 18.8$ and $n = 1050$ for $l_1 = 2.83 \times 10^{-3}$ cm.

The electrons were registered with a scintillation telescope consisting of two plastic scintillators, each measuring 7 x 3 x 0.5 cm, located on the two sides of the layered medium. The electrons were further deflected by a magnetic field to prevent their falling into the scintillation $\gamma$ spectrometer (NaI(Tl), 7 cm dia, h = 7 cm), which registered $\gamma$ quanta produced by the electron in the layered medium.

The radiation spectrum up to 100 keV was observed with an AI-100 pulse-height analyzer triggered by a coincidence circuit for the pulses from the telescope and the $\gamma$ spectrometer. The total length of the setup was 6.45 m.

The measurements were made also for a solid medium, comprising the same layers compressed to $\alpha = 0$. The quantity measured in this case was that part of the radiation in the layered medium, which was due to the electron bremsstrahlung in the layered medium itself and in the remaining matter on the path of the electron (scintillators, etc.), and also due to secondary effects ($\delta$-electrons, etc.).

Figure 1 shows the experimentally measured radiation spectra for different electron energies in one of the layered media consisting of 300 layers. The same figure shows the radiation spectrum in the solid medium; measurements at 600 and 250 MeV have shown that the latter does not depend on the electron energy.

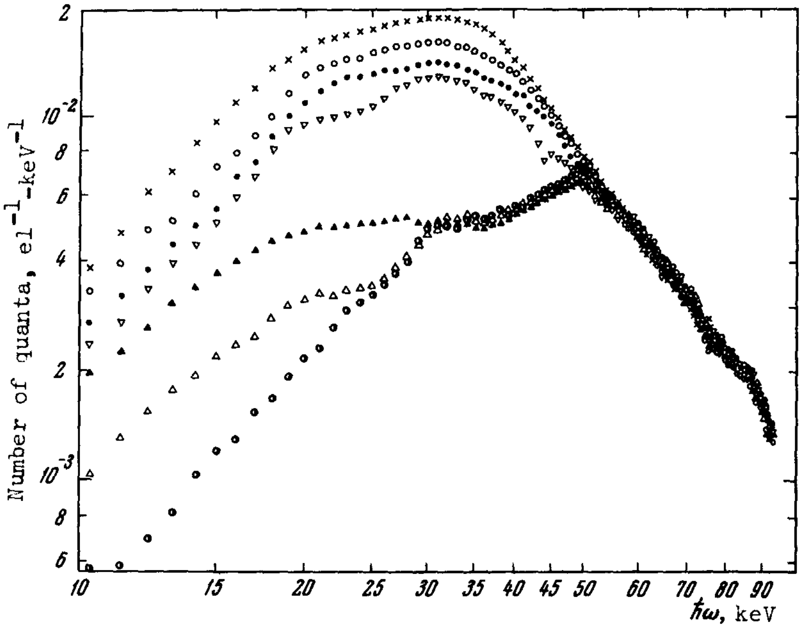

Fig. 1. Differential spectrum of the radiation of electrons having different energies in layered and solid media, $n = 300$, $\alpha = 8.85$, $l_1 = 2.43 \times 10^{-2}$ cm; × - 600, o - 550, ● - 500, ▽ - 450, ▲ - 300, △ - 250 MeV; ◑ - bremsstrahlung spectrum (solid medium).

The experimental data show that for relatively low $\gamma$ quantum energies the radiation intensity in a layered medium depends to a considerable degree on the enrgy of the electron and exceeds by many times the radiation intensity in the solid medium. With increasing $\gamma$-quantum energy the spectrum of the radiation in the layered medium gradually goes over into the spectrum of the solid medium, which does not depend on $\alpha$, $l_1$, or E when the amount of matter remains constant.

The difference in the radiation intensities in the layered and in the solid medium is compared with the results of the theory of resonance radiation with allowance for the $\gamma$-quantum absorption on their entire path (Fig. 2). We see that the experimental data exceed by many times the corresponding theoretical ones even without allowance for the $\gamma$-quantum absorption. The experimental values exceeded the theoretical ones also for all the investigated layered media with different $\alpha$, $l_1$, and n.

It seems to us that the observed difference is due to the appreciable scattering of electrons in the layered medium itself. In the theory of resonance radiation, with which the experimental data were compared, it was assumed that the multiple-scattering angle $\theta_{sc}$ at a distance on the order of the length of the period is much smaller than the characteristic radiation angle $\theta_{rad}$ [2], i.e.,

$$\frac{E_S^2}{E^2}\,\frac{l_1}{L} \ll \frac{8\pi^2 rc}{l_1(1+\alpha)\omega}\,, \qquad (1)$$

where L is the radiation length of the paper (in cm), $E_S$ = 21.2 MeV, and r the order of the radiation.

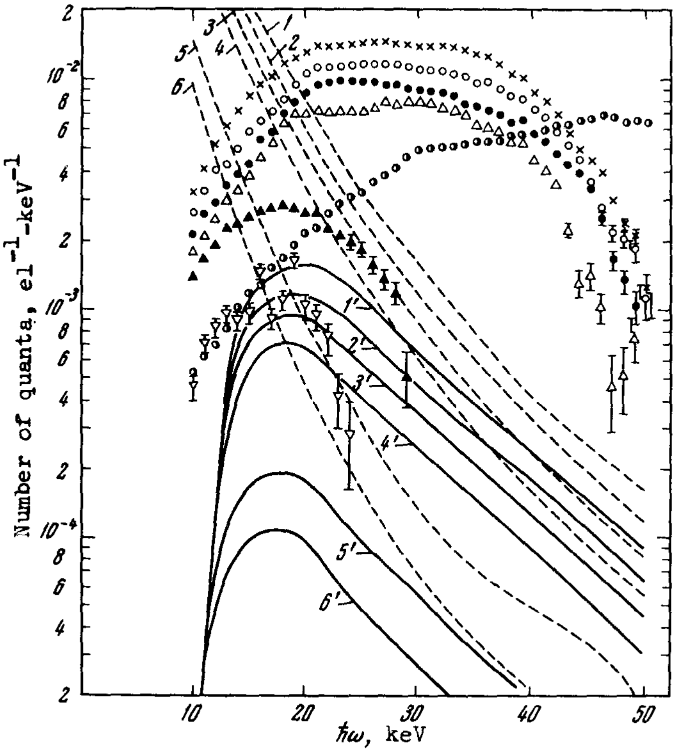

Fig. 2. Differential spectrum of resonance radiation, n = 300. Solid curves - theory of resonance radiation with allowance for absorption, dashed - without allowance for absorption. 1 and 1' - E = 600, 2 and 2' - E = 550, 3 and 3' - E = 500, 4 and 4' - E = 450, 5 and 5' - E = 300, 6 and 6' - E = 250 MeV; $\alpha$ = 8.85, $l_1$ = 2.43 x $10^{-2}$ cm; × - 600, o - 550, ● - 500, △ - 450, ▲ - 300, ▽ - 250 MeV; ◑ - bremsstrahlung spectrum (exp.).

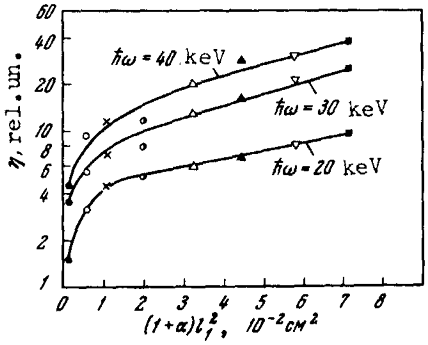

Fig. 3. The ratio ($\eta$) of the experimentally observed radiation intensity to that resulting from the theory of resonance radiation, with allowance for absorption, vs. $(1 + \alpha)l_1^2$:

● - $l_1$ = 2.83 x $10^{-3}$ cm, $\alpha$ = 18.8 ;
o - $l_1$ = 9.3 x $10^{-3}$ cm, $\alpha$ = 5.84;
× - $l_1$ = 9.3 x $10^{-3}$ cm, $\alpha$ = 11.6 ;
◑ - $l_1$ = 2.43 x $10^{-2}$ cm, $\alpha$ = 3.0 ;
△ - $l_1$ = 2.43 x $10^{-2}$ cm, $\alpha$ = 4.54;
▲ - $l_1$ = 2.43 x $10^{-2}$ cm, $\alpha$ = 6.59;
▽ - $l_1$ = 2.43 x $10^{-2}$ cm, $\alpha$ = 8.85;
■ - $l_1$ = 2.43 x $10^{-2}$ cm, $\alpha$ = 11.1 .

Condition (1) is not satisfied in this experiment, becoming worse with increasing $\alpha$. For example, for $l_1$ = 2.43 x $10^{-2}$ cm, $\hbar\omega$ = 20 keV, and E = 600 MeV we have $\langle\theta_{sc}^2\rangle/\theta_{rad}^2$ = 1.0 and 7.0 for $\alpha$ = 3 and 6.59 respectively.

Figure 3 shows the ration of the experimental and theoretical radiation yields ($\eta$) at E = 600 MeV for different $\alpha$ and $l_1$ vs. the quantity $l_1^2(1 + \alpha)$, which is proportional to $\langle\theta_{sc}^2\rangle/\theta_{rad}^2$. The data show that with increasing deviation from the condition (1), the value of $\eta$ increases, whereas $\eta \to 1$ as $\langle\theta_{sc}^2\rangle/\theta_{rad}^2 \to 0$.

It is known that the influence of multiple scattering in transition radiation should lead to the appearance in its spectrum of photons of relatively high energy, which do not appear when scattering is not taken into account [7]. Apparently a similar phenomenon takes place in resonance radiation, which is not taken into account in the theory.

The fact that there is no theory of resonance radiation with allowance for the influence of multiple scattering, together with the interference between the resonance and the bremsstrahlung radiations, does not permit a corresponding comparison between experiment and theory.

Thus, we have experimentally observed radiation of electrons in a layered medium, with an intensity that exceeds by many times in the x-ray region the intensity of the bremsstrahlung, and which depends strongly on the particle energy (like $E^n$, where $n \gtrsim 2$); this can be used to measure the particle energy.

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# CONSEQUENCES OF CROSSING SYMMETRY FOR πN-SCATTERING S WAVES

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The problems of symmetry and invariance have recently gained in importance for the study of elementary particles. In this connection, Wigner [1] proposed a general classification of invariance properties, according to which all the properties are divided into geometric and dynamic. An intermediate position in the proposed classification is occupied by the principle of crossing symmetry, which can be formulated in the language of events, i.e., without reference to any particular form of interaction. However, his formulation and the experimental verification have made it possible to propose that an analytic expression for the amplitude