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RADIATION OF RELATIVISTIC ELECTRONS IN LAYERED MEDIA

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We report the experimental results of a study of the properties of radiation in the x-ray portion of the spectrum arising on passage of electrons with energies up to 600 MeV through various layered media. We have studied the spectra of the radiation, and the dependence of intensity on the electron energy, on the period of the layered medium, and on the number of layers. In the γ-ray energy region up to 60—70 keV we have observed in a layered medium radiation whose intensity exceeds by many times the corresponding intensity of bremsstrahlung. The experimental results are compared with the theory of resonance radiation.[1,2] The data obtained on the absolute magnitude exceed the theoretical values in individual cases by more than an order of magnitude and indicate that this excess is due to the substantial scattering of the electrons.

1. INTRODUCTION

THE properties of resonance radiation arising on passage of relativistic charged particles through a layered medium consisting of alternating layers of two different materials has been discussed in detail previously.[1-3]

This radiation was experimentally observed for the first time by us in 1963,[4-7] in an experiment in which the high energy μ mesons of the horizontal cosmic ray flux were used as the primary particles. The μ mesons passed through a layered medium consisting of 300 layers of paper of thickness $l_1 = 2.1 \times 10^{-2}$ cm each, placed in air at a distance of 1 cm apart. Photons with energy above 35 keV produced by a charged particle in the layered medium were absorbed in xenon, and the radiation finally detected was the characteristic x radiation of the xenon atom with an energy of 35 keV.

The apparatus is similar to a Cerenkov counter both in the sense of its sensitivity to particle direction and its threshold properties but, in contrast to a Cerenkov counter, can operate in the region of $\beta = v/c$ different from unity in the eighth to tenth place.

As a consequence of the threshold properties of the radiation being studied, the efficiency of the experimental apparatus depends sharply on the energy of the μ mesons being recorded. Thus, for an increase in μ-meson energy from 700 to 1000 BeV the efficiency changes from 10^{-7} to 10^{-2}, and for E = 4000 BeV it reaches a value of 16%. An analysis shows that the efficiency of this apparatus can be raised to 50% by simple improvement.

The experimental results showed that there is no substantial difference between the data obtained and the theory of resonance radiation. According to the latter, the number of photons radiated by a charged particle with energy E in the frequency interval $d\omega'$ in 1 cm of a layered medium is given by the expression:[1-3]

$$dm = \frac{4p^2(1+\alpha)}{137\pi l_1} \sum_{r=1}^{r_{max}} \frac{d\omega'}{r^3\omega'^3} \frac{[1 - {}^1/_4(E_{1\,\mathrm{thr}}/E)^2\omega'/r - 1/\omega' r]}{(1-p/\omega' r)^2(1+p\alpha/\omega' r)^2}$$
$$\times \sin^2\left[\frac{\pi\alpha}{1+\alpha}\left(r - \frac{1}{\omega'}\right)\right], \tag{1}$$

where l_1 is the thickness of the layer of dense material and $l_2 = \alpha l_1$ is the distance between the layers:

$$p = (N_1 - N_2)/(N_1 + \alpha N_2),$$

where N_1 and N_2 are the densities of electrons (cm^{-3}) in the first and second media, respectively (for the layered media studied $\alpha N_2 \ll N_1$ and $p \approx 1$).

The frequency ω' in formula (1) is expressed in units of

$$\omega_{1\,min} = l_1 r_e c(N_1 + \alpha N_2), \tag{2}$$

where r_e is the classical electron radius and c is the velocity of light.

The radiation is the sum of radiations of different orders r, each of which arises at energies above a threshold value for the given value of r:

$$E_{r\,\mathrm{thr}} = mc^2 l_1[\pi^{-1} r_e(1+\alpha)(N_1 + \alpha N_2)]^{1/2}/r. \tag{3}$$

In formula (1) $E_{1\,\mathrm{thr}}$ is the threshold energy for the first harmonic (r = 1).

In the present experiment we studied the properties of resonance radiation arising on passage of electrons with energies up to 600 MeV through various layered media in the γ-ray energy range from 10 to 100 keV. In this case only harmonics of higher orders ($r \gg 1$) are generated, as a consequence of which the sharply expressed oscillations of intensity occurring on generation of the first harmonics are absent in the γ-ray energy interval studied. The dependence of intensity on γ-ray energy has the form of sharply falling smooth curves. For layered media with the same number of layers n and the same value of l_1 the yield of radiation does not depend on α. It should be noted that for $r \gg 1$ the resonance is destroyed and a simple summation of the transition radiation at the boundaries of the layered medium then occurs.

The angle at which the resonance radiation photons are emitted is

$$\theta_R \approx \left[\frac{4\pi rc}{\omega l_1(1+\alpha)} - \left(\frac{mc^2}{E}\right)^2 - \frac{\omega_0^2}{\omega^2}\right]^{1/2},$$
$$\omega_0 = (4\pi N_{\mathrm{eff}}\, l^2/m)^{1/2},$$
$$N_{\mathrm{eff}} = (N_1 + \alpha N_2)/(1+\alpha). \tag{4}$$

The properties of the resonance radiation have been discussed in detail previously.[2,3,7] Preliminary results of the present experiment have been reported briefly.[8]

2. EXPERIMENT

The present experiment was performed with the electron synchrotron at the Lebedev Institute with a maximum energy of 680 MeV. The experimental arrangement is sketched in Fig. 1.

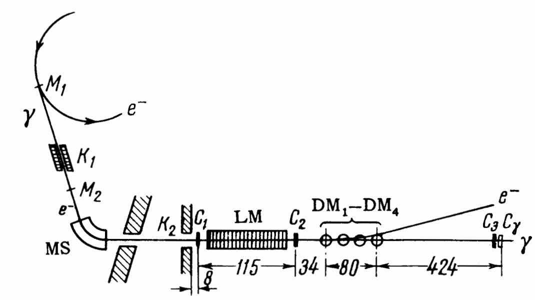

FIG. 1. Sketch of the experimental setup: M_1, M_2 – internal and external targets, K_1, K_2 – collimators, MS – magnetic spectrometer, LM – layered medium, DM_1–DM_4 – deflecting magnets, C_1, C_2, C_3 – scintillation counters, C_γ – γ spectrometer. Also shown are certain linear dimensions in centimeters.

By means of a slow spill of the accelerated electrons onto the target M_1 located inside the synchrotron vacuum chamber, a γ-ray beam was produced which had a duration of 0.5 sec. After a collimator K_1 the γ rays were converted in a lead target M_2 into electron-positron pairs. A magnetic spectrometer MS allowed separation of electrons of the desired energy with an energy spread of 2–5%. The number of electrons per pulse (the pulse repetition frequency was 1/6 sec^{-1}) detected by the experimental apparatus after collimator K_2 was $\sim 10^3$ for an electron energy E = 600 MeV and $\sim 10^5$ for E = 250 MeV. The electrons were detected by a telescope consisting of two thin plastic scintillators C_1 and C_2 of respective dimensions $3 \times 7 \times 0.5$ cm and $4 \times 7 \times 0.5$ cm, located before and after the layered medium LM and connected in coincidence.

The photons of the radiation under study are emitted at small angles to the direction of electron motion (see Eq. (4)) and in order to have the possibility of detecting them, the electrons were deflected from their initial direction by means of a magnetic field. The deflecting magnetic field was produced by four identical permanent magnets DM_1–DM_4 located beyond counter C_2. The action of the deflecting magnets was verified experimentally. We measured the ratio of $C_1 + C_3$ coincidences to $C_1 + C_2$ coincidences. The departure of this ratio from unity indicates that part of the electrons fail to be deflected by the magnets sufficiently to miss scintillator C_3, immediately beyond which is located the γ spectrometer C_γ which records the γ rays of the radiation under study. In the worst case (E = 600 MeV) about 9% of the electrons are not deflected and hit scintillator C_3. For this reason in the main measurements scintillator C_3 (dimensions $7 \times 7 \times 0.5$ cm) was connected in anticoincidence, and events in which a charged particle entered the γ spectrometer were excluded in this way.

The γ spectrometer consisted of a scintillation counter employing a NaI(Tl) crystal 7 cm in diameter and 7 cm thick. The crystal used completely absorbs γ rays of the energies being studied (up to 100 MeV) and has an efficiency close to 100% for this region.

All of the counters C_1, C_2, C_3, and the γ spectrometer C_γ utilized type FÉU-24 photomultipliers. The number of electrons passing through the layered medium were recorded by a scaling circuit counting coincidences of scintillators C_1 and C_2. The resolving time of the coincidence circuit was 10^{-8} sec. The final events detected were $C_1 + C_2 + C_\gamma - C_3$. This corresponds to an electron passing through counters C_1 and C_2 and then being deflected by the magnets, and producing in the layered medium a γ ray which is detected by the γ spectrometer.

To study the spectrum of the radiation, the pulses from the γ spectrometer were fed through a linear amplifier to the input of a 100-channel pulse-height analyzer of type AI-100, which was triggered by a pulse from the final coincidence circuit. Calibration of the γ spectrometer was accomplished with the radioisotopes Ce^{144} (30 and 134 keV) and Cs^{137} (662 keV). By adjustment of the gain of the linear amplifier and the γ-spectrometer photomultiplier we set the channel width of the pulse-height analyzer so that 1 V corresponded to a γ-ray energy interval of 1 keV. The results of the γ-spectrometer calibration were verified by measurement of the K line of the characteristic radiation of xenon (35 keV) and it was found that the width of the measured 35-keV line was 17%.

In all γ-ray spectrometers, as a consequence of the finite resolution of the apparatus, there is not an exact correspondence between the γ-ray energies and the pulse heights. In the most general case the problem of conversion from the raw pulse-height distribution to the desired energy distribution reduces to solution of the integral equation[9]

$$P(a) = \int N(E_\gamma) K(E_\gamma, a) \, dE_\gamma \tag{5}$$

to find $N(E_\gamma)$, where P(a) is the measured pulse-height distribution, $N(E_\gamma)$ is the desired γ-ray energy spectrum, and $K(E_\gamma, a)$ is the probability that a γ ray with energy E_γ produces a pulse with amplitude a. Using for $K(E_\gamma, a)$ the expression[10]

$$K(E_\gamma, a) = \left(\frac{\pi W^2}{\ln 2}\right)^{-1/2} \exp\left[-\frac{(E_\gamma - a)^2 \ln 2}{W^2}\right], \tag{6}$$

where W is the half-width of the photopeak, we solved Eq. (5) for the portion of the spectrum being studied, by the method of successive approximations with a Razdan-2 computer. These calculations show that the pulse-height spectra obtained experimentally may differ from the calculated energy spectra by only 10—20%, and that mainly in the beginning and end portions of the spectra.

Various layered media were used in the experiment. Each layered medium was assembled of sheets of paper mounted parallel in air. The choice of paper ($Z \approx 6$) was governed mainly by the low absorption of γ rays of the range being studied in the layered medium itself, the relatively low yield of bremsstrahlung, and the comparative simplicity of preparation of the medium. Paper of three different thicknesses was used: $l_1 = 2.43 \times 10^{-2}$ cm (Whatman paper), $l_1 = 9.3 \times 10^{-2}$ cm (writing paper), $l_1 = 2.83 \times 10^{-3}$ cm (duplicating paper).

To obtain a single period of the layered medium, the paper was glued to flat metal rings of transformer iron 5.37×10^{-2} cm thick with an internal diameter of 10 cm and external diameter of 14 cm. The metallic rings were subjected in advance to appropriate mechanical processing and cleared of burrs, and were satisfactorily flat. After glueing, the paper was slightly moistened; after drying, a paper layer tightly stretched on the ring was obtained. The necessary number of layers prepared in this way were stacked and tightly pressed by two metallic flanges 1.5 cm thick with an opening 10 cm in diameter. The distance between the layers $l_2 = \alpha l_1$ is given by the thickness of the metallic ring, and when we wished to obtain larger values of α, additional empty rings of the necessary number were placed between the layers. Repeated measurements of the thickness of the paper and the metallic rings, and of the period as a whole, showed that the mean-square error in the thickness values is less than 2%.

Study of the resonance radiation was performed in layered media with the following values of paper thickness l_1, the quantity α, the total length of the

Table I

l_1, cm	$2.43 \cdot 10^{-2}$						$9.3 \cdot 10^{-3}$			$2{,}83 \cdot 10^{-3}$
α	3.0	4,54	6,59	8,85	11.1	19.8	5.84	11,6	28.9	18.8
L, cm	29,2	40.2	55,1	71,3	87,2	49,5	49,7	91.4	38.0	58,6
n	300	300	300	300	300	100	780	780	130	1050
t, g/cm^2	6,2	6.2	6,2	6.2	6.2	2,07	6.2	6,2	1,03	3,52
$\omega_{1\,\min}$, keV	35,7	35.7	35.7	35,7	35.7	35,7	13.8	13.8	13,8	4,2
$E_{1\,\mathrm{thr}}$, keV	3840	4490	5260	6000	6652	8770	1920	2610	4065	998

Table II

l_1, cm	$2.43 \cdot 10^{-2}$							
α	11.1	11.1	11.1	11.1	11,1	4,54	6,59	8,85
L, cm	58,2	29,1	14.5	7.3	2,9	6.7	9.2	11,9
n	200	100	50	25	10	50	50	50
t, g/cm^2	4.15	2.07	1.04	0.52	0.21	1.04	1,04	1.04

layered medium $L = nl_1(1 + \alpha)$, the number layers n, and the quantity of material t (see Table I).

Table I also lists the corresponding values of minimum frequency of the first harmonic of resonance radiation $\omega_{1\,\min}$ (see Eq. (2)) and values of the threshold energy for the first harmonic $E_{1\,\mathrm{thr}}$ from Eq. (3). Study of the dependence of intensity of resonance radiation on the number of layers was performed for the layered media whose parameters are listed in Table II.

When an electron moves in a layered medium, bremsstrahlung occurs in addition to resonance radiation, and it is obvious that the latter can be observed only in the case when its intensity is at least comparable with the intensity of bremsstrahlung. It should be emphasized that bremsstrahlung occurs not only in the material of the layered medium, but also in the remaining material existing in the path of the electron (the material of the scintillators, their containers, air, etc.).

It is obvious that to separate the desired spectrum of resonance radiation from the total radiation observed experimentally, it is necessary to subtract the bremsstrahlung spectrum, which forms the background in the present case. For this purpose we performed measurements in which the layered media were compressed to $\alpha = 0$, and the metallic rings of the layered medium were absent. To verify the fact that the minute air gaps remaining between the individual layers after compression to $\alpha \approx 0$ did not lead to occurrence of additional radiation, the same measurements were made for a solid block of plastic of the same thickness (plastic is equivalent to paper as a medium for bremsstrahlung), the metallic flanges used to compress the layered medium also being absent in this case.

The spectra measured in the two cases agree completely with each other. In addition, the high-energy part of the spectra ($\hbar\omega \gtrsim 50$—60 keV; in this portion of the spectrum only bremsstrahlung occurs) in layered media with different numbers of metallic rings (different α) and the spectra in continuous media also agree. This indicates that γ rays scattered in the metallic flanges and rings are not recorded. It turned out also that, as would be expected from the theory of bremsstrahlung, the bremsstrahlung spectra for electrons with energies from 250 to 600 MeV do not depend on the electron energy.

An analysis shows that radiation produced by secondary processes (δ electrons, pairs, etc.) in the material, whose thickness for all of the media studied did not exceed 0.2 radiation lengths, amounts to not more than 10—15% of the bremsstrahlung from the primary particle. It is assumed that in subtraction of the background the contribution of the secondary processes is also automatically subtracted.

3. EXPERIMENTAL RESULTS AND DISCUSSION

Figure 2 shows the measured dependence on γ-ray energy of the ratio of the intensity of radiation of 600-MeV electrons in the various layered media to the intensity of radiation in the same amount of material of a continuous medium. In the initial portion of the spectrum the intensity in the layered medium considerably exceeds the bremsstrahlung intensity. This excess is as much as a factor of fifty, depending on the parameters of the

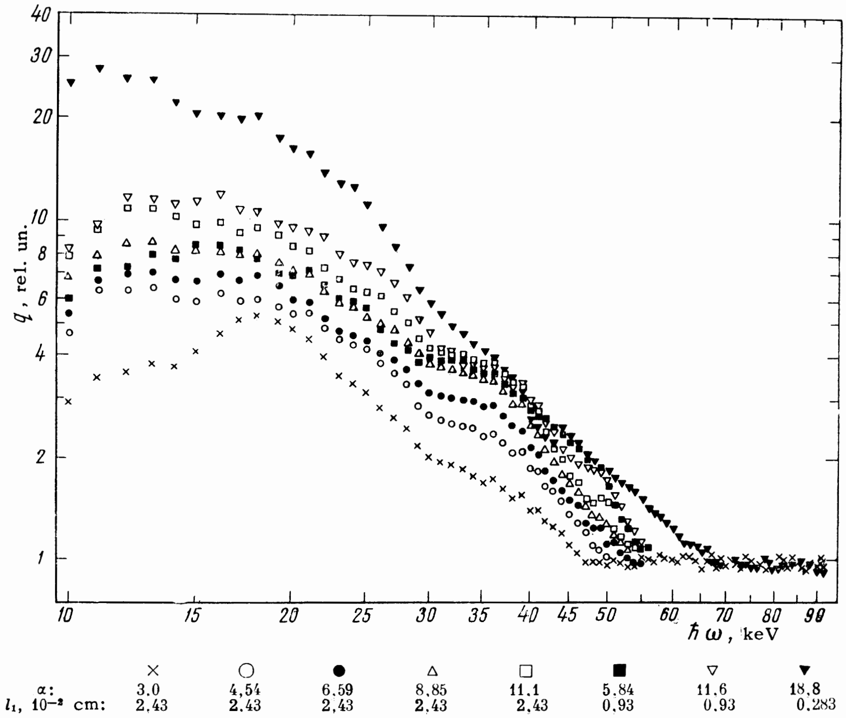

FIG. 2. Ratio of intensities of radiation in layered and continuous media; E = 600 MeV. The parameters of the layered media are as follows:

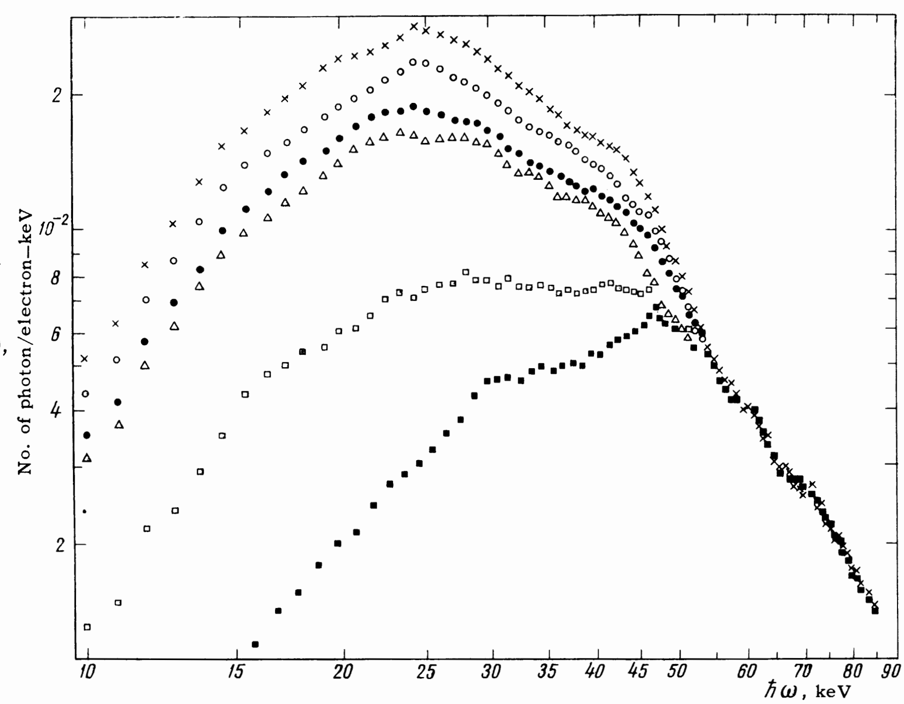

FIG. 3. Differential spectrum of radiation in a layered medium with $l = 9.3 \times 10^{-3}$ cm, $\alpha = 11.6$; n = 780. Electron energy (in MeV): × – 600, ○ – 550, ● – 500, △ – 450, □ – 300, ■ – bremsstrahlung spectrum.

layered medium in the different cases. With an increase in γ-ray energy the difference in the intensities of radiation in the layered and continuous media gradually disappears and for $\hbar\omega \gtrsim 50$—60 keV the radiation in the layered medium does not differ from the radiation in the continuous medium. This additional radiation with a high intensity in the x-ray part of the spectrum (up to $\hbar\omega \lesssim 50$ keV) arises as the result of nonuniformity of the medium. For electrons of lower energies this ratio has a similar dependence on γ-ray energy with the only difference that the yield of radiation in the layered medium decreases in absolute value, and the ratio of the intensities is comparable with unity for smaller γ-ray energies.

Figure 3 shows the experimentally measured spectra radiated by electrons of different energies in one of the layered media. Also shown are the spectra radiated in the continuous medium. The data show that for comparatively low γ-ray energies the intensity of radiation in the layered medium depends to a strong degree on the electron energy. With increasing γ-ray energy the spectrum of radiation in the layered medium gradually approaches the spectrum for the continuous medium, and the latter, for the same quantity of material, does not depend on E, l_1, and α. Similar radiation spectra were obtained for all the layered media whose parameters are listed in Table I, but all of the spectra are not shown.

The difference in the intensities of radiation in the layered and continuous media is identified with resonance radiation. Figures 4 and 5 show the experimental spectra together with the corresponding

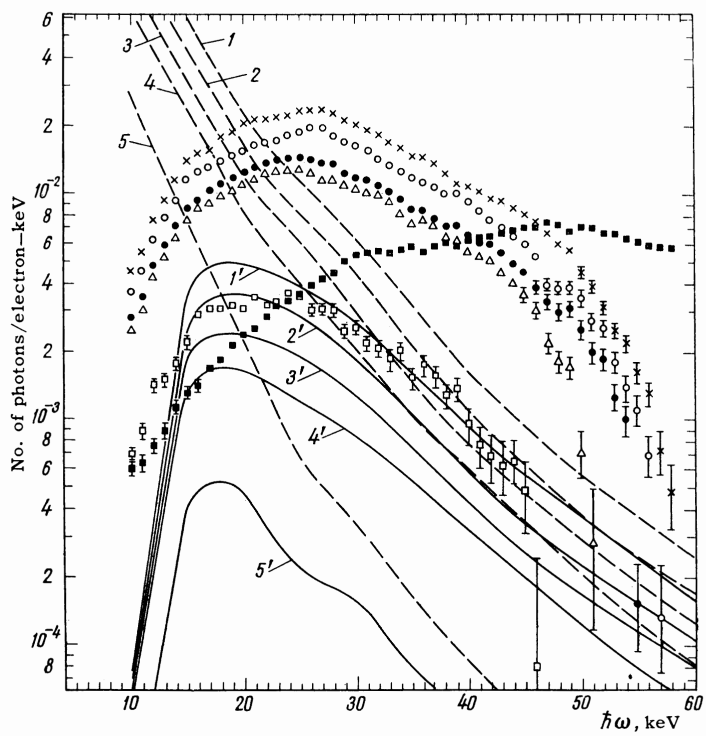

FIG. 4. Differential spectrum of resonance radiation in a layered medium with $l_1 = 9.3 \times 10^{-3}$ cm; $\alpha = 11.6$; n = 780. Curves 1–5 – theory of resonance radiation without inclusion of absorption, curves 1′–5′ – with inclusion of absorption. Electron energy (in MeV): ×, 1,1′ – 600; ○, 2,2′ – 500; ●, 3,3′ – 500; △, 4,4′ – 450; □, 5,5′ – 300; ■ – bremsstrahlung spectrum.

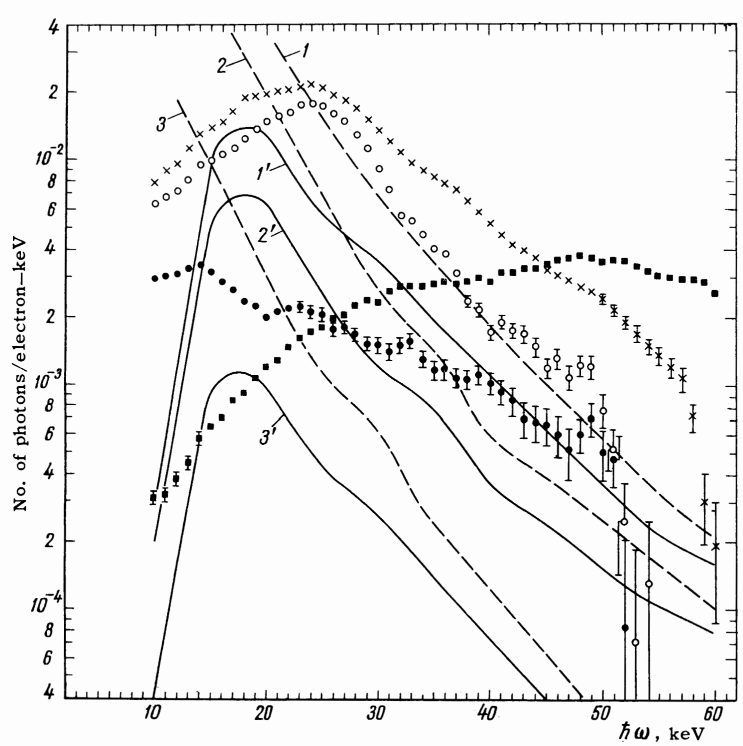

FIG. 5. Differential spectrum of resonance radiation in a layered medium with $l_1 = 2.83 \times 10^{-3}$ cm, $\alpha = 18.8$; n = 1050. Curves 1–3 – theory of resonance radiation without inclusion of absorption, curves 1′–3′ – with inclusion of absorption. Electron energy (in MeV): ×, 1,1′ – 600; ○, 2,2′ – 500; ●, 3,3′ – 300; ■ – bremsstrahlung spectrum.

theoretical spectra of resonance radiation, with inclusion of the effect of absorption in the layered medium itself and in the entire particle path (solid curves), and also without inclusion of this absorption (broken lines). As we can see from these figures, the experimental data exceed by many times the corresponding theoretical values obtained without taking into account γ-ray absorption, this discrepancy increasing with increasing γ-ray energy (not considering the region $\hbar\omega \lesssim 20$ keV, where accurate inclusion of the absorption is difficult). The same increase in discrepancy between experiment and theory occurs with an increase of l_1.

It should be noted that according to theory the intensity of radiation in the layered media studied, for electrons with energies up to 600 MeV for the same values of the layer thickness l_1 and the number of layers n, should not depend on α. However, the experimental data show that with increasing α the intensity of radiation increases.

In Fig. 6 we have shown for illustration the experimental spectra of resonance radiation produced by 550-MeV electrons in layered media with $l_1 = 2.43 \times 10^{-2}$ cm and $l_1 = 9.3 \times 10^{-3}$ cm for given values of α.

The dependence of the intensity of radiation on the electron energy for different γ-ray energies and

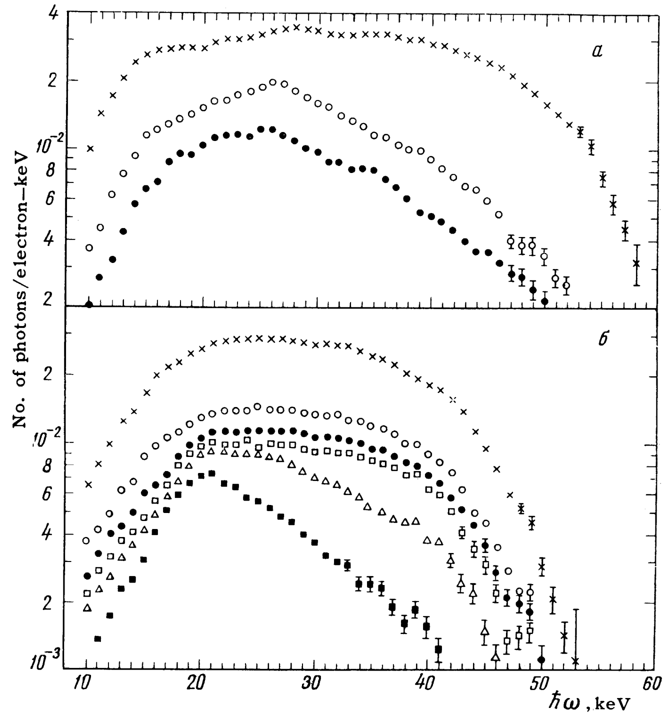

FIG. 6. Differential spectra of resonance radiation in layered media with different α (E = 550 MeV); a – $l_1 = 9.3 \times 10^{-3}$ cm; α = 28.8 (×), 11.6 (○), 5.84 (●); b – $l_1 = 2.43 \times 10^{-2}$ cm; α = 19.8 (×), 11.1 (○), 8.85 (●), 6.59 (□), 4.54 (△), 3.0 (■).

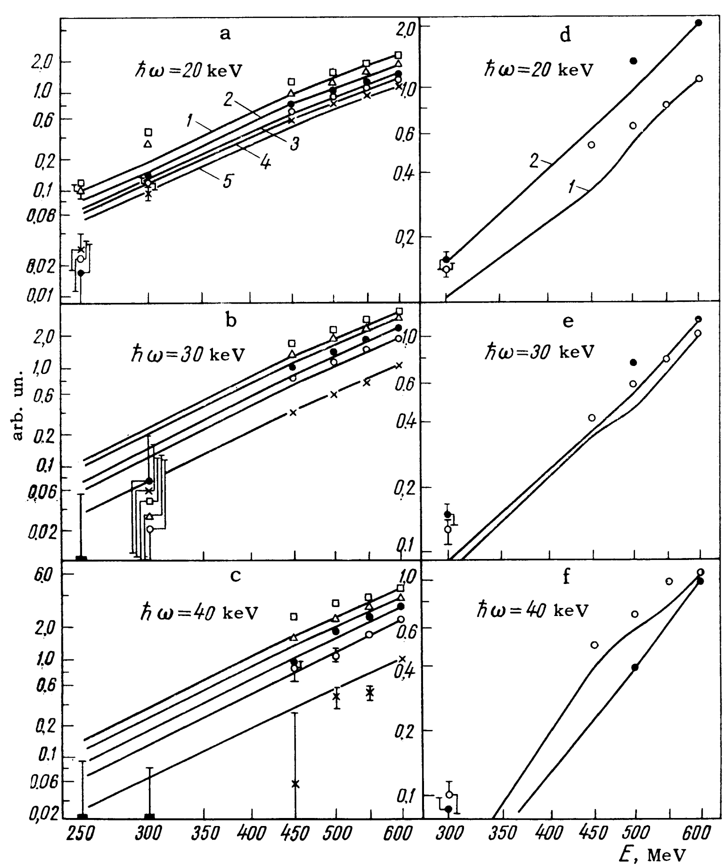

FIG. 7. Number of resonance radiation photons as a function of electron energy for different layered media and α-ray energies: a, b, c – for $l_1 = 2.43 \times 10^{-3}$ cm, n = 300, α = 3.0 (×), 4.54 (○), 6.59 (●), 8.85 (△), 11.1 (□); d, e, f – for $l_1 = 9.3 \times 10^{-3}$ cm, n = 780, α = 11.6 (○) and $l_1 = 2.83 \times 10^{-3}$ cm, n = 1050, α = 18.8 (●). The theoretical curves (solid line) are joined to the experimental data at the point E = 600 MeV.

for different layered media is shown in Fig. 7. The data are given in arbitrary units. In these plots the theoretical curves are normalized to the experimental data at the point E = 600 MeV. In the region of comparatively low electron energies a stronger dependence of intensity on electron energy is observed than is expected from theory. Over the entire energy region studied from 250 to 600 MeV this dependence has a form $\sim E^{\gamma}$, where $\gamma \gtrsim 2$.

The yield of radiation for a small number of layers is relatively large, which is due to the small absorption of the radiation in the layered medium itself. For a large number of layers this yield gradually approaches saturation. These data are shown in Fig. 8.

It appears to us that the observed excess of the experimental data over the theoretical values and the dependence of the yield of radiation on α are due to a substantial scattering of the electrons in the layered medium. Actually the theory of resonance radiation[2] with which the experimental data are being compared is based on the assumption that the multiple scattering angle $\langle\theta_s^2\rangle$ in a path of the order of the period of the layered medium must be considerably less than the characteristic angle of the resonance radiation, i.e.,

$$\langle\theta_s{}^2\rangle \ll \theta_R{}^2, \tag{7}$$

where $\langle\theta_s^2\rangle = E_s^2 l_1/E^2 L_1$, E_s = 21.2 MeV, L_1 is the radiation length of the material of the layered medium, and the angle of radiation θ_R is given by Eq. (4). In the present experiment, condition (7) is not fulfilled in most cases, particularly with increased values of α, l_1, and ω. For example, for $l_1 = 2.43 \times 10^{-2}$ cm, $\hbar\omega$ = 20 keV, and E = 600 MeV, the ratio $\langle\theta_s^2\rangle/\theta_R^2$ is respectively ~1.0 and ~7.0 for α = 3.0 and α = 6.59.

On the other hand, it is well known that the effect of multiple scattering in transition radiation should lead to appearance in its spectrum of relatively high-energy photons which are absent when this scattering is not taken into account.[11] In transition radiation the limiting frequency, up to which the spectrum of this radiation is broadened as the result of substantial scattering of the particle, is connected with the angle of emission of transition radiation mc^2/E. The angle of emission of resonance-radiation photons for the harmonics r which give the principle contribution to the intensity of the radiation is less than mc^2/E.

In addition, in transition radiation the scattering is appreciable in a coherence length, which in the case of resonance radiation is equal to the period of the layered medium and is r times larger than in transition radiation. However, under the conditions of the present experiment r_{min} is always $\gg 1$, where r_{min} is the minimum number of harmonics for which radiation occurs for a given electron energy, and its value is determined from the condition that the numerator in formula (1) is positive and approximately equal to

$$r_{\min} \approx \frac{1}{4\pi}\left(\frac{mc^2}{E}\right)^2 l_1(1+\alpha)\frac{\omega}{c}. \tag{8}$$

Therefore, as the result of scattering, the electron is carried outside the limits of angle of the radiation, at lower energies than occurs in transition radiation. Since the quantity r_{min} increases with

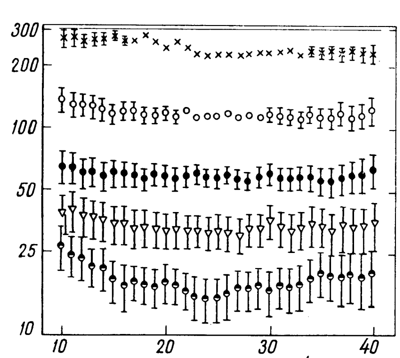

FIG. 8. Ratio of the yield of resonance radiation for different numbers of layers n to the yield for n = 300: × – n = 200, ○ – 100, ● – 50, ∇ – 25, ◒ – 10. The ordinate represents the relative yield of radiation, expressed in units of number of layers.

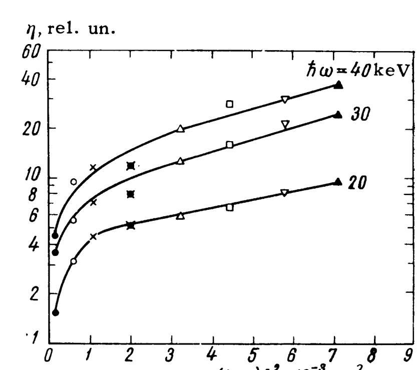

FIG. 9. The ratio (η) of the experimental yield of resonance radiation to the resonance radiation obtained from theory with inclusion of absorption, as a function of the quantity $(1+\alpha)l_1^2$ for different layered media. The parameters of the layered media are as follows:

	●	○	×	⊗	△	□	▽	▲
l_1, 10^{-2} cm:	0.283	0.93	0.93	2.43	2.43	2.43	2.43	2.43
α:	18.8	5.84	11.6	3.0	4.54	6.59	8.85	11.1

increasing l_1, α, and ω, the excess of the experimental data over the theoretical values also increases correspondingly.

This is illustrated by Fig. 9, which shows the ratio (η) of the experimentally observed yield of radiation to the theoretical value as a function of the quantity $l_1^2(1 + \alpha)$, which is roughly proportional to the ratio $\langle\theta_s^2\rangle/\theta_R^2$. The data are shown for E = 600 MeV and for three γ-ray energies, and show that with increasing degree of violation of condition (7) the value of η increases, while for $\langle\theta_s^2\rangle/\theta_R^2 \to 0$ the value of $\eta \to 1$. With decreasing electron energy an increase in the degree of excess of the experimental data over the theoretical values is also observed, which also follows from formula (8). For accurate comparison of experiment with theory it is necessary to take into account strictly in the theory the multiple scattering of particles in the layered medium.

Summing up, we can state that we have experimentally observed in a layered medium radiation from relativistic electrons with an intensity in the x-ray portion of the spectrum exceeding by many times the intensity of all forms of radiation known up to this time; we have studied in detail the main properties of this radiation. The intensity of the radiation depends to a strong degree on the electron energy, which opens up the possibility of its efficient use to detect and measure the energy of superhigh-energy particles.

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