Effect of the medium on the bremsstrahlung spectrum of 40-GeV electrons

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An experiment is described on the Landau-Pomeranchuk effect, using the 40-GeV electron beam of the Serpukhov accelerator (High Energy Physics Institute). Energy spectra of the bremsstrahlung emitted by these electrons between 20 and 80 MeV in thin (0.05–0.15 radiation lengths) tungsten, lead, aluminum, and carbon targets are reported. The bremsstrahlung intensity in this energy range is found to be higher in the case of heavy targets (by 30–60%) than in light targets. Comparison with theoretical predictions shows that the reduction in emission from heavy substances is not less than predicted by the Landau-Pomeranchuk-Migdal theory.

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INTRODUCTION

It is well known (see, for example, [1-8]) that the interaction between a high-energy electron and a dense medium is collective in character, and this leads to a reduction in bremsstrahlung intensity as compared with the Bethe-Heitler spectrum. The reduction in emission probability may be due to different effects in the medium. Landau and Pomeranchuk [1] were the first to show that the bremsstrahlung spectrum might be modified as a result of multiple scattering. The effect of the polarization of the medium has been investigated in detail by Ter-Mikaelyan. [2] A more rigorous quantum-mechanical approach to the bremsstrahlung spectrum has been used by Migdal [3] who took into account both multiple scattering and polarization effects. The fact that photon absorption might affect the bremsstrahlung spectrum was pointed out by Landau and Pomeranchuk. [1] The absorption of virtual photons was subsequently considered by several workers. [4-6] Reasonably complete reviews of theoretical work on bremsstrahlung processes in a dense medium are given in [7,8].

The number of experimental papers concerned with the verification of these theories is, however, much smaller. The polarization effect was considered in some detail in [9]. Agreement was established with the theoretical spectrum corrected for the polarization effect in the low-energy region for primary electrons with energies below 1 GeV. The effect of multiple scattering has been investigated in connection with cosmic rays. [10,11] The bremsstrahlung intensity from electrons with energies in excess of 10^4 GeV was found to be much lower than predicted by the Bethe-Heitler theory. Difficulties in the determination of the primary energy of electrons and in the accumulation of adequate statistical material have prevented an improvement in the precision of the experimental data, which would enable a comparison to be made between experimental and theoretical spectra.

Studies of the shape of the bremsstrahlung spectrum from ultrarelativistic electrons have become possible since the advent of high-energy (tens of GeV) electron accelerators. Calculations performed during the runup to the present experiments showed that, even at electron energies of 30–40 GeV, multiple scattering in a dense medium should lead to a substantial modification of the bremsstrahlung spectrum at low energies as compared with the Bethe-Heitler spectrum. Figure 1 shows the results obtained with the Migdal formulas [3] for 40 GeV primary electrons. This figure also shows the Bethe-Heitler spectrum. The difference between the spectra at bremsstrahlung energies in excess of a few MeV is connected with the reduction in intensity due to multiple scattering.

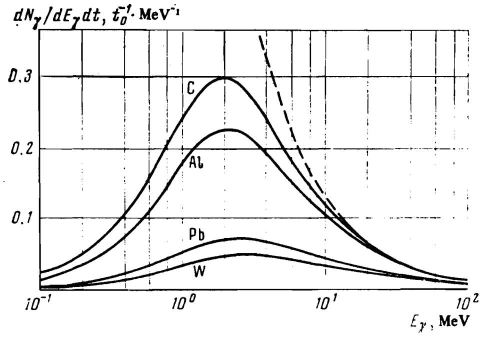

FIG. 1. Bremsstrahlung spectra for 40-GeV electrons in carbon, aluminum, lead, and tungsten, calculated from the Migdal formulas. Broken curve—Bethe-Heitler spectrum.

In this paper, we report measurements of the effect of multiple scattering on the bremsstrahlung from 40-GeV electrons in different targets. The experiments were performed using the electron beam of the Serpukhov accelerator (High-Energy Physics Institute).

1. EXPERIMENTAL ARRANGEMENT

The aim of the experiment was, essentially, to determine the number of gamma rays (with energies up to a few tens of MeV) emitted by electrons in thin targets of the material under investigation. The experimental arrangement is illustrated in Fig. 2. The 40-GeV electrons (channel 2E) are defined by the scintillation counters S_1, S_2, and the total-absorption Cerenkov spectrometer C_1. Gamma rays emitted by the electrons in the target T were passed through the collimator K and recorded by the total-absorption scintillation spectrometer C_2 with a single-crystal NaI radiator. The spectrometer was surrounded by the anticoincidence screen S_3–S_6. The magnet M_1 (9 kG) deflected electrons so that the primary beam missed the spectrometer C_2 ($\alpha_1 \sim 27$ mrad). The magnet M_2 (18 kG) was used to separate the electron beams and the gamma rays emitted by them in the target T ($\alpha_1 \sim 54$ mrad).[1)]

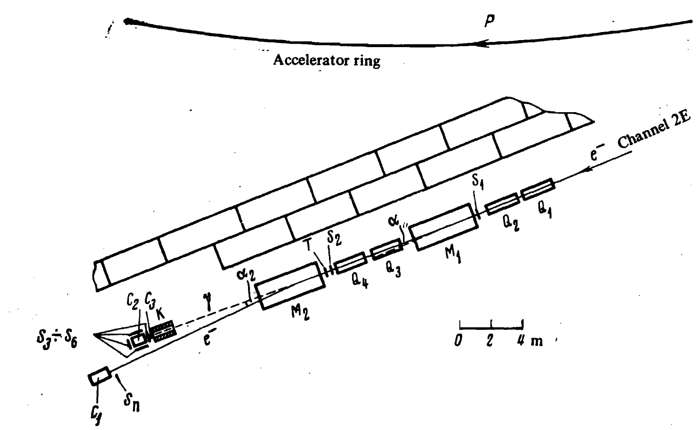

FIG. 2. Experimental arrangement.

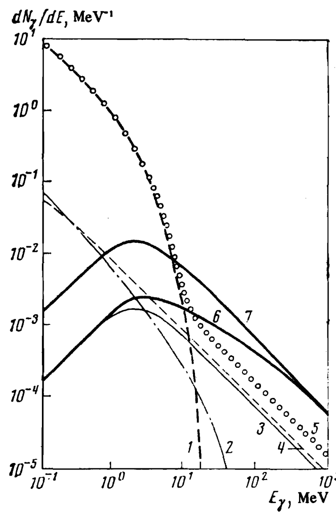

FIG. 3. Radiation spectra accompanying the 40-GeV electron beam: 1—synchrotron radiation spectrum, 2—emission by electron due to presence of counter walls, 3—emission in the defining counter, 4—bremsstrahlung in air along the beam path, 5—resultant background radiation, 6—bremsstrahlung in tungsten ($0.05t_0$), 7—bremsstrahlung in carbon ($0.05t_0$).

The output signal from the spectrometers C_1 and C_2 was a linear function of the energy of the recorded particles in the working energy region. The experiment was based on standard fast electronics developed at the High Energy Physics Institute.[13] The energy spectra of the electrons and the bremsstrahlung photons were recorded with the AI-128 pulse height analyzers. The gating signal initiating the detection of bremsstrahlung photons was taken in the form $M_a = S_1S_2C_1\overline{S_3S_4S_5S_6}$. The number of electrons reaching the radiator was taken to be $M_0 = S_1S_2$. The gain in the spectrometer channel was checked in the course of the experiment by determining the position of the ionization peak for relativistic background muons in the crystal of the spectrometer C_2.

The optimum radiator thickness was chosen to be ~ 0.1 radiation lengths. In thinner radiators ($\lesssim 0.01$ radiation lengths), the bremsstrahlung intensity was found to be comparable with the intensity emitted at the radiator boundaries, so that the formulas for bremsstrahlung in a continuous medium were no longer valid. On the other hand, shower processes which mask the measured effect become important at greater thicknesses. Figure 3 shows the calculated radiation spectra related genetically to the electron beam under our experimental conditions. Comparison of these curves shows that, at low energies ($\lesssim 10$ MeV), the intensity of the attendant background radiation exceeds the intensity of bremsstrahlung proper. On the other hand, for photon energies $\gtrsim 100$ MeV, the difference between the bremsstrahlung intensities from light (C) and heavy (W) radiators is small. Under our experimental conditions, therefore, the energy range between 20 and 80 MeV may be regarded as optimal.

In practice, there is always an attendant background of muons that are genetically related to the radiating electrons through a single primary interaction process in the internal target of the accelerator. Since the anticoincidence system has a finite efficiency, some of these muons could be recorded by the spectrometer C_2. The experimental results were therefore corrected for this effect (see below). To reduce the number of counts in the spectrometer C_2 due to these muons, the accelerator operating conditions were chosen to ensure that the muon intensity in the channel was at a minimum (~ 1000 muons per cycle).

2. MEASUREMENT RESULTS

The production of a narrow electron beam with a low gamma-ray background turned out to be a relatively complicated matter. The electron-beam profile was investigated with the scintillation counters S_1, S_2 (diameter 50×1.5 mm) and a "finger" counter S_f ($1 \times 1 \times 20$ cm). The profile of the gamma-ray beam from the target was examined with the counters S_1 and S_2 and the counter C_3 (NaI crystal, 1.5 cm in diameter). The size of the working beams at the counters C_1 and C_2 was found to be the same. Figure 4 shows the profiles of the gamma-ray beams. The influx of soft gamma rays (dashed curve) was due to synchrotron radiation in the field of the bending magnets M_1, M_2.

The main measurements of the bremsstrahlung spectra from the radiators were carried out in short series in the following sequence: bremsstrahlung spectrum from light material, bremsstrahlung spectrum from heavy material, background measurements in the absence of radiator, and spectrum of ionization losses by relativistic muons. For each radiator thickness, we usually obtained statistical data corresponding to about

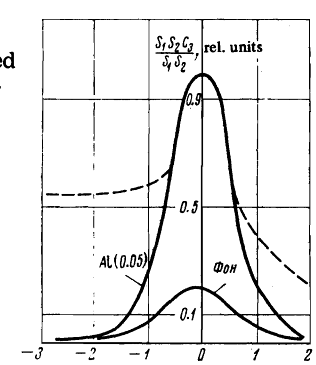

FIG. 4

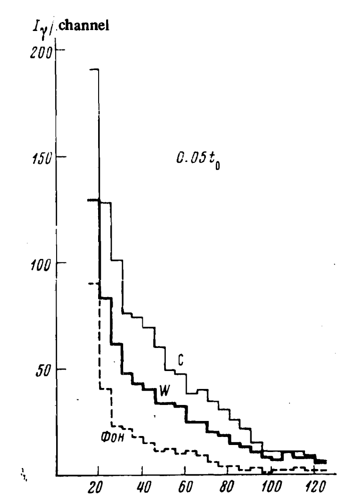

FIG. 5

FIG. 4. Profile of beams of gamma rays with energies above a few MeV. Broken curve—horizontal profile of gamma-ray beam with energy of a few MeV.

FIG. 5. Pulse-height distribution of pulses from C_2 when carbon and tungsten radiators of $0.05t_0$ were placed in the electron beam. The background corresponds to the analogous distribution without the radiator in the electron beam.

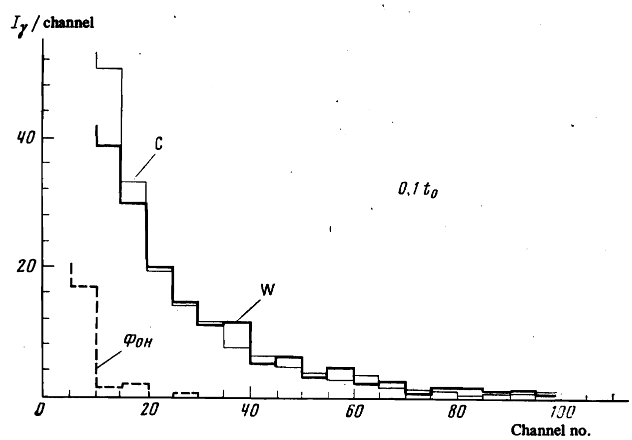

FIG. 6. Pulse-height distribution of pulses from C_2 when tungsten and carbon radiators were placed in the electron beam. The range of recorded pulses is broader by a factor of 40 as compared with Fig. 5.

10^5 counts in the monitor S_1, S_2. We used tungsten, lead, aluminum, and carbon radiators of thickness equal to 0.05, 0.10, and 0.15 radiation lengths. The radiation lengths were corrected for the use of the Born approximation and for processes in the field of atomic electrons (see [14]), so that, in the absence of multiple scattering, the bremsstrahlung intensity from the different materials was the same for equal radiator thickness expressed in radiation lengths. The thickness of the radiators in each of the series was the same to within 1–3%.

The pulse-height spectra recorded in one of the main series of measurements are shown in Fig. 5. It is clear that the bremsstrahlung intensity from the heavy radiators is lower than from the light radiators of corresponding thickness.[2)] In the case of more energetic photons (with energies of a few GeV), the difference between the corresponding spectra becomes negligible (Fig. 6). These results in themselves (without detailed analysis) indicate that the emission processes are reduced in heavy materials in the soft part of the spectrum. More definite conclusions would require elimination of the contribution of the background from the measured spectra.

3. ANALYSIS OF RESULTS AND COMPARISON WITH THEORY

Let the probability of recording emitted radiation with total energy E (spectrum) when the radiator lies in the electron beam be denoted by $P^e(E)$ and the corresponding probability in the absence of the radiator (background spectrum) be denoted by $P^b(E)$. Furthermore, let $P^{br}(E)$ represent the required energy spectrum of radiation losses in the radiator (bremsstrahlung spectrum). Our problem is to determine the spectrum $P^{br}(E)$ from the measurement data. We note that, since the apparatus affects the shape of the spectra (due to the finite detection efficiency and nonideal spectrometer line shape[3)]), the experimental spectra do, in fact, differ from the required gamma-ray spectrum. Analysis based on the specific spectrometer line shape showed, however, that, for these particular spectra (close to exponential and power-law profiles), the effect of the C_2 line shape on the measured spectrum was small, on the average, if the upper energy discriminator for photons entering the spectrometer substantially exceeded the upper boundary of the spectral interval under consideration.

The maximum shift of the curve in the vertical direction (for heavy elements) is 10–20%. In the first approximation, we may suppose, for the purposes of further analysis, that the experimental pulse-height spectra have the same shape as $P^e(E)$ and $P^b(E)$, and differ from them only by numerical factors of the order of unity. We shall use this approximation to analyze the contribution of the background. For the resultant spectrum, we have

$$P^e(E)=P_0^b P^{br}(E)+P_0^{br}P^b(E)+\int_\epsilon^E P^b(E')P^{br}(E-E')\,dE',$$

where P_0^b is the probability that background radiation with energy $\geq\epsilon$ is absent, P_0^{br} the probability that an electron produces no bremsstrahlung in the radiator, and ϵ is the maximum energy of the background photons which do not affect the shape of the spectrum of the radiation under investigation within the limits of precision used in the analysis. We shall suppose that ϵ is of the order of the width of the energy channel (1–10 MeV; see below). Since, at least to begin with, we are interested only in very rough approximations, we may suppose that ϵ is equal to the width of the average interval, i.e., ~10 MeV, and replace $P^{br}(E)$ by the experimental spectrum $P^e(E)$ under the integral sign. It may be shown that the contribution of the convolution is then substantially (roughly by an order of magnitude) lower than the background intensity, so that it can be neglected, and the experimental spectrum can be represented as the sum of two spectra (from the target and the background) with statistical weights of P_0^b and P_0^{br}, respectively. The analysis given below, which is designed to yield a more accurate estimate for the contribution of the convolution, will therefore have only a slight effect on the spectra and cannot lead to a substantial difference between the intensities.

To obtain an improved estimate for the contribution of the convolution, we use the fact that the spectra P $P^{br}(E)$ and $P^b(E)$ are nearly exponential in form, but the background curve is much steeper. The convolution can then be written in the form $P^{br}(E)\int_\epsilon^E P^b(x)dx$. The integral is, in fact, not very dependent on E (when $E \gtrsim 20$ MeV). This means that the required spectrum can be written in the form

$$P^{br}(E)=[P^e(E)-P_0^{br}P^b(E)]\frac{M_0^b}{M_a^b}.$$

In this expression, the ratio of the total number of electrons, M_0^b, recorded by the system during background measurements, to the number of electrons, M_a^b, accompanying the master pulse, is taken to be the reciprocal of the probability of recording a soft bremsstrahlung photon[4)]

$$P_0^b+\int_\epsilon^{E_{max}} P^b(x)\,dx.$$

Figures 7 and 8 show the experimental and theoretical results on the intensity ratio for heavy and light radiators. The solid curves show the spectra of energy losses by bremsstrahlung, and were obtained from special shower calculations by the Monte Carlo method using the Migdal formulas.[3] Points show the experimental results corrected as described above. We note that, in this case, there is no dependence on the soft-photon detection probability (M_a^b/M_0^b), and the dependence on the spectrometer line shape and its efficiency is smaller still. Finally, the broken curve (mean value of the ratio

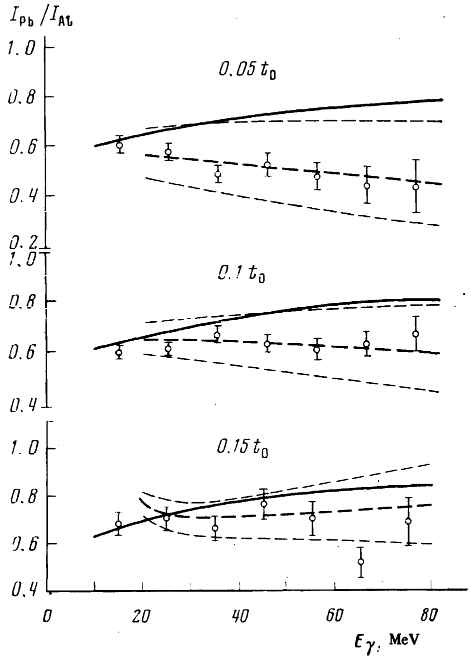

FIG. 7. Experimental and theoretical dependence of the bremsstrahlung intensity ratio for aluminum and lead as a function of gamma-ray energy (see text for explanation).

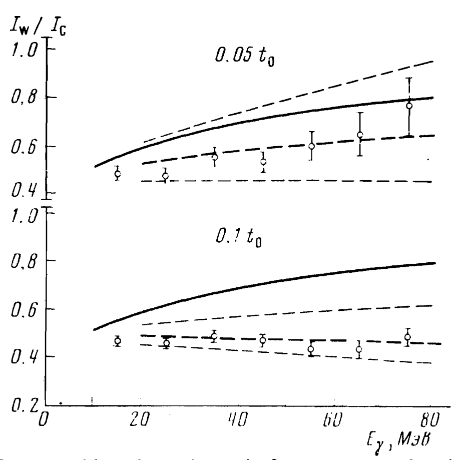

FIG. 8. Bremsstrahlung intensity ratio for tungsten and carbon radiators as a function of gamma-ray energy.

within the error band) shows the results obtained by numerical solution of the equation

$$P^e(E)=P_0^{br}P^{br}(E)+\int_0^E P^{br}(E')P^b(E-E')dE'.$$

The experimental spectra were initially approximated to by a sum of exponentials. The error band was obtained graphically from maximum deviations from the mean.

It is clear from these data that the bremsstrahlung intensity from heavy materials (Pb, W) is substantially less than from light materials (Al, C) for photons of 20–80 MeV, and this indicates that multiple scattering does affect the bremsstrahlung from electrons. Comparison with theoretical curves shows that this reduction is not less than that predicted by the theory. In individual cases (lead and aluminum of thickness $0.05t_0$ and $0.10t_0$), the difference from the theoretical spectrum is somewhat greater. This can be explained by systematic experimental errors in some series of measurements due to the overloading of the counting equipment through beam transport in the accelerator. When the latter measurements are excluded, the agreement with theory is improved (the result shown in Fig. 6 is an experimental indication that the apparatus was functioning correctly). Figures 7 and 8 show the experimental data including all the series of measurements.

The experimental results thus show the presence of the multiple-scattering effect for 40-GeV electrons in heavy materials (Pb, W), and agree to within experimental error with the Landau-Pomeranchuk-Migdal theory.

In conclusion, the authors regard it as their pleasant duty to thank Academician A. A. Logunov and Corresponding Member Yu. D. Prokoshkin for placing the accelerator facilities at their disposal, Corresponding Member I. I. Gurevich for his support and valuable advice, and S. P. Denisov and F. A. Ech for their help during the accelerator experiments. The authors are also indebted to all those who helped them during preparatory work and during the experiment on the accelerator.

1)A more detailed description of the system is given in [12].

2)The background intensity was much less than the bremsstrahlung intensity from the radiators.

3)One would expect that the effect of disturbing factors which distort the spectra is also described by the spectrometer line shape.

4)The quantity P_0^Γ was determined theoretically from the Migdal formulas. [3].

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