Radiation from electrons in tungsten crystals

V. N. Baĭer,[1)] V. A. Baskov, V. B. Ganenko,[2)] B. B. Govorkov, Yu. V. Zhebrovskiĭ,[2)]
V. M. Katkov,[1)] V. V. Kim, L. Ya. Kolesnikov,[2)] B. I. Luchkov,[3)] V. A. Maisheev,[4)]
A. L. Rubashkin,[2)] V. I. Sergienko, V. P. Sorokin,[2)] V. M. Strakhovenko,[1)]
V. Yu. Tugaenko,[3)] and V. A. Khablo

P. N. Lebedev Physics Institute, Russian Academy of Sciences
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The radiation losses of 28-GeV electrons in 1 and 0.3 mm thick tungsten crystals oriented along the ⟨111⟩ axis have been measured. The radiation loss calculations, performed using a coherent theory and the constant-field approximation, agree with the experimental data to within 10%. The relative radiation losses of electrons up to 1 GeV in the same crystals are presented.

Radiation losses of 28-GeV electrons were measured as part of a program for investigating quantum electrodynamic processes in strong fields of oriented crystals.[1] The measurements were performed on the Kaskad setup[2] at the Institute of High-Energy Physics (Protvino). An electron beam with momentum 28 ± 1 GeV/s, intensity $\sim 10^3$ electrons/s, and divergence at the base of not more than ± 1 mrad was directed onto a crystal secured in a goniometer. The goniometer had two rotation axes with 17 and 48 μrad steps. Beam proportional chambers determined the track of each electron to within 0.1 mrad. In the crystal the electrons emitted γ-ray Bremsstrahlung and were deflected by the field of a magnet, placed behind the goniometer. the γ-rays passed along a helium line into a total absorption Cherenkov spectrometer, which determined their energy. The radiation was recorded in a solid angle of $1.3 \cdot 10^{-4}$ sr.

The target consisted of tungsten single crystals whose ⟨111⟩ axis, which exhibited the highest potential, made a right angle with the surface of the crystal. Crystals 1 mm thick were used at 293 K and 0.3 mm thick at 293 and 77 K. Preliminary orientation of the ⟨111⟩ axis of the crystals parallel to the momentum of the beam electrons was performed on the linear electron accelerator at the Khar'kov Physicotechnical Institute. The angle between the ⟨111⟩ axis and the normal to the surface of the crystal was determined with the help of a reflected laser beam. On the Kaskad setup the ⟨111⟩ axis of the crystal was oriented approximately parallel to the beam with the help of a laser. The further precise orientation was performed using the Bremsstrahlung spectrum, recorded with the total-absorption spectrometer. It should be noted that precise orientation was also achieved by analyzing the amplitude of the signals from the scintillation counter, placed directly behind the crystal and recording the charged particles emitted from the crystal.[3]

If the angle between the ⟨111⟩ axis and the electron momentum $\theta \ll \theta_v = v_0/m$ (m is the electron mass and v_0 is the reduced potential, which is equal to 420 eV for the ⟨111⟩ axis), then the properties of the radiation, which was of a magnetobremsstrahlung character, are determined by the parameter

$$\chi = v_0 E_0 / a_s m^3,$$

where E_0 is the electron energy and a_s is the screening radius.[4,5] For $E_0 = 28$ GeV we have $\chi = 0.8$ and the radiation is substantially quantum radiation. Previously the radiation from electrons moving near the ⟨110⟩ axis in Ge crystals with $E_0 = 150$ GeV (Ref. 6) and Ge and Si with $E_0 = 107$ GeV (Ref. 7) was measured. The values of the parameter χ were equal to 0.8 and 0.9 (Ge) and 0.5 (Si), respectively. Thus using tungsten makes it possible to investigate the quantum properties of radiation at significantly lower energies.

The orientational dependence of the average energy of the radiation from electrons in a tungsten crystal is presented in Fig. 1. The errors are random errors. In order to calculate average energy we selected events in which the spectrometer recorded energy release $E_\gamma \geqslant 100$ MeV. The motion away from the ⟨111⟩ axis along the angle θ occurred in a direction perpendicular to the $(\bar{1}10)$ plane. The spectrum includes three regions: the strong-field region, where the magnetobremsstrahlung mechanism of radiation makes the main contribution; an intermediate region ($\theta \approx \theta_v$); and a

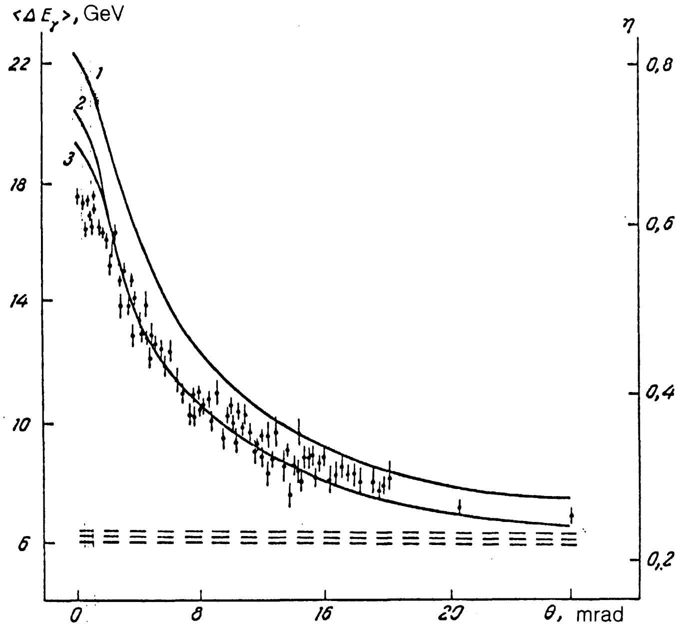

FIG. 1. Orientational dependence of radiation losses of electrons with energy $E_0 = 28$ GeV in a 1 mm thick tungsten crystal. The dashed lines represent the radiation losses in a disoriented crystal; the traces 1–3 are theoretical curves (see text); $\eta_0 = \langle \Delta E_\gamma \rangle / E_0$.

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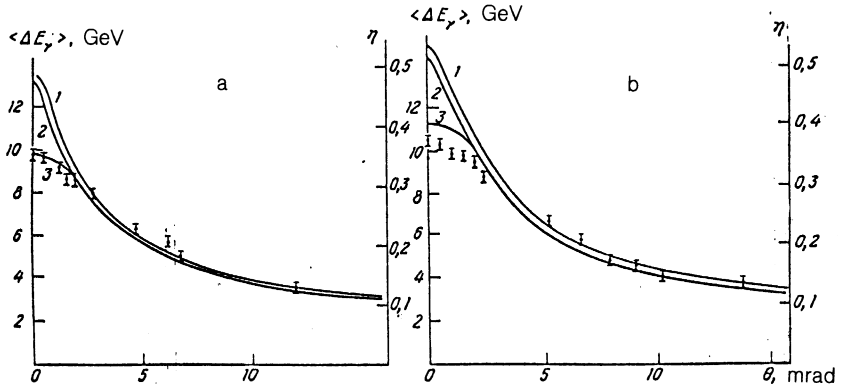

FIG. 2. Orientational dependence of radiation losses of electrons with $E_0 = 28$ GeV in a 0.3 mm thick tungsten crystal at temperatures 293 (a) and 77 K (b).

region of coherent emission ($\theta \gg \theta_v$).[4,5] The curves in Fig. 1 were calculated for three cases: 1) the orientational dependence of the radiation for ideal conditions (ideal tungsten crystal, the radiation is completely recorded with the spectrometer); 2) same as curve 1, but the absorption of photons in the crystal is taken into account; 3) orientational dependence for the conditions of the experiment, absorption of photons, multiple scattering, imperfection of the crystal, and beam divergence are taken into account.

Figure 2 shows the orientational dependences of the radiation from electrons in a crystal 0.3 mm thick at different temperatures. At $\theta = 0$ the averge energy of the radiation for the "warm" and "cold" crystals was equal to 9.7 ± 0.2 and 10.5 ± 0.2 GeV and for the disoriented crystal it was equal to 2.2 ± 0.2 and 2.1 ± 0.2 GeV, respectively. The curves in Fig. 2 were calculated for the same cases as in Fig. 1. One can see that under ideal conditions (high-quality crystal, narrow beam) the average radiation losses would be appreciably higher (curves 1 and 2). It is also obvious that as the thickness of the crystal decreases photon absorption will play a smaller and smaller role.

It follows from Figs. 1 and 2 that the measured energy losses agree, to within 10%, with the predictions of theory in the entire range of angles for both thicknesses of the crystal. We also note that for above-barrier electrons the intensity of the radiation is 15% higher in the cold crystal than in the warm crystal.

The radiation length of amorphous tungsten is equal to 3.5 mm and is virtually constant for high-energy electrons. The radiation length of a tungsten crystal depends on a number of factors and can be significantly shorter. In the present work the radiation length, calculated taking into account γ-ray absorption in the crystals, for 28-GeV electrons moving in a strong field along the ⟨111⟩ axis was equal to 0.86 ± 0.05 mm for the 1 mm thick crystal and 0.76 ± 0.07 mm for the 0.3 mm crystal. As the energy increases the radiation length should decrease right down to its minimum value $L_{\rm ch} \approx 0.30$ mm at $E_0 = 200$ GeV.[5] The radiation length was also observed to decrease in Refs. 6 and 7.

Radiation losses of electrons with energies of up to 1 GeV were measured on the beam of the linear accelerator at the Physicotechnical Institute (Khar'kov) during preliminary orientation of the tungsten crystals. The same crystals, 0.3, 1.0, and 1.8 mm thick, with the ⟨111⟩ axis of the crystal oriented along the axis of the beam ($\theta = 0$) were employed. The γ-rays were detected with a Wilson photonmeter.[8] Figure 3 shows the relative radiation losses η as a function of θ_c/θ_γ (θ_c is the collimation angle and $\theta_\gamma = mc^2/E_0$ is the emission angle of the photons) with electron energies $E_0 = 892$, 607, and 951 MeV. The measurements were performed for channeling along the axis ($\theta = 0$) and

$$\eta_0 = W_\gamma / W_e = \langle \Delta E_\gamma \rangle / E_0$$

(W_γ and W_e are the total energies of the γ-rays and electrons). The values of η_0, obtained previously in Ref. 9, agree quite well with the experimentally observed dependence $\eta_0 = f(\theta_c/\theta_\gamma)$.

Figure 4 shows as a function of θ_c/θ_γ the ratio $\alpha = \eta_0/\eta_r$ for the same crystals and electron energies, where η_r are the relative radiation losses for dissoriented crystals.

The results presented show that at energies up to 1 GeV the experimental dependence of η_0 and α on θ_c/θ_γ is identical for tungsten crystals with thicknesses ranging from 0.3 mm up to 1.8 mm. The relative radiation losses increase from $\approx 1.3\%$ for $\theta_c/\theta_\gamma = 9$ at energies up to 1 GeV up to $\approx 63\%$

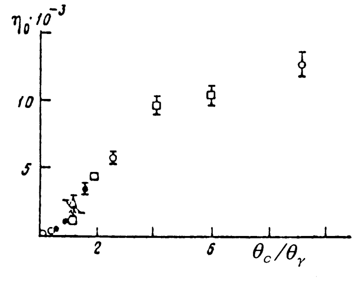

FIG. 3. Relative radiation losses $\eta_0 = f(\theta_c/\theta_\gamma)$ of electrons with different energies E_0 in a crystal with thickness T: □—$E_0 = 951$ MeV, $T = 0.3$ mm; ○—$E_0 = 607$ MeV, $T = 1.0$ mm; ●—$E = 892$ MeV, $T = 1.8$ mm; ▲ and △—$E_0 = 900$ MeV, $T = 0.29$ mm and 0.64 mm.[9]

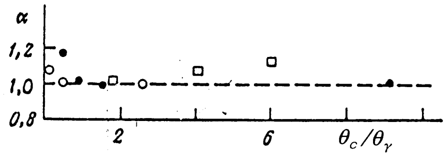

FIG. 4. $\alpha = \eta_0/\eta_r = f(\theta_c/\theta_\gamma)$. The designations are the same as in Fig. 3.

($\approx 35\%$) for 1 mm (0.3 mm) thick crystals with electron energy of 28 GeV and no collimation.

[1)]Institute of Nuclear Physics, Novosibirsk.
[2)]Physicotechnical Institute, Khar'kov.
[3)]Engineering-Physics Institute, Moscow.
[4)]Institute of High-Energy Physics, Protvino

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