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Development of electromagnetic showers in oriented tungsten crystals

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Experiments on the development of electromagnetic showers produced by 28-GeV electrons in oriented tungsten crystals are reported. The crystal thicknesses were 0.07, 0.3, and 1.0 mm. At this energy, the "constant strong field" comes into play, and the development of showers in oriented crystals differs from that observed in an amorphous substance.

In the interaction of electrons and photons at energies of tens and hundreds of GeV in single crystals, a mechanism of a "constant strong field" comes into play along with the mechanism of a coherent emission of electrons and the creation of e^+e^- pairs by γ rays over a wide range of the angles at which the particles enter the crystals with respect to a crystallographic axis (or plane). This strong-field mechanism leads to a significant increase in the cross sections for all electrodynamic processes.[1,2] The region of a constant strong field is determined by the condition $2V_0\epsilon/m^2 \gg 1$ and exists for angles $\theta \ll \theta_{sf} = V_0/m$, where $V_0 \approx Ze^2/a$ is a scale value of the average potential of the axis (or plane), m and e are the mass and charge of an electron, a is the distance between atoms in the lattice, Ze is the charge of the nucleus, and ϵ is the energy of the electron or γ ray incident on the crystal.[3] Certain effects of a constant strong field have been studied (Refs. 4 and 5, for example), but the question of the development of an electromagnetic cascade in oriented crystals has received less experimental attention than other questions.[6-8]

In a continuation of the overall program of research on constant-strong-field effects in the interaction of electrons and γ rays with single crystals, a study has been made of electromagnetic showers initiated by 28-GeV electrons in oriented tungsten crystals. The experiments were carried out on the Kaskad installation[9] at the accelerator of the Institute of High-Energy Physics. The single crystals had thicknesses of 0.07, 0.03, and 1.0 mm. They were oriented with their ⟨111⟩ axis along the beam (this is the axis with the smallest lattice constant, $a = 2.7$ Å, and the highest potential, $V_0 = 417$ V/cm). The crystals were either "warm," at a temperature of 293 K, or "cold," at 77 K (cooled with liquid nitrogen). The divergence of the electron beam was $|v| \leqslant 0.2$ mrad at the base. A crystal whose axis deviated by an angle $\theta = 20$–30 mrad from the crystallographic axes or planes was regarded as "disoriented." The shower leaving the crystal continued to develop in a composite Čerenkov shower spectrometer[10] positioned behind the crystal. This spectrometer consisted of nine independent light-tight radiators of TF-1 lead glass with a thickness of 1 radiation length. An amplitude signal could be taken from each radiator.

Figure 1 shows cascade curves measured for the cases of oriented and disoriented cold tungsten crystals 1 mm thick. It follows from Fig. 1 that the cascade develops more intensely in an oriented crystal than in a disoriented one. In the case of the oriented crystal, the maximum of the cascade development is displaced ~2 radiation lengths toward the point at which the cascade began to develop. The relative magnitude of this "speeding up" of the cascade development, equal to the ratio of the signal amplitudes in the cases of oriented and disoriented crystals, is shown as a function of the depth of the cascade development in the Čerenkov shower spectrometer in Fig. 2. The extent to which the energy evolution in a cascade nucleated in an oriented crystal is higher reaches a maximum at the beginning of the development $\langle \Delta E_0 \rangle / \langle \Delta E_p \rangle \approx 4$ in the first radiator of the spectrometer) and falls to a value below 1 beyond the maximum of the development.

The observed compression of the cascade can be explained in a qualitative way by the large radiative loss of electrons in a crystal when the electrons pass at small angles from a crystallographic axis. The radiation length in the crystal ceases to be a constant

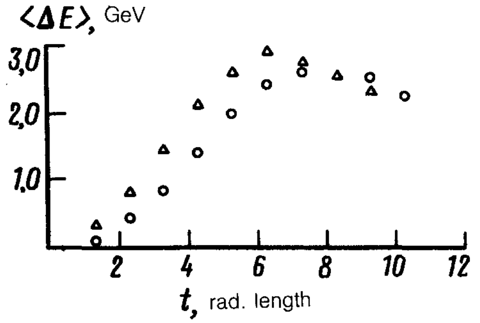

FIG. 1. Development of an electromagnetic cascade nucleated by 28-GeV electrons in a composite Čerenkov shower spectrometer (tungsten, 1.0 mm thick, $t = 77$ K). Here $\langle \Delta E \rangle$ is the fraction of the energy of the electromagnetic shower which is evolved in each radiator of the spectrometer. ▲—$\theta = 0$ mrad; ●—$\theta = 51.6$ mrad.

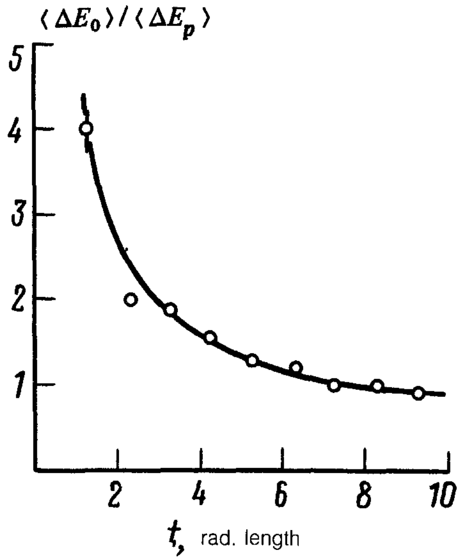

FIG. 2. Ratio of the amplitudes of the signals for an oriented crystal ($\langle \Delta E_0 \rangle$) and a disoriented crystal ($\langle \Delta E_p \rangle$) versus the depth in the Čerenkov spectrometer (tungsten, 1.0 mm thick, $t = 77$ K).

and decreases in proportion to the increase in the energy of the electrons and the decrease in the entrance angle. This effect results from the combined influence of the strong-field effect and the capture of electrons into channeling.

Figure 3 shows the amplitude of the signal from the first radiator of the Čerenkov spectrometer as a function of the thickness of an oriented tungsten crystal in front of

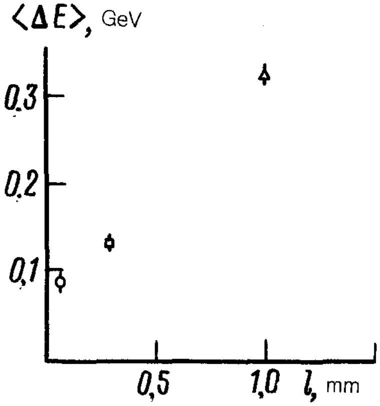

FIG. 3. Amplitude in the first radiation of the Čerenkov spectrometer versus the thickness of the oriented crystal in front of it. ●—0.07 mm ($t = 293$ K); ■—0.3 mm ($t = 293$ K); ▲—1.0 mm ($t = 77$ K).

the spectrometer (the crystals 0.07 and 0.3 mm thick were warm, while that 1.0 mm thick was cold). The signal amplitude increases with increasing crystal thickness, but in order to record the entire curve, it is necessary to carry out measurements with thicker tungsten crystals.

These experimental results show that at an electron energy of 28 GeV the development of the electromagnetic cascade in an oriented tungsten crystal is more intense than that in an amorphous substance. This difference is important for identifying the mechanism for the constant-strong-field effect in single crystals. The compression of the cascade observed here may find practical use in the development of miniature and relatively light directional spectrometers for experiments in high energy physics and space research.

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