Orientational dependence of the development of electromagnetic showers in a tungsten crystal

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The orientational dependence of electromagnetic showers emerging from a cooled tungsten crystal interacting with a beam of 28-GeV electrons has been studied. The showers detected differ from those which develop in an amorphous material.

The interaction of high-energy electrons ($E > 100$ MeV) with a single crystal is a coherent collective interaction at certain angles of incidence, in contrast with the interaction at individual centers in an amorphous medium (the Bethe-Heitler mechanism).[1] At electron and γ-ray energies in the range 10–1000 GeV, at small angles of incidence ($\theta \ll \theta_{sf} = V_0/m$), the coherent mechanism has a feature which has come to be called a "constant strong field." As a result of this feature, the cross sections for all electromagnetic processes increase sharply. The validity of the constant-strong-field approximation for various crystals is determined by the condition $V_0\epsilon/m^2 \gg 1$, where $V_0 \simeq Ze^2/a$ is the scale of the average potential of an axis (or plane), e and m are the charge and mass of an electron, a is the lattice constant, and ϵ is the energy of the electron or γ ray.[2,3] One of the most interesting manifestations of the constant-strong-field mechanism, yet one of the least studied, is the development of an electromagnetic cascade in an oriented crystal, in which case the theory predicts several effects.[4,5] To test these predictions, we need a crystal with a high crystallographic-axis potential and a small lattice constant, and we need an electron beam with an energy sufficient to satisfy the condition for the constant-strong-field effect at the corresponding angles of incidence θ. At an electron energy of 28 GeV, these conditions are satisfied by a tungsten crystal, for which the highest potential (for the $\langle 111 \rangle$ axis) is $V_0 = 417$ V/cm.

Studies of electromagnetic showers initiated by 28-GeV electrons in an oriented tungsten crystal have been carried out on the Kaskad apparatus of the Serpukhov accelerator.[6] In the present letter we are reporting a continuation of a series of studies of the development of electromagnetic showers in oriented tungsten crystals.[7] In the present study we used a tungsten single crystal 1.0 mm thick cooled with liquid nitrogen to 77 K. The crystal was oriented along the $\langle 111 \rangle$ crystallographic axis; the beam divergence was $|v| \leqslant 0.1$ mrad. A crystal was regarded as "disoriented" if its axis made an angle $\theta = 20$–30 mrad with the beam axis. The electromagnetic cascade emerging from the crystal continued to develop in a composite total-absorption lead-scintillation spectrometer behind the crystal. This total-absorption spectrometer contained nine identical, independent sandwich total-absorption counters, each consisting of four lead

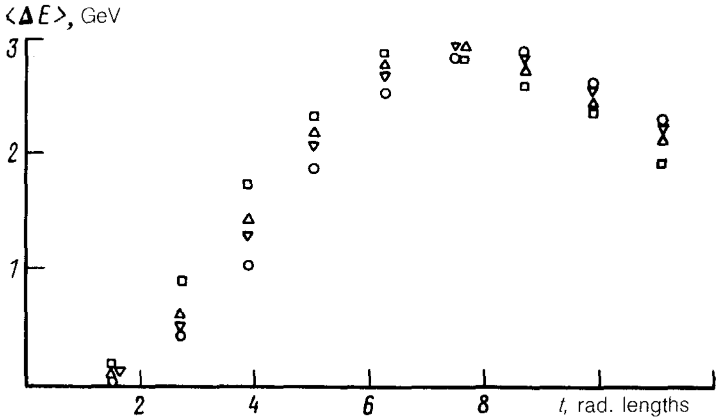

FIG. 1. Development of an electromagnetic cascade caused by electrons with an energy of 28 GeV versus depth in the total-absorption spectrometer, for various orientations of the crystal (in front of this spectrometer) with respect to the ⟨111⟩ axis (tungsten, 1.0 mm thick, $T = 77$ K). Here $\langle \Delta E \rangle$ is the fraction of the energy of the electromagnetic shower which is evolved in each counter of the spectrometer. ●—$\theta = 52$ mrad; ▽—$\theta = 10$ mrad; △—$\theta = 5$ mrad; □—$\theta = 0$ mrad.

plates 1.5 mm thick, alternating with four scintillator plates 5 mm thick. The overall thickness of the spectrometer along the beam path was 10.8 radiation lengths. An amplitude signal could be taken from each counter of the spectrometer, so the development of the electromagnetic shower along depth could be studied.

Figure 1 shows cascade curves measured by the total-absorption spectrometer for electrons entering the crystal at various angles with respect to the ⟨111⟩ axis. As in Ref. 7, we see that the cascade begins to develop more rapidly at small values of the angle θ than at large values. The maximum of the shower development begins to shift toward the beginning of the development. The observed contraction of the cascade, which is predicted by the theory, is explained at a qualitative level by the large radiation loss of the electrons which pass at small angles with respect to the axis of the crystal, as a result of the combined influence of the constant-strong-field effect and the partial capture of electrons into channeling.

The amplitude spectra taken from each counter of the spectrometer change shape not only with the orientation of the crystal but also with cascade development depth. As a characteristic of the spectrum we selected the spectrum conversion coefficient $\beta = (N_r/N_l)_o/(N_r/N_l)_d$, where $(N_r/N_l)_{o,d}$ is the ratio of the number of particles in the right-hand side of the spectrum to that in the left-hand side for the oriented (disoriented) crystal. The channel with respect to which the transformation occurs is found by an optimization method. Figure 2 shows the transformation coefficient β as a function of the cascade development depth in the total-absorption spectrometer for various orientations of the crystal. The effect of the oriented crystal increases by a factor of more than 12 at $\theta = 0$, and the transformation of the spectrum occurs over essentially the entire depth of the total-absorption spectrometer. This result means that a "memory" of the passage of an electron through the crystal with a certain orientation is retained in the cascade. At large depths ($t > 8$–10 rad. lengths) β be-

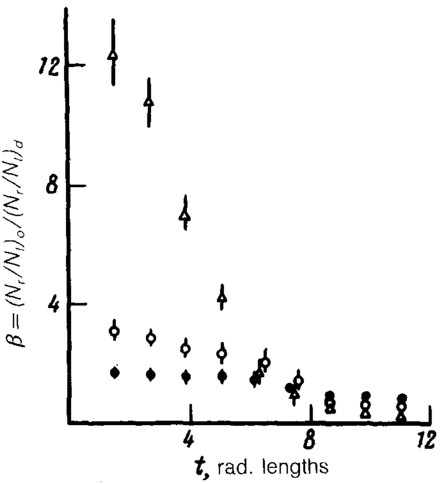

FIG. 2. Spectrum transformation coefficient β versus depth of development of the electromagnetic cascade in the total-absorption spectrometer, for various orientations of the crystal in front of the spectrometer (tungsten, 1.0 mm thick, $T = 77$ K, $\langle 111 \rangle$ axis). $\triangle$—$\theta = 0$ mrad; ○—$\theta = 5$ mrad; ●—$\theta = 10$ mrad.

comes less than unity; i.e., the energy spectra of the loss are softer than for an amorphous material.

These experimental results show that at an electron energy of 28 GeV the electromagnetic showers which are formed in an oriented tungsten crystal differ from those in an amorphous material. The primary distinction is that the energy evolution in the cascade becomes very sensitive to the orientation of the crystallographic axis. This orientational dependence is retained to a large depth.

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