Hard-Photon Emission from 150-GeV Electrons Incident on Si and Ge Single Crystals near Axial Directions

R. Medenwaldt, S. P. Møller, A. H. Sørensen, S. Tang-Petersen, and E. Uggerhøj
Institute of Physics, University of Aarhus, DK-8000 Aarhus C, Denmark

K. Elsener
CERN, CH-1211 Geneva 23, Switzerland

M. Hage-Ali, P. Siffert, and J. Stoquert
Centre de Recherches Nucleaires, F-67037 Strasbourg CEDEX, France

K. Maier
The Max-Planck Institut für Metallforschung, D-7000 Stuttgart 80, Federal Republic of Germany
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The emission of high-energy photons from 150-GeV electrons traversing single crystals near axial directions is studied experimentally for Ge and, for the first time, also for Si. Enhancements relative to random of up to 2 orders of magnitude are observed. For incident angles much less than the critical channeling angle ψ_1 a pronounced peak appears in the photon spectra near $\sim 85\%$ of the electron energy for both the Si and the Ge crystals. The peak disappears for incident angles larger than $\sim 0.3\psi_1$. The experimental findings are compared to theoretical results.

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When a parallel beam of electrons or positrons traverses a crystalline target in directions far from major crystal axes or planes, the well-known incoherent bremsstrahlung (IB) is emitted. As the direction of incidence is turned towards axial or planar directions, the projectiles start to "feel" the crystalline structure, and coherence in the emitted radiation results in an enhancement over IB and under suitable conditions in peak structures; this phenomenon is known as coherent bremsstrahlung (CB).¹ The spectra are the same for electrons and positrons. If the projectiles are incident nearly parallel to axial or planar directions, a strong steering effect appears called *channeling*.^{2,3} Particles interact with the crystal through a continuum potential obtained by smearing the atomic charges along the considered crystallographic direction and the flux in directions transverse to the corresponding axes or planes is nonuniform. Channeling motion also gives rise to coherence effects in the photon emission; the associated radiation is called *channeling radiation* (CR).⁴ The structure of CR is strongly dependent on the form of the continuum potential but is not directly connected to the lattice parameters. Channeled positrons are pushed away from the atomic axes or planes, whereas channeled electrons are focused around the axes or planes. Since they move in different potentials, their CR spectra will be different.

At GeV energies, particles which are nearly aligned with crystal axes or planes move along classical trajectories.^{5,6} Nevertheless, at energies above roughly 20 GeV, a classical description of the radiation emission gradually becomes invalid, the reason being that the coherent part of the radiation spectra extends to an ap-

preciable fraction of the particle energy whereby the recoil due to photon emission cannot be neglected. At these high energies, on the other hand, the transverse excursions of the particle during the time of photon emission are small compared with the distances over which the derivative of the continuum potential varies substantially. The emission, therefore, appears approximately as in a constant electromagnetic field.⁷⁻⁹ The characteristic angle θ_0 for coherent emission in single crystals at high energies is given by⁹ $\theta_0 = U_0/mc^2$, where U_0 is the scale of the axial or planar potential and m is the electron mass. For incident angles $\theta < \theta_0$ the constant-field approximation (CFA) applies and, for $\theta > \theta_0$, the first-order Born approximation (CB¹) applies. Lowest-order corrections are given in Ref. 9.

Recently the radiation from 150-GeV (Ref. 10) and 170-GeV (Ref. 11) electrons and positrons traversing thin crystals was investigated. In general, the intensity of the emitted radiation was enhanced by factors of 20 (Ge) to 50 (Si) for incident angles smaller than θ_0 . Electrons and positrons give the same spectra for incident angles larger than the Lindhard channeling angle ψ_1 (Ref. 2) and there is fair agreement with CFA calculations. For 150-GeV electrons,¹⁰ however, an unexpected peak in the photon spectra was found for incident angles smaller than ψ_1 . Different explanations of the peak have been given.¹²⁻¹⁵ In general, it is accepted that a well-aligned electron will emit several photons while traversing a Ge crystal of a few hundred μm , the energy of which will be added up by the photon detector. Furthermore, it is proposed that the multiple scattering of the electrons, which tends to increase their transverse

FIG. 1. Enhancement, relative to random, of γ radiation for 150-GeV electrons incident on a 205- μm Ge $\langle 110 \rangle$ crystal. Typical error bars are shown on the aligned spectrum.

energy, is counteracted and for some states of motion more than compensated by radiative “cooling” from photon emission. Surprisingly the intensity of the peak changed drastically by tilting the crystal 17 μrad ($=0.3\psi_1$) even in a beam with divergence of $\pm 30 \mu\text{rad}$, which called for more detailed studies. In this paper we present the first detailed investigations of the angular dependence of this effect on both Si and Ge crystals.

The experiment was performed in the upgraded north area of the CERN super proton synchrotron in a tertiary electron beam. The experimental arrangement is shown in Ref. 16. The angular resolution of the incident electrons was $\sim 2 \mu\text{rad}$, obtained with the drift chambers.

In Fig. 1 are shown the emitted photon yields (power spectra) as a function of photon energy when 150-GeV electrons traverse a 205- μm -thick $\langle 110 \rangle$ Ge crystal. The spectra are normalized to IB for the same thickness of amorphous foil, where the IB is defined as the ratio of the crystal thickness to the radiation length. As mentioned above the angular resolution of the drift-chamber system is extremely good ($\sim 2 \mu\text{rad}$), which allows for detailed investigations of the radiation spectra as a function of incident angle. For very well-aligned electrons a pronounced peak is found. The enhancement in the peak for the best-aligned particles is a factor of roughly 60. On the other hand, the peak disappears already for incident angles of 15–21 μrad to the $\langle 110 \rangle$ axis. This angle should be compared to the Lindhard angle ψ_1 which for the present case is 56 μrad . So only channeled electrons with low transverse energy give rise to the peak. The present results confirm the peak in the photon spectra from Ge crystals observed by Belkacem *et al.*¹⁰

In Fig. 2 are shown the results of similar investigations for 150-GeV electrons transmitted through a 500- μm -

FIG. 2. Same as Fig. 1, but for a 500- μm Si $\langle 110 \rangle$ crystal.

thick $\langle 110 \rangle$ Si crystal. Here the same effect as in Ge is found and the enhancement in the peak is even more dramatic, namely a factor of 85 above random yield. For Si $\langle 110 \rangle$, the channeling angle at 150 GeV amounts to 37 μrad , so also in Si the peak disappears for incident angles larger than around $0.3\psi_1$. The fact that the enhancement of emitted radiation is far more pronounced for Si than Ge is in good agreement with our results for 1–20-GeV electrons and positrons.^{5,6} For a comparison, a measurement on a 200- μm -thick $\langle 100 \rangle$ W crystal (mosaic spread $\sim 120 \mu\text{rad}$) gave a maximum enhancement of 15 for 150-GeV aligned electrons.¹⁷

Theoretical photon spectra obtained under the assumption of each impinging electron emitting no more than a single quantum appear very different from the spectra of Figs. 1 and 2; cf. Ref. 11. To investigate the influence of multiple-photon emission, we have therefore set up a computer code on the basis of a simple theoretical model analogous with the one proposed by Kononets and Ryabov.¹⁵ (i) The crystal is divided into slices so thin that in each slice the probability for emission of more than one photon is negligible. (ii) The radiation probability for each slice is described by the formulas of Baier, Katkov, and Strakhovenko;⁹ for the thermally averaged continuum potential we make the same choice as in Ref. 11. (iii) For an electron of given transverse energy, the probability distribution in direct space is uniform inside the accessible area (statistical equilibrium). (iv) The transverse energy $E_\perp$ of a given electron is unchanged throughout the crystal. The results of our calculations are superimposed on Figs. 1 and 2. The distribution over $E_\perp$ is taken equal to the one obtained immediately inside the surface. In general, the theoretical multiphoton spectra reproduce nicely the experimentally recorded total energy loss. Note that no rescaling is involved, contrary to Ref. 15—our choice of potential leads to lower yields.

FIG. 3. Energy-loss spectra for 150-GeV electrons traversing a 500- μm Si $\langle 110 \rangle$ crystal. The spectra are calculated for given transverse energies specified on the figure by the maximum distance $r_{\perp}$ to the string relative to r_0 , $E_{\perp} = U(r_{\perp})$.

In the channeling region, however, our calculation does not reproduce the shape of the experimental spectra completely: Right at the axis our calculation produces no peak whereas a small peak, unseen in the experiment, shows up at angles of 10–20 μrad . If we abandon the assumption of statistical equilibrium for zero incidence angle and instead apply one-dimensional distributions corresponding to electrons of zero angular momentum oscillating through the axis, the theoretical yield is lowered slightly, but no peak is produced. The major difficulty instead lies in the distribution and redistribution of transverse energies. Figure 3 spells out the spectra computed according to (i)–(iv) above for electrons of different transverse energies in Si. The spectra are seen to vary drastically with $E_{\perp}$. Obviously, even minor changes of the weights given to the spectra of Fig. 3 may result in substantial changes in the shape of the final spectrum, e.g., producing a high-energy peak if the weight of transverse energies $U(0.1r_0) \leq E_{\perp} \leq U(0.2r_0)$ is increased (πr_0^2 defines the single-string area and U the

continuum potential). Therefore, we conclude that the detailed shape of the spectrum for incidence nearly parallel to the axis is indeed very sensitive to multiple scattering and radiation cooling—but also that it appears highly likely that the experimental spectrum may be reproduced by properly accounting for these processes. For incidence beyond ψ_1 , multiple scattering and radiation cooling are less important processes since the lower-transverse-energy levels are not populated.

In conclusion, it can be stated that the pronounced peak in the photon spectra from 150-GeV electrons found by Belkacem *et al.*¹⁰ is confirmed and for the first time also seen in Si. The peak is due to very well channeled electrons with low transverse energy and disappears for incident angles larger than around $0.3\psi_1$.

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