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Experimental Investigations of Hard Photon Emission from Strong Crystalline Fields

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Abstract

For the first time very pronounced high energy photon peaks have been measured in the radiation emission from 70, 150 and 240 GeV electrons incident at 0.1 mrad to 1.0 mrad to the axis in diamond and Si crystals. The energy of the photons in the peaks is (0.7-0.8) times the particle energy with yields of 50 times the Bethe-Heitler one (in diamond). The peaks consist of single photons and are caused by the influence of strong crystalline fields on the emission of coherent bremsstrahlung - emitted when the ultrarelativistic electrons cross the rows of atoms in a crystal plane. The effect could be envisaged as a source for nearly monoenergetic photons in the multihundred GeV - region.

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When multihundred-GeV electrons/positrons penetrate single crystals near axial/planar directions dramatic effects appear. The large Lorentz factors ($\gamma \sim 10^5$ - 10^6) enhance the electric fields along axes/planes to overcritical values within the electron frame. Overcritical in this context means that the perturbation theory is no longer applicable, but a full description of QED in strong fields has to be used. Bremsstrahlung and pair production cross sections are strongly enhanced. Especially radiation emission attracts continuing interest because high-energy electrons incident on single crystals give for the first time a unique opportunity to investigate QED-processes in intense external fields. The influence of such fields on QED processes is strongly dependent on the parameter $\chi = \gamma E/E_1$, where E is the local field strength and $E_1 \simeq 1.3 \cdot 10^{16}$ V/cm. In radiation processes χ determines the magnitude of quantum effects on recoil. For $\chi \ll 1$ classical electrodynamics can be used but already for $\chi \sim 0.1$ strong quantum effects set in. In the present experiments χ is between 0.5 and 1.0.

For penetration of ultrarelativistic particles through single crystals two characteristic angles come into play. For incident angles Θ to crystal axis/planes smaller than the Lindhard channeling angles¹ (Ψ_1/Ψ_p) a strong steering effect appears, where electrons are focused around the nuclei and positrons are pushed away whereby hard photon yields are enhanced for electrons but reduced for positrons. The second characteristic angle Θ_0 is given by $\Theta_0 = U_0/mc^2$, where U_0 is the scale of the axial/planar continuum potential and m the electron mass. For incident angles $\Theta \gg \Theta_0$ the emitted radiation is of dipole type and the theory for coherent bremsstrahlung (CB) is valid. For $\Theta \ll \Theta_0$ the radiation has synchrotron radiation nature and can be described as originating from a constant field - the constant field approximation (CFA), (for a review see ref. 2).

Both theoretically and experimentally the CB is described in detail in the literature (for a review see ref. 3). For multi-hundred GeV electrons CB has been proposed as a source for monoenergetic photons^{2, 4, 5}. Experiments at these high energies have recently been performed⁶. For incidence along axial/planar directions i.e. $\Theta < \Psi_1$ more detailed investigations on radiation emission have been carried out in the high energy region. Pronounced photon peaks were found in spectra from 150 GeV electrons on Ge-crystal⁷. Measurements by our group⁸ have shown that the peaks are due to multi-photon effects and are not found for thin crystals. In these investigations a pronounced high-energy photon peak was also observed for 150 GeV electrons incident on a thin (200 μ m) W-crystal at angles around 1 mrad to the $\langle 100 \rangle$ axis. The origin of this peak could not be readily understood, thus initiating the investigations presented in the following. In the present experiment the radiation emission from (70-240) GeV electrons was measured for incident angles in the transition region between channeling radiation and CB i.e. $\Theta \geq \Theta_0$ using diamond and silicon crystals.

The experiment (NA43) was performed in the upgraded north area of the CERN SPS in a tertiary electron beam with an angular spread of ± 30 μ rad. The experimental arrangement is discussed in ref. 6. By means of the two drift chambers situated 60 m. apart an angular resolution around 2 μ rad was obtained on the incident side. The goniometer was placed in a temperature stabilized hut giving an accuracy in angular setting of around 5 μ rad. Two different types of diamond were used, namely a 500

μm thick synthetic crystal grown by the Johannesburg group and a natural 200 μm thick one brought by the Yerevan group. The mosaic spread was measured with x-rays and found very low ($\leq 5 \mu\text{rad}$). The photons were detected in a standard leadglass detector. In the following the experimental spectra are all power spectra normalized to the averaged Bethe-Heitler yields for corresponding target thicknesses. The photon energies are plotted relative to the incident electron energies.

Fig. 1 shows photon spectra from 150 GeV electrons incident on the 0.5 mm thick $\langle 100 \rangle$ diamond crystal. The spectra are shown for increasing incident angle to the $\langle 100 \rangle$ axis. The beam divergence was $\pm 30 \mu\text{rad}$ with the center of the beam core parallel to the $\{110\}$ plane. For incident angles around 0.3 mrad to the $\langle 100 \rangle$ axis a high energy photon peak appears at ~ 0.7 times the electron energy E_0 . The lower energy photons with maximal enhancement around $0.2 \cdot E_0$ is attributed to channeling radiation (Ch R) from the $\{110\}$ plane⁶. The energy of the high-energy photon peak increases for increasing incident angle θ .

In fig. 2 is shown a detailed investigation of the variation of photon spectra for 0.3 mrad incidence to the $\langle 100 \rangle$ axis and for three angular regions to the $\{110\}$ plane in the 0.5 mm thick diamond crystal. In fig. 2a the incident angles to the $\{110\}$ plane are within the Lindhard angle for planar channeling ($\Psi_p = 8 \mu\text{rad}$). Here the spectrum clearly consists of two distributions: a) channeling radiation from the $\{110\}$ plane with a maximum around $0.2 \cdot E_0$ b) a photon peak at $0.7 E_0$, which is the new effect. From the theoretical calculations¹⁰ (discussed below) it can be seen that these high energy photons arise from coherence in radiation emission when the projectiles cross the planar rows of atoms at an angle of 0.3 mrad. For increasing incident angles to the $\{110\}$ plane the Ch R from the $\{110\}$ plane turns into normal CB with a first harmonic at $\sim 0.3 E_0$ (fig. 2c), whereas the coherent peak at $0.7 E_0$ is gradually reduced.

Fig. 3 shows the spectra corresponding to 70 GeV, 150 GeV and 240 GeV electrons all incident at 0.3 mrad to the $\langle 100 \rangle$ axis and within the angular region for planar channeling on the $\{110\}$ plane. For increasing electron energy the influence of multiphotons increase - especially in the Ch R-spectra. This is observed in the low energy maximum which gets broader and move to higher energies - going from fig. 3a to fig. 3c. For the high energy photon peak the enhancement is around 50 for 70 GeV and 150 GeV but decreases somewhat for 240 GeV electrons. In this context, however, it should be remembered that for 240 GeV electrons the critical angle for planar channeling is $5 \mu\text{rad}$, which is at the limit of experimental angular resolution. Furthermore, the requirements to perfection of the crystals are very strong. So, in general, the energy dependence of this new high energy photon peak is weak.

Fig. 4 shows a comparison of the results for the two different diamond crystals together with a 0.6 mm thick Si crystal. On the thin diamond (fig. 4b) the influence of multiphotons is strongly reduced but the high energy photon peak is still pronounced. This shows that the peak consists of mostly single photons. The enhancement of the planar channeling radiation is, however, smaller than for the 0.5 mm one, which could be a result of multiphotons. For Si the maximal enhancement for the high energy photon peak was found at 0.54 mrad from the $\langle 110 \rangle$ axis and an incident angle region of $\pm \Psi_p$ around the $\{111\}$ plane. For a comparison pure planar

Ch R spectra are inserted both for diamond (fig. 4b) and silicon (fig. 4c). Clearly the planar Ch R curves (from ref. 6) are flat from $\sim 0.5 E_0$ and up to E_0 . For the inserted Si-spectrum the enhancement is somewhat larger because a more narrow incident angle region (0-5 μ rad) was used around the {110} plane in ref. 6. The reduction in enhancements from diamond to silicon are in fair agreement with the theory of Baier et al.⁹ which predicts the maximum enhancement of radiation is inversely proportional to the atomic numbers of the targets.

Recently Baier et al. developed a general theory for radiation emission from high-energy particles interacting with strong crystalline fields¹⁰. The theory covers a wide range of incident angles θ around crystal axes/planes. For $\theta \ll \theta_0$ the theory describes the emission of radiation in the continuum potential from axes/planes where the CFA is a good approximation. For $\theta \gg \theta_0$ the theory is reduced to the standard theory for CB. For $\theta \geq \theta_0$ the general theory is used taking into account the change of the effective electron mass in the continuous crystal potential. For $\theta \geq \theta_0$ it is shown that the energy of the first harmonics in the emitted coherent radiation varies with the azimuthal angle around the axis. The maximum photon energy is obtained for incidence along the {110} planes in a $\langle 100 \rangle$ fcc-crystal. In such a situation the photon spectrum will consist of Ch R from the {110} planes and strongly enhanced high energy photon peaks from the strong fields. This theory was used by one of the authors (V.M.S.) to calculate spectra for the present experimental conditions. The results are shown in fig. 5 for 70, 150 and 240 GeV electrons incident on a 0.5 mm thick $\langle 100 \rangle$ diamond crystal at an angle of 0.3 mrad to the axis. For the dashed curves, the influence of multiphotons is disregarded but is taken into account for the full drawn curves. The agreement with experimental data (fig. 3) is very good both with respect to energy and intensity of the coherent peak and Ch R from the {110} planes. Experimentally, it was found that positrons give the same results for the high-energy photon peak as electrons but a reduced planar Ch R.

In conclusion: Ultrarelativistic electron penetrating single crystals close to axial/planar directions "feel" very strong fields which result in emission of real hard photons (as seen in W⁸). The most pronounced photon peaks are obtained for incidence of (0.3-0.6) mrad to the axis and parallel to planar directions. This type of coherent bremsstrahlung is emitted when the electrons cross the rows of atoms forming the crystal planes (strings of strings' region¹), whereas normal CB originates from electrons crossing different planes. This new effect could eventually be used as a source for nearly monoenergetic γ -rays. For higher electron energies the photon peaks are much more pronounced and with energies close to E_0 . Other types of crystals - like Fe and W - should be investigated in detail, because here the fields are much stronger than in Si and diamond. Electrons and positrons well-aligned with crystal planes close to strong axis will "feel" different planar fields - giving rise to a difference in the intensity of the photon peak. This difference could be an experimental technique for investigations of the influence of strong fields on QED-processes. An area where other experimental attempts with the strongest available laboratory fields have failed until now.

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Figure captions:

- Fig. 1 Radiation spectra from 150 GeV electrons incident on the 0.5 mm thick diamond crystal as a function of incident angle to the $\langle 100 \rangle$ axis - angles given in the figures. The beam divergence was $\pm 30 \mu\text{rad}$ with the center of the beam core around the $\{110\}$ planes.
- Fig. 2 Radiation spectra from a 150 GeV electron beam (angular spread after off-line cuts $\pm 2 \mu\text{rad}$) incident on the 0.5 mm diamond crystal at 0.3 mrad to the $\langle 100 \rangle$ axis. The incident angles to the $\{110\}$ planes were; a : (0-8) μrad , b: (8-15) μrad and c: (22-36) μrad .
- Fig. 3 Radiation spectra from 70 GeV (a), 150 GeV (b) and 240 GeV (c) electrons incident on the 0.5 mm thick diamond at 0.3 mrad to the $\langle 100 \rangle$ axis. The angular regions around the $\{110\}$ planes were; a: (0-11) μrad , b: (0-8) μrad and c: (0-5) μrad .
- Fig. 4 Radiation spectra from 150 GeV electrons incident on the 0.5 mm thick $\langle 100 \rangle$ diamond (a), the 0.2 mm thick $\langle 100 \rangle$ diamond (b) and on 0.6 mm thick $\langle 110 \rangle$ Si crystals (c). The incident angles were; a: 0.3 mrad to $\langle 110 \rangle$ and (0-8) μrad around the $\{110\}$ plane, b: 0.3 mrad to $\langle 100 \rangle$ and (0-10) μrad around the $\{110\}$ plane and c: 0.54 mrad to $\langle 110 \rangle$ and (0-10) μrad to the $\{111\}$ plane. For comparison, the pure planar Ch R spectra from the $\{110\}$ and $\{111\}$ planes are inserted in figures b and c, respectively (ref. 6).
- Fig. 5 Calculated radiation spectra for 70 GeV (a), 150 GeV (b) and 240 GeV (c) electrons incident on a 0.5 mm thick diamond crystal at an angle of 0.3 mrad to the $\langle 100 \rangle$ axis. Angular regions around the $\{110\}$ planes were; a: (0-11) μrad , b: (0-8) μrad and c: (0-5) μrad . In the full drawn curves multiphoton effects are folded in, which is not the case for the dashed ones.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

- 150 GeV on 0.5 mm C (110) plane
0.3 mrad from $\langle 100 \rangle$ axis

Fig. 5