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PHOTON MULTIPLICITY IN THE HARD RADIATION OF 150-GeV ELECTRONS IN AN ALIGNED GERMANIUM CRYSTAL

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ABSTRACT

Mean values m of photon multiplicity in the radiation of 150-GeV electrons directed at and near the $\langle 110 \rangle$ axis of a 0.185-mm thick Ge crystal cooled to 100 K have been deduced from the measurements of pair conversion probabilities. Depending on the distribution of multiplicity assumed, values of m ranging from 3.8 to 4.3 are obtained for the previously reported anomalous radiation peak.

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Earlier we reported¹ on the observation of an anomalous high energy peak in the radiative energy spectrum of 150-GeV electrons directed at the $\langle 110 \rangle$ axis of a 0.185-mm thick germanium crystal cooled to 100 K. This anomalous peak, lying at an energy relative to the incident beam energy of $x \simeq 0.86$, appears only when the tilt angle ψ between the beam and $\langle 110 \rangle$ axis is within and close to the channeling critical angle ($\psi_c \simeq 62 \mu\text{rad}$). Since the theory² based on the synchrotron approximation has accounted reasonably well for the previously reported features of ultrarelativistic-electron and -positron radiation in aligned crystals, it was natural for us to attempt to reproduce the peak feature using the same approximation with a non-uniform flux distribution which characterizes channeling. The simple approach was unsuccessful because we did not include the competing effects of 'radiation cooling' and multiple scattering; the successive photon emission by a channeled electron lowers its transverse energy while the overall scattering process produces an opposite result. Both effects have been shown independently by Tikhomirov³ (VT) and Artru⁴ (XA) recently to be crucial factors in their obtaining a reasonable reproduction of the anomalous peak. There remains, however, the perplexing problem that the predicted mean value m of photon multiplicity per electron appears to be much larger than our preliminary experimental value. In view of this discrepancy, a more complete analysis of our data connected with the anomalous peak has been undertaken and we report here the results.

Photon multiplicity can be deduced from the intensity attenuation of the radiation passing through a material of known composition and thickness. Figure 1 schematically illustrates the experimental set up we used¹ at CERN. Immediately upstream of the counter B_3 (2.5-cm thick plastic

scintillator) was a 1-mm thick lead foil. In units of the radiation length L_R , the thickness of matter extending from downstream of the magnet M to and including B_3 is 0.30, and this constitutes the effective converter thickness for our multiplicity measurements. The photon calorimeter consisted of a 9-cm thick BGO ($L_R = 1.1$ cm) placed in front of a 45-cm thick lead glass ($L_R = 2.4$ cm). The electron beam was obtained by a two-step conversion of the primary 450-GeV proton beam and thus hadron and muon contaminations were insignificant. An annular-shape scintillator T was used so that a trigger signal of $B\bar{T}$ for data acquisition ensured that events associated with the beam halo were vetoed. At the crystal position the electron beam had a spot size of 1 cm in diameter and a divergence of ~ 20 μ rad (r.m.s.) in half cone angle. After traversing the germanium crystal (2 cm x 3 cm in area) which was cooled to 100 K, the electrons were magnetically deflected and their radiation in the initial beam direction recorded by registering event-by-event the contents of the ADC connected to the B_3 counter and photon calorimeter and the status of all other counters. The parallel-beam approach employed here may be less sophisticated than the divergent-beam technique⁵, but it avoids the latter's *inherent statistical bias against* yield measurements at precisely the most interesting point of perfect axial alignment. Indeed the observation of the anomalous radiation peak would likely to have been missed had we employed the divergent-beam technique.

Figure 2 shows the radiative energy spectra per unit crystal thickness, $x \frac{d^2 N}{dx d\Omega}$, obtained with the photon calorimeter for a range of angles ψ . An anomalous high-energy peak feature is clearly evident at perfect alignment and is seen to disappear when $\psi > \psi_c$. Indeed the similarity¹ of the $\psi = 102$ μ rad spectra obtained with 150-GeV electrons and with the same

energy positrons indicates that channeling effects are no longer significant for $\psi \geq 102 \mu\text{rad}$. Such an anomalous peak feature was not apparent in the radiation spectra obtained⁶ earlier with thicker crystals (0.4 mm and 1.4 mm) because it is masked by the significantly larger pile-up effects in those cases.

Additional insight into the process is gained by knowing the probability distribution $P_m(x)$ of photon multiplicity in the radiation events of energy x . It is however impractical to directly determine $P_m(x)$ because the parameters required for the deconvolution procedure are many and these must be determined with an unrealistically high precision. But information on the mean value of the distribution can be obtained by comparing the predicted and measured intensity attenuations through a known material layer of thickness ξ . For the energy range concerned here, the attenuation proceeds predominantly by conversion into electron-positron pairs and, thus, the transmission factor

$$T(x) = \sum_{m=1}^{\infty} P_m(x) \exp[-m\alpha\xi] \quad [1]$$

has a conversion coefficient which, to a good approximation, is a constant $\alpha = \left(\frac{9L_R}{7}\right)^{-1}$.

In the discussion below, we will focus on the conversion factor defined as $R(x) = 1 - T(x)$. Experimentally this can be constructed from the bin-by-bin ratio

$$R(x) = \frac{Y(B_3; x)}{Y_o(x)}, \quad [2]$$

where $Y_o(x) \equiv \frac{dN}{dx}$ is the differential yield and $Y(B_3; x)$ is the corresponding one obtained with the additional requirement that B_3 must have registered

at least one pair-conversion event. The background case with the crystal removed was used to check the measurement method. Poisson distribution⁷ should apply in this case and we have determined the multiplicity to be $m = 1.18$. The thickness ξ deduced from the measured average conversion factor (for the entire range of x) differs from that of the known absorber layers by only 2%. We thus used $\xi = 0.30 L_R$ in all our analysis.

Displayed on Fig. 3 are the measured conversion factors $R(x)$ of three spectra.⁸ Each $R(x)$ value can be transformed via Eq. 1 to a mean value $m(x)$ of photon multiplicity if the distribution $P_m(x)$ is specified. The transformation scales shown on Fig. 3 are for the two extreme forms of distribution: Poisson (m_P) for an uncorrelated pile-up phenomenon, and delta function (m_D) for a unique multiplicity which would arise if all photons came from an intermediate state (real or virtual). In the random case, the expected independence upon x is observed. Since in this case the yield consists of 83% background, the deduced m values are expected to be nearly those of the background and that is indeed the case. As the crystal is tilted from $\psi = 102 \mu\text{rad}$ to $\psi = 0$, the multiplicity is seen to get progressively larger with increasing x for $x \geq 0.3$ but seems to remain constant for $x < 0.3$.

The mean conversion factor $\bar{R}$ averaged over $0.82 \leq x \leq 0.9$ (position of the anomalous peak) for $\psi = 0$ is $\bar{R} \simeq 0.59$. This converts to a multiplicity of $m = 3.8$ and 4.3 for the Poisson and delta-function distributions, respectively. In contrast, the 'radiation cooling' model of VT³ requires $m_{th} \simeq 12$. This number may even be a lower limit value since he used a low photon-energy cut off of 3 GeV for the incoherent part of the radiation spectrum.

The work of XA⁴ differs from that of VT basically in the computational methods employed. XA used a Monte Carlo approach instead of an analytic one and the more general formula of Baier, Katkov and Fadin⁹ instead of the synchrotron approximation. Although the corresponding XA multiplicity would be slightly lower than 12 because the ‘photon formation length’ is taken into account, the number XA quoted is low because his calculational results are sensitive to the low photon-energy cut off and he had selected¹⁰ a value which ensured a unit multiplicity at $x \approx 0$. Moreover, from $x = 0.85$ to $x = 0.925$, XA predicts an increase of 1 unit in the m value whereas our measurements show a definite decrease.

While the dynamic range chosen for the calorimeter’s ADC dictated a low-end cut off of 3 GeV ($x=0.02$) in our energy measurements, a lower threshold value actually applies to the results on multiplicity. This is because in our analysis of the B_3 data leading to the contents of Fig. 3, only events with two or more converted particles were accepted. The pair conversion efficiency, while not exactly constant, decreases only slowly with decreasing energy; dropping from 90% at 600 MeV to 80% at 150 MeV and to 50% at 50 MeV. It should be emphasized that, contrary to the ‘radiation cooling’ results of VT and XA, the experimental multiplicity values at perfect alignment are not sensitive to the low photon-energy cut off. A confirmation follows from a re-analysis of the B_3 data in which the low energy cut is lowered to accept also single converted-particle signals. In this case, the addition of Compton scattering to the pair creation process results in a conversion coefficient α (see Eq. 1) which is nearly constant down to ~ 1 MeV. Applying the new value of α extracted from the background measurement to the measured conversion factor for $\psi = 0$ yielded a value of m_D (or

m_P) which is slightly smaller (rather than larger) than the corresponding one on Fig. 3. Thus the apparent discrepancy between the required mean photon multiplicity in the model of VT and XA and the measured value noted earlier is real and remains unresolved.

Background correction has not been applied to the data on Fig. 3 and estimates of its effects are needed. The correct procedure should take into account the fact that there is a finite probability for both the background and crystal radiation to come from the same electron. In a radiation spectrum divided into bins of equal sizes, let $\mathcal{B}_1(x)$ designate the probability for the electron to radiate into a bin of energy x via the main process and $\mathcal{B}_2(x)$ that via the background process (the two processes need not have the same distribution of multiplicity). There are then three contributions to the resultant transmission factor: the main process alone, the background process alone and their pile up. Suppressing the explicit dependence on x for clarity, we have

$$T = \frac{\mathcal{B}_1(1 - \mathcal{B}_2)T_1 + \mathcal{B}_2(1 - \mathcal{B}_1)T_2 + T_{12}}{\mathcal{B}_1(1 - \mathcal{B}_2) + \mathcal{B}_2(1 - \mathcal{B}_1) + \mathcal{B}_{12}}, \quad [3]$$

where

$$T_{12}(x) = \sum_{x'=x_{th}}^{x-x_{th}} \mathcal{B}_1(x')\mathcal{B}_2(x-x')T_1(x')T_2(x-x'), \quad [4]$$

$$\mathcal{B}_{12}(x) = \sum_{x'=x_{th}}^{x-x_{th}} \mathcal{B}_1(x')\mathcal{B}_2(x-x'), \quad [5]$$

x_{th} is the effective threshold energy, and T_1 and T_2 are the corresponding transmission factors when only one process is present. The sum in the denominator which ensures a proper normalization is simply the resultant radiation probability $\mathcal{B}(x)$. Here we want to extract the $T_1(x)$ factors from

the experimentally measured values of $T_2(x)$, $T(x)$, $B_2(x)$ and $B(x)$. This is accomplished by an iterative procedure starting from the lowest value of x because, for a given x , the summation of Eqs. 4 and 5 involves only $x' < x$. A value of $x_{th} = 3.3 \times 10^{-4}$ (50 MeV) was used. For $x_{th} \leq x < 0.02$ where we have no experimental data, we assumed that the required input values are independent of the tilt angle and are governed by the Bethe-Heitler radiation formula. For the $\psi = 0$ case, the extracted value $R_1(x) \equiv 1 - T_1(x)$ differs from the uncorrected $R(x)$ value on Fig. 3 only by a factor of 0.97, 1.00 and 1.02, respectively, at $x = 0.1$, 0.5 and 0.86. The corresponding factors for the $\psi = 102 \mu\text{rad}$ case are 0.94, 0.94 and 0.97. Such magnitudes of correction are of the order of the statistical fluctuations of the data points in Fig. 3 and, thus, the neglect of background correction should not affect the conclusions drawn or to be drawn from the comparison of experiment and theory.

We now return to the features of the spectra on Fig. 2. The shape seems to be nearly independent of ψ for $\psi \geq 102 \mu\text{rad}$, and also for $\psi < 102 \mu\text{rad}$ over the restrictive interval $0 < x < 0.3$. This suggests that the yield $Y_o(\psi; x)$ perhaps consists of an incoherent addition to the $\psi = 102 \mu\text{rad}$ spectrum over the entire range of x for $\psi < 102 \mu\text{rad}$;

$$Y_o(\psi; x) = Y_{pk}(\psi; x) + Y_{bs}(102\mu\text{rad}; x). \quad [6]$$

If that is indeed the case, the Y_{pk} peak is seen to be asymmetric with a tail on the low energy side. Moreover, when the crystal is increasingly tilted away from perfect alignment, the magnitude of the peak intensity decreases but there is no apparent change in its position and width.

Also interesting is the mean multiplicity $\bar{m}_{pk}$ of the Y_{pk} peak. This can

be deduced using Eq. 3 (with the subscripts $\{1, 2\}$ changed to $\{pk, bs\}$). However different electrons are responsible for the two radiation components in this case and thus all terms involving $\mathcal{B}_{pk}\mathcal{B}_{bs}$ in Eq. 3 are absent. The results using our experimental data averaged over the interval $0.82 \leq x \leq 0.9$ are shown on Fig. 4a. The $\bar{m}_{pk}$ values exhibit virtually no dependence on ψ . Interestingly, the radiation yield and spectral shape recorded with the low energy BGO detector¹¹ also are observed to be nearly independent of the tilt angle over $0 \leq \psi \leq 102 \mu\text{rad}$; although the yields are ~ 3.6 times smaller than that measured in a random orientation. Furthermore a separate analysis shows that there are no significant pile up effects in the BGO spectra. These results and that on Fig. 2 together suggest that pile up into the high energy bins at or near the alignment condition involves mainly photons with $x < 0.08$, and that little if any of these low energy photons contribute to the anomalous peak itself.

The near invariance of the $\bar{m}_{pk}$ value and the peak shape in the $Y_{pk}(x)$ spectrum with changing ψ justifies *a posteriori* the decomposition of the radiation yield into two incoherent parts. It also suggests that electrons responsible for the Y_{pk} component all produce nearly the same amount of radiation energy and number of photons. If only radiative processes are involved and one assumes that these electrons radiate with a unity probability (a reasonable assumption for the ‘radiation cooling’ model), their fraction f_{pk} at a given tilt angle can be extracted from the measured total radiation probability, since electrons in the remaining $(1 - f_{pk})$ fraction would radiate with a probability equal to that measured at $\psi = 102 \mu\text{rad}$. Values of f_{pk} extracted under the preceding assumption are displayed on Fig. 4b. The fall off with increasing tilt angle is reminiscent of the behaviour

of the initial fraction f_{ch} of channelled electrons. Computed f_{ch} fractions, for a beam divergence of $20\ \mu\text{rad}$ (r.m.s.) in half-cone angle, are thus shown as a solid curve on Fig. 4b for comparison. The degree of similarity between the two sets of fractions suggests that *initially* channelled electrons are responsible for the Y_{pk} yield. However, the initial distribution of transverse energies, which depends on the tilt angle, seems to play no role since these electrons appear to radiate nearly the same amount of energy and number of photons.

In conclusion, our detailed analysis here is seen to give new information on the nature of the anomalous radiation peak. The challenge then is to come up with an explanation which can account simultaneously for the observed yield and mean photon multiplicity, and their dependence upon the tilt angle. Further clues or clarifications will be forthcoming from the new set of measurements being prepared at CERN in which the background radiation will be practically eliminated, and thinner crystals and additional beam energies will be used. We thank X. Artru for helpful discussion.

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⁷ A modified version is used because the normal $m = 0$ term does not apply here and thus has been omitted. Of course the distribution has to be renormalized and its mean value recomputed.

⁸ The conversion factors $R(x)$ presented earlier [doctoral thesis of A. Belkacem, Université Claude Bernard Lyon-1, France, 1986 (unpublished); CERN Report EP/87-206; and Proc. of the 12th Intl. Conf. on Atomic Collisions in Solids, Okayama, Japan, Oct. 1987] were based on the scintillator counter V_4 which was placed in front of the lead foil and B_3 counter. This V_4 counter was connected only to a fast discriminator and the lack of pulse height distribution information led to large uncertainties in the transformations of $R(x)$ to $m(x)$ values.

⁹ V.N. Baier, V.M. Katkov and V.F. Fadin, **Radiation of Relativistic Electrons**, (Atomizdat, Moscow, 1973) [in Russian].

¹⁰ Quoted in Ref. 5 is $x_{min} = 0.002$ (300 MeV) but an oral communica-

tion from XA indicated that his use of an arbitrary phase factor cut off $\Delta\phi_{min} = 3\pi$ actually translates to an energy threshold of ~ 750 MeV.

¹¹ Two photomultiplier tubes were attached to the BGO slab. The high gain one was used to record low energy events in the approximate range of 0.1-3 GeV while the low gain one was combined with the lead-glass photomultipliers to ensure a linear energy response (up to the full beam energy) for our total energy detector system. The low energy BGO spectra mentioned in the text have been obtained by imposing the requirement that the total energy of each event be less than 3 GeV.

FIGURE CAPTIONS

Fig. 1 - Schematic diagram of the experimental set up: B , T , and B_3 are plastic scintillators and M is a magnet.

Fig. 2 - The radiative energy spectra obtained at tilt angles near the $\langle 110 \rangle$ axis of a 0.185-mm thick Ge crystal cooled to 100 K. For clarity, only smooth curves drawn through the data points are shown.

Fig. 3 - The fraction $R(x)$ of radiation events in which at least one photon has been converted into an $e^- - e^+$ pair by the material extending downstream of M to and including B_3 . The scales on the right side show the mean values of photon multiplicity corresponding to a Poisson ($\bar{m}_P$) and a delta-function ($\bar{m}_D$) distribution.

Fig. 4 - The tilt angle dependence of: a) the mean multiplicity $\bar{m}_{pk}$ of the Y_{pk} peak with the filled and open symbols corresponding to the Poisson and delta-function distribution, respectively, and statistical error bars shown only for the filled symbols to avoid cluttering; and b) the experimentally inferred f_{pk} fraction (open symbols) and the computed fraction f_{ch} of initially channelled electrons for a beam divergence of 20 μ rad (r.m.s.) in half-cone angle (solid curve).

FIG. 1

FIG. 2

FIG. 3

FIG. 4