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**PLANAR EFFECTS IN 150 GeV POSITRON RADIATION
OFF A THIN GERMANIUM CRYSTAL**

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ABSTRACT

Radiation spectra measured for 150 GeV positrons directed at or close to the $(1\bar{1}0)$ planar direction of a 0.185 mm thick Ge crystal show clear evidence for increasing lower cut-off frequency with decreasing pathlength in the planar electric field. The observed features are well reproduced by the theory of "synchrotron-like" radiation off a continuum planar potential.

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Earlier, we reported¹ on the observation of substantially enhanced radiation by 70-150 GeV electrons and positrons when they are aligned with or close to the germanium $\langle 110 \rangle$ axis. While the general features of the spectra are reproduced well by the theory of 'synchrotron-like' radiation off a 'uniformly charged string'², there are effects of channeling motion and multiple photon emission which complicate the analysis. Here we present the results for 150-GeV positrons directed at or close to the germanium $(1\bar{1}0)$ plane. The planar case provides a degree of contrast in simplicity: first, the planar field strength is weaker than the axial one and thus, for the same beam energy, there will be less spectral distortion due to multiple photon emission; second and more significant is the fact that the continuum planar electric field is one dimensional instead of two, and this means that all particles of a non-divergent beam will encounter exactly the same field in their passage through the crystal except for perfect alignment. Perhaps the most dramatic of the planar results is the clear cut evidence for the effect of increasing lower cut-off frequency with decreasing path length in the crystal's electric field.

The experimental set up used is identical to that of the earlier study.¹ Briefly, the 0.185-mm thick germanium crystal target was cut such that its 1 cm x 2 cm surface is perpendicular to the $\langle 110 \rangle$ axis. Its mosaic spread was deduced from the earlier studies¹ to have a r.m.s. value $< 10 \mu\text{rad}$. A two-axis goniometer provided a mount which allowed the crystal to be rotated around both the horizontal $\langle 1\bar{1}0 \rangle$ axis and the vertical $\langle 001 \rangle$ axis, and be cooled to 100 K. The positron beam had an angular divergence restricted in both the horizontal and vertical dimensions to a r.m.s. value of $20 \mu\text{rad}$. Since the radiation can be influenced by a major axis (even

at an angle as large as 10 mrad), the projected angle between the beam direction and $\langle 1\bar{1}0 \rangle$ axis in the vertical plane was kept to a constant value of $\Theta_V = 70$ mrad. Thus the angular scan was done by varying only the corresponding projected angle in the horizontal plane, Θ_H , which was also the angle relative to the $(1\bar{1}0)$ plane. We termed Θ_H the tilt angle for brevity.

Figure 1 displays the tilt angle dependence of the measured mean radiated energy which has been obtained by integrating the power spectrum. This radiated energy is seen to increase with decreasing tilt angle, and to reach a maximum value at perfect alignment. Moreover, the angular width of the enhancement is much larger than the channeling critical angle, $\Psi_c \simeq 22 \mu\text{rad}$, and there is no obvious indication of channeling effects. The latter may simply be due to the fact that the beam angular divergence is comparable to Ψ_c .

Superimposed on Fig. 1 are two theoretical curves. The dashed one labelled CB follows from the integration over photon energy of the standard coherent bremsstrahlung differential cross section which is based on the Born approximation. The effect of finite beam angular divergence³ has been included here and in Fig.3. For large tilt angles ($\Theta_H \geq 200 \mu\text{rad}$), excellent agreement with experimental data is obtained. However, in the angular range near the $(1\bar{1}0)$ plane, little or no enhancement is predicted. This dramatic contrast to the observation may be attributed to the break down^{4,5} of the Born approximation for small tilt angles. We note in passing that a similar break down of the CB theory has also been observed¹ for alignment near an axis. But in that case the predicted yield is considerably

larger than the measured one.

A better account of the experimental data is clearly given by the solid curve labelled SC in Fig. 1. It is the prediction of a theory² based on the semiclassical formalism developed by Baier et al.⁶ The premise here is that, at this high energy, the positron behaves like a classical particle in a nearly straight-line trajectory and the photon emission process results in negligible motion in the transverse direction. Thus, in the continuum approximation where a crystal plane becomes a slab-like charge distribution, a positron encounters a constant transverse electric field at perfect alignment, and transient field for imperfect alignment.

The SC results shown in Fig. 1 were obtained for a single, isolated charged slab using the computational procedure of Ref. 2. An empirical expression similar to that employed for the axial case² was used to characterize the electric field. Values for the two theoretical parameters have been obtained by fitting the expression to the continuum-averaged field of the Doyle-Turner potential for Ge.⁷ Because the individual lattice atoms can still contribute incoherently, the same angle-independent value as for the CB curve has been added to the SC results shown. A short dashed-segment of the SC curve in a small angular region near the axis is an extrapolation to the *synchrotron radiation* value at $\Theta_H = 0$. The effect of finite beam angular divergence has not been folded into the computational results. At small tilt angles, its inclusion would narrow the observed difference between theory and experiment. The remaining discrepancy is likely the ignored effect of channeling motion which steers the positron away from the strong field region and thus lowers the radiation probability.

More details on the radiation can be seen in Fig. 2 where the power spectrum obtained at several tilt angles are displayed. The symbols E , k , N and l denote the beam energy, photon energy, number of photons and target thickness, respectively. Thus the ordinate is the number of photons emitted per unit target thickness in the photon energy interval of k and $k+dk$. As the tilt angle is increased, a remarkable feature is seen in Fig. 2: the peak intensity becomes attenuated and shifted to a larger x value but the high energy tail is virtually unaffected in both magnitude and shape. It looks as if a cutter has chopped off the low energy portion with a cut-off value x_c which increases with increasing tilt angle. Such details are reproduced well by the SC theory described above. Examples of the calculated SC results are shown on Fig. 3 for two planar spectra. In part a) of the figure the inadequacy of the CB theory for small tilt angle ($\Theta_H = 52 \mu\text{rad}$) is also evident. The SC prediction is for the *thin-target* yield and its agreement with experiment implies that there is no significant spectral distortion due to multiple photon emission. This is consistent with the results of our concurrent measurements of the mean value of photon multiplicity per positron.

There is a simple explanation for the observed behaviour of the low-energy cut off in terms of the effective path length L associated with the particle motion in the strong field of the crystal plane and the length L_k associated with the formation of a photon with energy (or frequency) $k = xE$. When $L < L_k$ there is insufficient time for the photon to appear and thus a photon of energy less than k will be cut off. For a straight-line trajectory, the path length is $L=b/\Theta_H$, where b is the characteristic extend of the transverse electric field of a single plane. The formation length can

be written⁴ as $L_k = (2\hbar/mc)(E/mc^2)(1-x)/x$. Thus increasing Θ_H means decreasing L , and this places a restriction on L_k which translates to an increasing cut off of low frequency radiation x_c . More precisely, x_c can be obtained from the condition $L = L_k$ by specifying b . Figure 4 displays the result for $b = 0.37 \text{ \AA}$, which spans the region of maximum strength for the squared electric field down to $\frac{1}{2}$ of the maximum. Also shown in the figure are experimental x_c which were taken simply as those values corresponding to the maximum intensity point of the power spectrum. Note that for the case of near axial alignment the same theoretical consideration predicts a distribution of cut-off frequencies. This is because, for a non-zero tilt angle, a uniform flux of particles in a straight-line trajectory traverse different path lengths or segments of the axially symmetric field. Thus no sharp frequency cut off is expected for that case.⁸

Good agreement between the theoretical and experimental x_c values in Fig. 4 is clear except for the $17 \mu\text{rad}$ point. In that case the alignment is inside the channeling critical angle and the assumption of straight-line trajectory is inappropriate. Indeed channeling steers positrons away from the strong-field region and this results in an apparent path length shorter than the one computed from a straight-line trajectory (as suggested by the larger experimental x_c in Fig. 4). In the $228 \mu\text{rad}$ case, the effects of crossing adjacent planes may be significant. An indication of this can be seen in Fig. 3b where the presence of interference structure is suggested. The same structure is also responsible for the relatively large uncertainty in the experimental x_c . Interference peaks are of course built⁹ into the CB theory but there seems to be some discrepancies in the peak positions between prediction and observation in Fig. 3b. Unfortunately the experimental

points were obtained with poor statistics (background rate twice that of the crystal) and this precludes a more definitive conclusion.

In summary, the experimental radiation spectra recorded for 150-GeV positrons directed at or close to the Ge (1 $\bar{1}$ 0) planar direction show evidence for increasing lower cut-off frequency with decreasing path length in the strong field. This and other features are reproduced well by the theory of 'synchrotron-like' radiation off a 'a uniformly charged slab'.

FIGURE CAPTIONS

Fig. 1 - The mean radiated energy obtained from the measured radiative power spectrum of 150-GeV positrons traversing a 0.185 mm-thick Ge at 100 K is shown as a function of the tilt angle between the beam and $(1\bar{1}0)$ planar direction. The dash (CB) and solid (SC) curves are, respectively, the predictions of coherent breemmstrahlung and semiclassical ‘synchrotron-like’ theories described in the text.

Fig. 2 - The radiative power spectra corresponding to the few selected tilt angles of Fig. 1. A bin size which increases with increasing x has been used to minimize the scatter of data points and curves are drawn with no other purpose than to guide the eye.

Fig. 3 - The power spectra obtained at tilt angles of a) $52\ \mu\text{rad}$ and b) $228\ \mu\text{rad}$ are displayed with the predictions of coherent breemmstrahlung (dashed curve) and semiclassical ‘synchrotron-like’ (solid curve) theories described in the text. An equal bin size has been used here.

Fig. 4 - The experimentally inferred lower cut-off frequencies x_c are compared with the predictions (solid curves) based on a consideration of characteristic lengths in the continuum planar electric field which is characterized by a mean transverse dimension of $b = 0.37\ \text{\AA}$ (see text for details).

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- ⁸ All except one of the positron radiation spectra in Ref. 1 are affected significantly by axial channeling effect. A careful examination of the unpublished data for larger tilt angles, where a straight-line trajectory description is more appropriate, indeed shows no indication of frequency cut off effect.
- ⁹ Interference structure would be predicted by the SC theory if the periodic nature of the electric field due to the crossing of planes were taken explicitly into account.

Fig. 1

Fig. 2

Fig. 3

FIG. 4