Observation of Electric Synchrotron Radiation in a Crystal

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Enhanced radiation of up to 0.4 of the incident beam energy, measured for 4-, 15-, and 17.5-GeV positrons directed along the $\langle 100 \rangle$ axis of an 80-μm-thick diamond crystal, is reported for the first time. The results are in excellent agreement with the recently proposed theory of crystal-assisted radiation based on the synchrotron formalism.

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Investigations of channeling radiation[1] with energetic electrons and positrons have been heretofore confined exclusively to relatively low-energy photons (< 0.1 times the particle energy) which are sensitive to the details of the channeling motion. We report here the first observation of enhanced radiation of much higher-energy photons. Measurements were made using positrons of energies $E_0 = 4$, 15, and 17.5 GeV directed along a $\langle 100 \rangle$ crystal axis of an 80-μm-thick diamond single crystal. Detailed analyses of the results confirm three recent predictions of Kimball and Cue[2] for high-energy radiation from charged particles in an aligned crystal. Namely, (1) the synchrotron process dominates the radiation; (2) quantum recoil effects are important; and (3) the channeling flux distribution can be deduced directly from the photon spectrum. The experimental results may constitute the first laboratory observation of these quantum recoil effects in synchrotron radiation.

Our measurements utilized the existing setup at the Stanford Linear Accelerator Center which previously has been used to investigate low-frequency line features of channeling radiation.[3,4] Briefly, the momentum-analyzed positron beam ($\Delta p/p \simeq \pm 0.1\%$ and 1 to 3 e^+/pulse at 10 pps) is directed to the target after passing through a four-jaw slit system of 1-mm × 1-mm opening and a scintillating veto counter (S_1) having a center hole 2 mm in diameter. With the two collimators separated by 14.3 m, the long-term directional drift of the beam (intrinsic angular spread of ± 2.5 μrad) is restricted to the range of ± 105 μrad. This is adequate for our purpose since the estimated channeling critical angle is ± 108 μrad at 15 GeV. The beam transmitted through the diamond target mounted on a remote controlled two-axis goniometer (step size of 23 μrad) is magnetically deflected and monitored by a scintillator (S_2) that intercepts positrons of 0.4–1 times E_0. Forward directed photons produced in the target are analyzed by an 8-in. diameter × 16-in. long NaI (Tl) detector system, in front of which is a thin charged-particle veto counter (S_3). The photon signal is digitized and then recorded event by event when the condition $\bar{S}_1 S_2 \bar{S}_3$ is satisfied. This requirement also places a sharp upper energy cutoff of $\hbar\omega/E_0 \simeq 0.6$ on the photon spectrum, but this is of no practical consequence since the region of significant yield is not affected. The data presented here have been corrected for the photon detection efficiency, which is calculated by Monte Carlo simulations to be > 89%. Detector energy calibration has been made previously[4] and its energy resolution at 15 GeV is measured to be 2% by directing the incident positrons into the detector.

The photon yields, N, obtained for the incident beam aligned with the diamond $\langle 100 \rangle$ axis are displayed in Figs. 1 to 3 as relative excess yields $(N - N_{BH})/N_{BH}$, where N_{BH} is the corresponding theoretical Bethe-Heitler (BH) yield for fully screened atoms in a randomly oriented target. Figure 1(a) also includes a spectrum recorded when the crystal axis is tilted away from the beam direction so that it is, in effect, a random spectrum. Displayed in this case are the ratios N/N_{BH} and these have been averaged over a wider energy interval because of poor statistics. Within the statistical errors the expected ratio of one is seen, providing an independent check on our yield measurements.

According to Kimball and Cue,[2] it is convenient to view the crystal field as segments of uniform transverse electric fields distributed symmetrically on a string (or plane) of atoms. Transition rate calculations are then simplified since they can be expressed in terms of the rates for a particle in a uniform field. The total rate follows straightforwardly by taking the appropriate weighted sum of the contributions from the field segments. In the present context, the process is just synchrotron radiation. The synchrotron description is valid if the classical characteristic synchrotron frequency ω_c exceeds the radiation frequency ω_d characteristic of the periodicities of channeling trajectories, and if the photon emission process leaves the particle in nearly the same field. For the present crystal and range of photon energies, the conditions translate into a requirement of $E_0 > E_c \simeq 5$ GeV, and this is fulfilled by our use of 15- and 17.5-GeV positrons. Comparison of the theory with data requires the introduction of a path length parameter L which attenuates mainly the low-frequency radiation and is justified on the basis of the limited time interval over which the particle effectively undergoes synchrotron radiation.[2]

Calculations were performed with use of the QED expression for synchrotron radiation in a field derived from a thermally averaged Moliere potential. Our 15-GeV data are sufficiently accurate to make conclusions about the particle flux distribution. The results for a uniform flux distribution are shown in Fig. 1(a) for several values of L. It is clear that the path length correction affects more the lower-energy photon intensity, and that no value of L can bring the predictions into agreement with the experimental spectrum for this flux distribution. In contrast, the same calculations using an equilibrium flux distribution of channeled particles based on an unaltered entrance transverse-energy distribution at perfect alignment and $L = 5$ μm, as shown in Fig. 1(b), give an excellent account of the data.

The use of an effective path length L may seem somewhat arbitrary but it does provide a simple procedure to take into account the average effects associated with noncircular channeling paths and scattering, which are intrinsic factors, as well as the experimental factors of crystal imperfections and beam angular divergence and misalignment. Indeed the success of the path length approach can further be judged from Fig. 2 where the 17.5-GeV data are displayed such that the low-frequency region is emphasized. The theory with $L = 5$ μm is seen to fit the data remarkably well down to the lowest measured frequency. This degree of agreement has also been noted[2] for the low-frequency data of 55-GeV positrons in Si(110) planes.

Earlier, the condition for the applicability of the synchrotron description was stated as $E_0 > E_c$, as deduced from $\omega_c > \omega_d$. Our results suggest that when $E_0 \gtrsim 3E_c$, the description is valid over the entire photon spectrum. However, even when $E_0 < E_c$, there will still be photons which are emitted with $\omega > \omega_d$, and the theory should then apply. This is indeed the case as demonstrated in Fig. 3 by

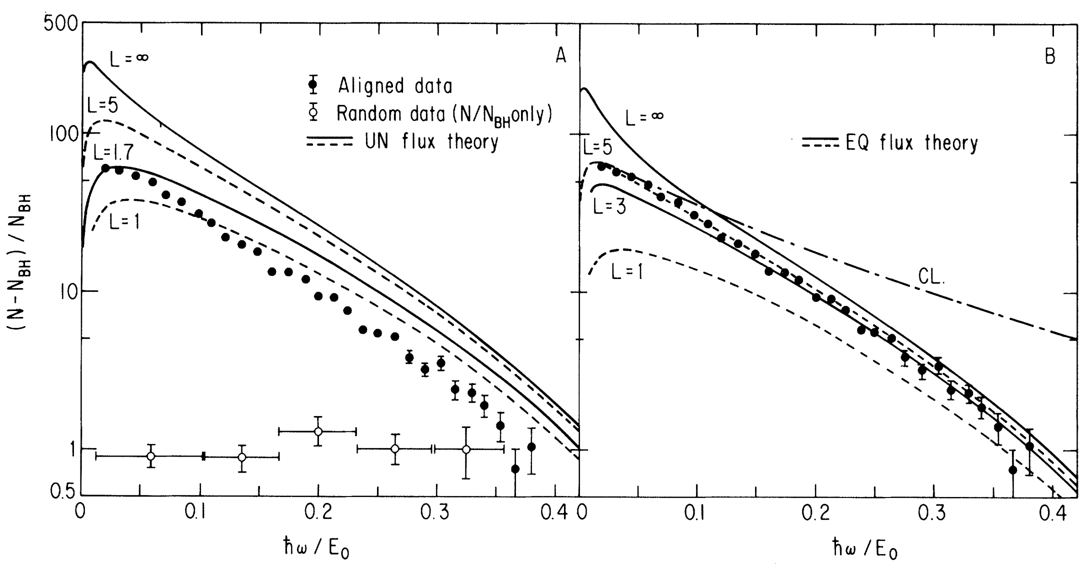

FIG. 1. Measured photon yields N for 15-GeV positrons directed along the ⟨100⟩ axis of an 80-μm-thick diamond single crystal shown as relative excess yields, $(N - N_{BH})/N_{BH}$, over the corresponding Bethe-Heitler values for fully screened atoms. The curves are predictions based on the QED theory of Ref. 2 with L in micrometers: (a) for a uniform particle-flux distribution and (b) for an equilibrium particle-flux distribution. Yields obtained in the random direction are also displayed in (a) but as ratios N/N_{BH}. Also shown in (b) is the corresponding classical theory for $L = 5$ μm.

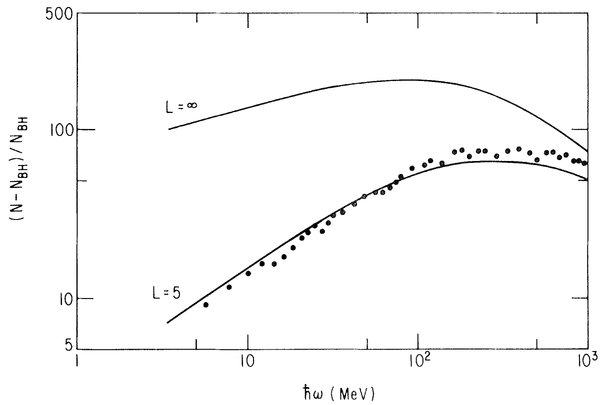

FIG. 2. The low-frequency part of the photon spectrum obtained at 17.5 GeV is compared with theoretical predictions analogous to those in Fig. 1(b).

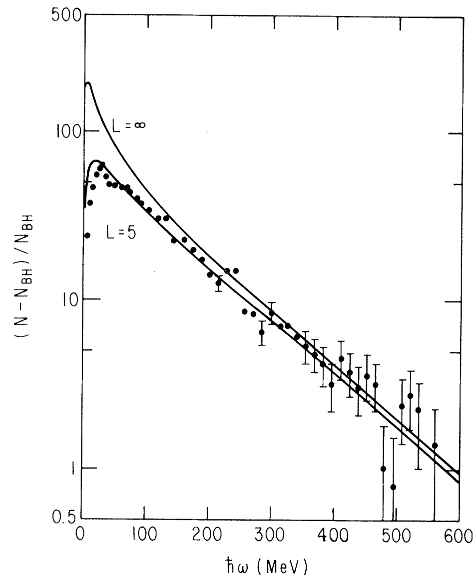

FIG. 3. The entire photon spectrum obtained at 4 GeV is compared with theoretical predictions analogous to those in Fig. 1(b).

our 4-GeV data. There is structure around 50 MeV due to the radiation correlated with the periodicities of channeling trajectories. But above 80 MeV, the synchrotron theory with the same $L = 5$ μm again gives an excellent fit to the data.

It is interesting to compare the value of $L = 5$ μm required to fit the data here with those deduced[2] earlier for an equilibrium distribution applied to the data available only for the low-frequency end. There, comparable values of $L = 4$–6.5 μm were deduced for positrons while significantly lower values of $L = 0.5$–0.9 μm were obtained for electrons. These L values are much smaller than the dechanneling length associated with channeling motion. Their clustering into two distinctive groupings merits further investigations.

The agreement between theory and experiment as demonstrated in Figs. 1(b), 2, and 3 confirms the dominance of the synchrotron process for high-energy radiation of channeled particles. If the classical expression for synchrotron radiation in the same electric fields is used, the yield is increasingly overestimated for increasing photon energy as can be seen in Fig. 1(b) for 15 GeV and $L = 5$ μm (the curve labeled CL). Clearly, quantum recoil effects are important. Also, except for very small values of path length L ($\lesssim 1$ μm), the high-energy portion of the photon spectrum depends only slightly on L. Thus, for the positron case, comparison of theory and experiment at the high-energy portion alone is sufficient for the deduction of the channeling flux distribution even if L is not precisely known. In the present case, the implication of a nearly equilibrium flux rather than a uniform one is not unreasonable, since a substantial redistribution of the entrance (uniform) particle flux at these energies can be expected for an 80-μm-thick crystal. More detailed information on the flux distribution will require data more precise than those obtained here.

Finally, the validity demonstrated here of viewing the crystal as presenting segments of uniform transverse electric fields should provide a firm basis for application to other high-energy processes in the crystal field.

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