Radiation of ultrarelativistic positrons moving in a crystal near crystallographic axes and planes

R. O. Avakyan, I. I. Miroshnichenko,[1)] J. J. Murray,[2)] and T. Vigut[2)]

Erevan Physics Institute
(Submitted 26 January 1982)
Zh. Eksp. Teor. Fiz. **82**, 1825–1832 (June 1982)

The radiation of high-energy positrons channeled in a diamond crystal is studied experimentally. Spectral distributions are given for the intensity of radiation in planar channeling in the (011) plane of positrons of energy 2, 4, 6, 10, 14, and 16 GeV and in axial channeling of positrons with energies 4, 6, 10, and 14 GeV along the ⟨100⟩ axis.

PACS numbers: 61.80.Mk

The present experiments are devoted to study of the radiation in channeling of high-energy positrons in crystals as theoretically predicted by Kumakhov.[1]

Experimental studies of the radiation spectra of high energy positrons undergoing channeling were carried out by us at the SLAC electron linear accelerator for positron energies 2, 4, 6, 10, 14, and 16 GeV during 1978 to 1979. Preliminary data were published in Ref. 2. The experimental apparatus is shown in Fig. 1.

The electron accelerator beam with energy 22 GeV hit a tungsten target which served as a source of secondary positrons. A system of collimators, deflecting magnets, and quadrupole lenses focused a positron beam onto a goniometer in which two diamond crystals of thickness 0.08 and 0.6 mm were placed alternately. Further adjustment of the beam in the horizontal and vertical planes was accomplished by means of correcting magnets. Control and monitoring of the beam during tuneup of the beam line was accomplished by means of remotely controlled scintillation counters. Directly in front of the crystal was placed a scintillation counter S4 with a center opening 2 mm in diameter, in order to avoid the effect of beam halo and possible deviations of the positron beam from the central location. The momentum spread of the positron beam was ±0.1%. The beam was shaped in such a way that at the point of location of the crystal an approximately parallel beam of positrons was provided, with a total angular spread $\Delta\theta \sim 10^{-5}$ rad. After passing through the crystal the positrons were deflected by a magnet and detected by scintillation counter S6, the size of which was chosen sufficiently large to record practically the entire spectrum of scattered positrons. The flux of photons from the crystal was measured by a total-absorption spectrometer employing an NaI(Tl) crystal of thickness $10x_0$ (x_0 is the radiation length).

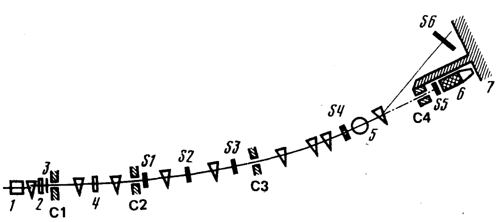

FIG. 1. Diagram of experiment. 1—Pulsed magnet, 2—tungsten target, 3 and 4—secondary emission monitors, 5—goniometer, 6—NaI(Tl) spectrometer, 7—lead shield, C1–C4—collimators, triangles—bending magnets, S1–S6—scintillation counters.

The experiment utilized a goniometer with the possibility of rotation of the crystal in two mutually perpendicular directions with an accuracy of angle setting equal to $2.30 \cdot 10^{-5}$ rad.

The photons traveled the entire path from the crystal to the spectrometer in a specially constructed chamber. In front of the spectrometer at a distance of 20 m from the diamond crystal was placed a photon collimator 50 mm in diameter which provided a photon angular collimation equal to $1.25 \cdot 10^{-3}$ rad, considerably larger than the expected angular spread of the emitted photons in the channeling process. An appropriate coincidence and anticoincidence technique was used for selection of useful events and provided control of a multichannel analyzer which served to analyze the γ-ray pulses recorded by the spectrometer. The detector signal was recorded 2 μsec after the accelerator pulse. Appropriate electronic circuitry was used to select possible background events which appeared during the accelerator pulse of duration 1.6 μsec. Cases of coincidence of signals from counter S4 and the spectrometer, and also the appearance of two pulses in the spectrometer during the accelerator pulse, vetoed the transmission of the signal from the spectrometer to the input of the pulse analyzer. The analyzer was triggered by coincidence of the accelerator synchronization pulse and a signal from the positron counter S6.

All measurements were made at an average positron beam intensity no greater than one positron per accelerator pulse. All information from the counters was read by a microcomputer and recorded on floppy disks. As information was stored, operative control was accomplished by means of tabular and graphical displays. The information was then transferred from the floppy disks to the magnetic tape of the SLAC computation triplex and processed to obtain the final results.

The number of positrons hitting counter S4 during the experiment varied from 1% to 3% of the total positron beam, depending on the quality of shaping of the electron beam at the accelerator output. Calibration of the spectrometer in the low-energy region was accomplished by means of radioactive sources of Cs^{137} ($E_\gamma = 0.661$ MeV), Co^{60} ($E_\gamma = 1.17$ and 1.33 MeV), Po–Be ($E_\gamma = 4.4$

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MeV), and Cm-C^{13} ($E_\gamma = 6.13$ MeV). In the high-energy region the calibration was carried out by measurement of the spectrum of positrons with energies 2, 4, 6, 10, 14, and 16 GeV.

The γ-ray spectrometer, which employed a NaI(Tl) crystal of length $20x_0$, was linear in the energy region up to 16 GeV. Correctness of the calibration was checked in an experiment in which the cross section for bremsstrahlung from an amorphous target was measured and checked against the Bethe-Heitler cross section. In addition, calibration measurements were made of the bremsstrahlung spectra from a carbon target (equivalent to the diamond) and from a disoriented crystalline target.

Orientation of the diamond crystals mounted in the goniometer was accomplished by means of the well known effects of coherent bremsstrahlung of electrons in crystals. The following well known regularities of coherent bremsstrahlung were utilized[3]: a) the photon energy spectrum contains coherent peaks associated with definite sites of the reciprocal lattice; b) the position of a peak in the spectrum is uniquely related to the crystal orientation angles; c) the number of photons in the spectrum increases when the energy of the main peak in the spectrum approaches zero. On the basis of these facts it is possible to determine the orientation angles of the diamond crystal for which a rapid decrease of the intensity of low-energy photons is observed.

In the experiment we used a diamond plate of thickness 80 μm with an orientation at which the (100) crystal plane was placed perpendicular to the positron beam. The vertical axis of rotation was perpendicular to the (011) plane. We measured the number of γ rays recorded by the spectrometer as a function of the orientation angle of the crystal in one plane for a fixed angle with respect to the other plane. For orientation purposes it is sufficient to measure several points along the most effective row of the reciprocal lattice, in order to determine the "zero" orientation of the crystal $\theta_v = 0, \theta_h = 0$. Nevertheless in the experiment we obtained a complete set of data necessary for constructing an orientation map of the crystal.

In the experiment we carried out a careful measurement of the dependence of the total photon intensity on the crystal orientation near the angles corresponding to planar and axial channeling. All measurements were made with a step of $2.3 \cdot 10^{-5}$ rad. To monitor the correctness of choice of the crystal orientation and the processing of the results, we measured the coherent bremsstrahlung spectrum of positrons with $E_0 = 10$ GeV under conditions of orientation of the diamond crystal in which the energy of the photons of the coherent peak occurs at 5 GeV (Fig. 2).

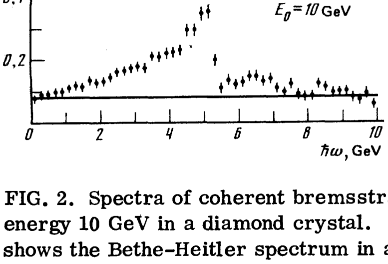

FIG. 2. Spectra of coherent bremsstrahlung of positrons with energy 10 GeV in a diamond crystal. The horizontal solid line shows the Bethe-Heitler spectrum in an amorphous material.

In the experiment we measured the spectra of electromagnetic radiation in planar and axial channeling of high-energy positrons in the diamond crystal. In Figs. 3–5 we have shown the measurements of the radiation spectra of positrons with energy 2–16 GeV in planar channeling in the diamond crystal. The ordinate gives the intensity of radiation $d^2W/d(\hbar\omega)dl$ per centimeter of length and per positron. The horizontal solid lines in Figs. 2 and 4 correspond to the Bethe-Heitler spectrum:

$$\frac{d^2W_{B-H}}{d(\hbar\omega)\,dl} = \frac{16\alpha^3 Z(Z+1)\hbar^2 n}{3(mc)^2}\ln(183Z^{-1/3}),$$

where $\alpha = e^2/\hbar c = \frac{1}{137}$, Z is the charge of the nucleus, and n is the density of atoms of the material.

In all spectra we observed distinct peaks whose intensity significantly exceeds the intensity of radiation in an amorphous medium. With increase of the positron

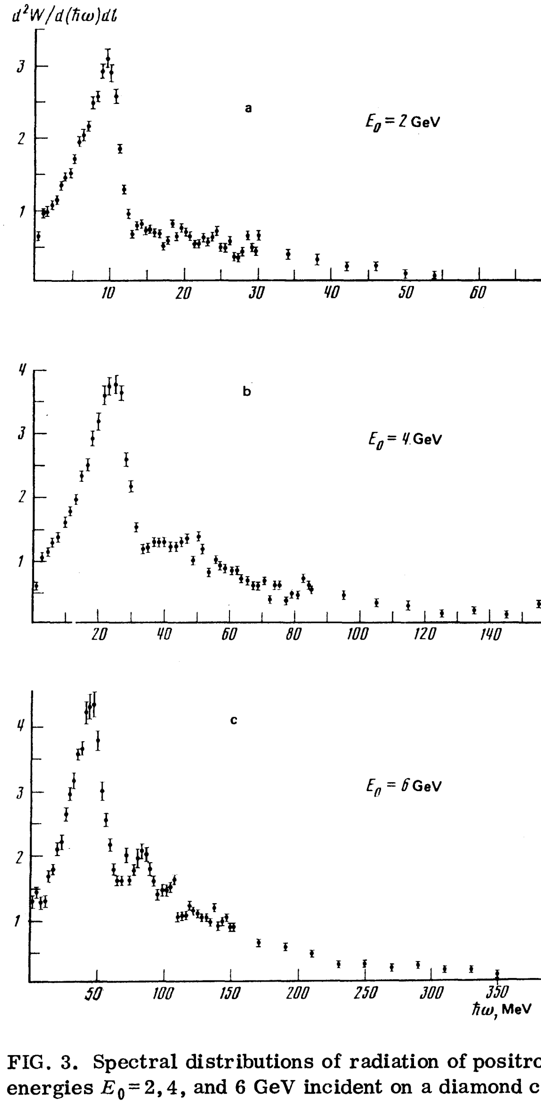

FIG. 3. Spectral distributions of radiation of positrons with energies $E_0 = 2, 4$, and 6 GeV incident on a diamond crystal along the (110) crystallographic plane.

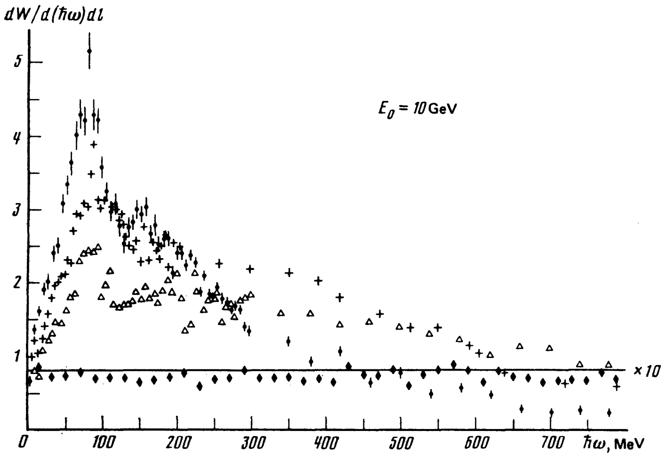

FIG. 4. Spectra of radiation of positrons with energy $E_0=10$ GeV incident on a diamond crystal along the (110) plane, as a function of the orientation angle θ of the (011) crystal plane with respect to the direction of the positron momentum: circles—$\theta=0$, crosses—$\theta=6.96\cdot10^{-5}$ rad, triangles—$\theta=9.28\times10^{-5}$ rad, rhombs—Bethe-Heitler spectrum ($\times10$).

energy up to 10 GeV the intensity of radiation at the maximum increases; at higher energies a decrease of the intensity and monochromaticity of the radiation is observed. The widths of the peaks increase with increase of the initial energy of the positrons. The energy of the photons in the peak approximately follows an $E_0^{3/2}$ law up to positron energies 10 GeV, after which the rise of the peak photon energy slows down and becomes proportional to $E_0^{1/2}$.

At all positron energies, especially above 10 GeV, a second maximum appears in the radiation spectra at approximately twice the frequency of the first maximum.

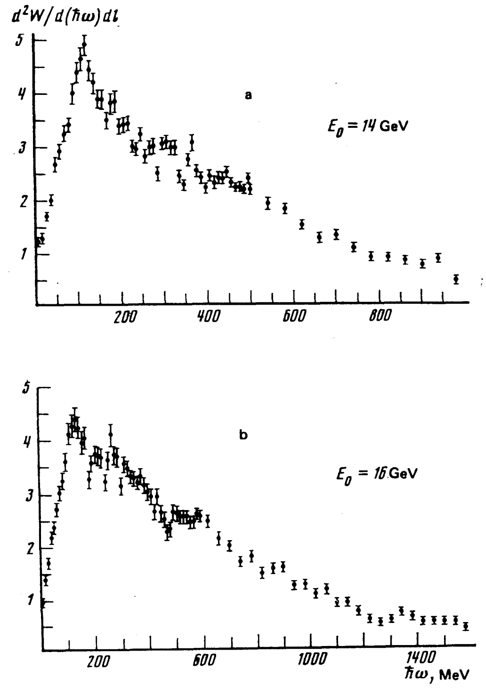

FIG. 5. Spectral distributions of radiation of positrons with energies $E_0=14$ and 16 GeV incident on the crystal along the (110) crystallographic plane.

In Fig. 4 we have shown the radiation spectra of positrons with energy 10 GeV as a function of the orientation angle of the (011) plane of the crystal with respect to the direction of the positron momentum. As can be seen from the figure, the intensity in the peak is sensitive to the crystal-plane orientation angle θ relative to the positron momentum. The intensity of the peak

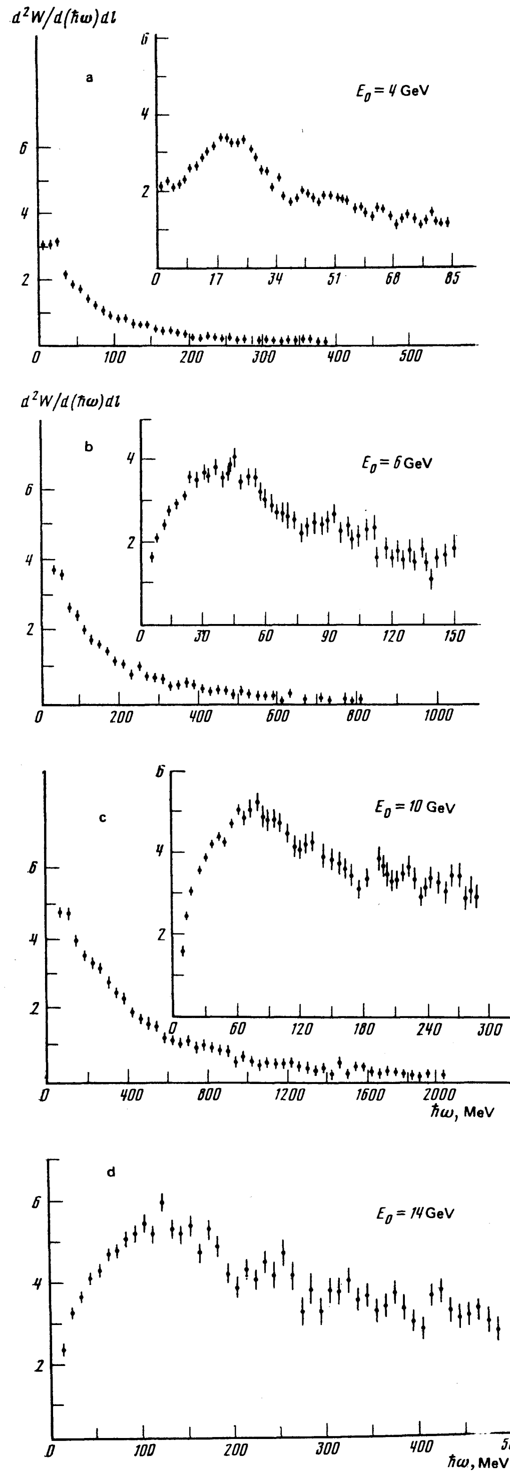

FIG. 6. Radiation spectra in axial channeling of positrons with energies 4–14 GeV along the ⟨100⟩ axis in a diamond radiator of thickness 80 μm; $\theta_v=0$, $\theta_h=0$.

is greatest for $\theta = 0$; on increase of the angle within the critical channeling angle the peak intensity falls off, but the energy of the photons in the peak does not change, and for $\theta > \theta_{cr}$, where θ_{cr} is the critical channeling angle, the peak in the spectrum almost disappears and the radiation is already completely due to superbarrier particles and can be qualitatively described by the behavior of coherent bremsstrahlung.

In Fig. 6 we have shown the radiation spectra in axial channeling of positrons with energy 4–14 GeV along the $\langle 100 \rangle$ axis in a diamond radiator of thickness 80 μm. A peaked structure of the radiation spectrum is also observed. The intensity of radiation in the peak is somewhat higher than the level of the planar case, but the total intensity is significantly higher as the result of the width of the peaks and their slow falloff. The peak energy of the protons in the axial case is somewhat higher than in the case of planar channeling.

The authors express their gratitude to Professors W. Panofsky, R. Taylor, A. Ts. Amatuni, and P.V. Sorokin for their support in the performance of this work.

[1)] Khar'kov Physico-technical Institute, Khar'kov.
[2)] Stanford Linear Accelerator Center, USA.

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Translated by Clark S. Robinson