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CHANNELING RADIATION FROM POSITRONS

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Radiation from 56-MeV positrons channeled along the (110), (111), and (100) planes and along the <110> axis in silicon has been observed. The energies of the observed spectral peaks agree well with theory. Potentially the radiation can be used as a tunable x-ray source in the 10-keV to 10-MeV energy region.

Introduction

A relativistic positron passing through a crystal can be channeled between the crystal planes if the energy of the particle associated with the motion normal to the planes is less than the energy required to cross over into an adjacent planar channel.[1,2] That is, the array of atoms in the crystal establishes a potential well that can constrain the positron's trajectory to the region between planes.

When channeling does occur there is a periodicity to the motion which can result in the emission of forward-directed electromagnetic radiation of relatively narrow linewidth.[3,4] From a quantum viewpoint the positron is trapped in eigenstates associated with the potential well of the crystalline field, and radiation results from spontaneous transitions between these states.

The emitted photon energy depends upon the energy of the positron and the crystal field strength. Assuming an harmonic potential well with a non-relativistic transition energy $\hbar\omega_0$, the relativistic increase in mass and the Doppler shift of the emitted photon result in a forward-directed photon energy $\simeq 2\gamma^{3/2}\hbar\omega_0$ in the laboratory frame. This means that the photon energy can be varied by changing the incident particle energy. For 50-MeV positrons channeled between (110) planes in silicon this photon energy is ≃ 32 keV.

The linewidth is determined primarily by the anharmonic contribution to the potential, the number of cycles over which periodic motion can be maintained, beam divergence, multiple scattering in the direction parallel to the planes, and the solid angle of the detector.[4] Typical linewidths are 10 to 25%.

Other interesting features of the radiation are that it is highly directional with a half-angle equal to γ^{-1}, it is linearly polarized, and it is considerably more intense than ordinary bremsstrahlung on a per-unit solid-angle, per-unit frequency-interval basis if the beam quality is sufficient to channel a major fraction of the incident particles [e.g., an enhancement by a factor of 14 over ordinary bremsstrahlung is calculated for a 1-mrad beam divergence for 50-MeV positrons channeled in (110) silicon.[4]] The time structure of the radiation will be determined by the time structure of the beam. For an s-band linear accelerator, it will consist of a series of very short (≃ 5ps) pulses separated by a much larger interval (≃ 350ps).

Areas of application for channeling radiation are: investigation of the channeling process; the study of the properties of the crystal in which channeling occurs; and development of channeling radiation as a practical source. One interesting aspect of channeling that can be studied by the radiation mechanism is dechanneling, since the lineshape and ratio of channeling emission to bremsstrahlung depend upon the dechanneling process. It should also be possible to obtain data on crystalline fields since the emission lineshape depends upon the shape of the potential well in which channeling occurs. The effect of dislocations, imperfections, and defect formation (caused by the incident particle beam) on the channeling radiation also can be investigated.

Channeling radiation as a source has several desirable properties: the ease with which the photon energy can be varied, its relative monochromaticity, its linear polarization, its high directionality, and its high intensity compared with other sources in the 10-keV to 10-MeV part of the spectrum. Such properties make it almost unique as a calibration standard for polarization-sensitive detectors in the x-ray range, an application of considerable interest in astrophysics. In the energy range from 10 to 100 keV, potential applications include lithography, radiography, radiotherapy, x-ray tomagraphy, and extended x-ray absorption fine structure spectroscopy. The micro-time structure might be suitable for measuring fast relaxation processes and/or for performing radiography with millimeter spatial resolution. Channeling radiation at higher energies might be very useful for measuring certain photonuclear cross sections, especially because of its intensity and polarization properties.

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Experiment

The positron beam for the present experiment was produced at the Lawrence Livermore Laboratory Electron-Positron Linear Accelerator Facility.[5,6] Positrons from the tungsten-rhenium positron converter were formed into a beam, energy analyzed to $\Delta p/p \simeq 0.01$, and transported to the experimental area by means of standard bending and focusing elements. At the selected beam energy of 56 MeV and accelerator repetition rate of 1440 pps (100-ns pulse duration) the beam intensity reaching the target averaged 0.1 to 0.3 nA. Radiation-shielding walls separate the experimental area from the accelerator and positron converter.

A schematic diagram of the experimental area is shown in Fig. 1. The collimated and energy-analyzed positron beam enters from the left, is focused in the three-segment quadrupole lens to achieve acceptable beam divergence, and impinges upon the silicon crystal target mounted in the goniometer. After passing through the crystal the beam is either deflected into a dump hole or allowed to pass undeflected approximately 6 m down the beam pipe where it finally exits the vacuum system through a 0.2-mm thick aluminum window. Remotely insertable collimators, immediately upstream from the crystal (1.0-cm diam) and downstream from the deflection magnet (0.5-cm diam) allow collimation of the positron beam striking the crystal and of the field of view of the crystal seen by the detectors, respectively. A plastic-scintillator detector immediately behind the exit window can be used to monitor the transmitted positron beam with the deflection magnet degaussed. With the deflection magnet energized, and the scintillation detector removed, the intrinsic-germanium detector (at the far right in Fig. 1) is used to measure the photon spectrum.

Because beam collimators cannot be tolerated where they will contribute to unwanted bremsstrahlung background in the germanium detector, a special beam-tuning procedure was adopted. First, with no crystal target in the goniometer, the beam was tuned to produce a spot ≃ 1 cm in diam on the insertable viewing screen upstream from the goniometer and, simultaneously ≃ 2 cm

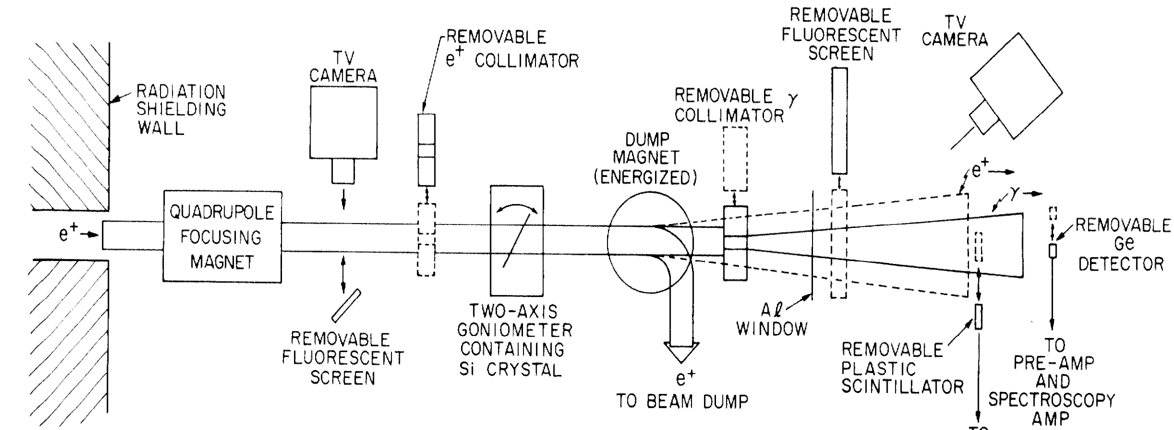

Fig. 1. Schematic diagram of the experiment. Solid lines indicate the experimental arrangement for measurement of the channeling-radiation spectrum. Dashed lines show the arrangement for positron transmission measurements.

in diam on the viewing screen at the end of the beam pipe. (Although the weak (≈ 0.1-nA) positron beam could be seen on the CsI crystals with a standard TV camera, we found that use of a high-sensitivity silicon-intensified-target camera greatly improved visibility.) The centering of the beam relative to the crystal then was checked by inserting the upstream (1-cm diam) collimator and monitoring the beam intensity reaching the scintillation detector.

To measure the actual beam divergence, a copper disk with a 0.3-cm diam hole was inserted into the beam in approximately the target location. The CsI screens were removed and the beam profile was measured with a 0.5-cm diam scintillation detector mounted on a two-dimensional translation stage. After obtaining an acceptable beam and measuring its divergence, the crystal target was mounted.

The crystal used in the present experiment was a high-purity single crystal of silicon, cut parallel to a (110) plane. The crystal was etched (with ethylene diamine) to 18 μm in thickness over an area ≈ 1.6 cm in diam. Crystal thickness was measured by the alpha-particle energy-loss technique.

The goniometer is capable of orienting the crystal in 0.04-mrad increments over an angular range of ± 7° about either of two axes approximately perpendicular to the beam direction. The exact orientation of the crystal, when mounted, was determined by scanning the crystal about one goniometer axis while monitoring the forward transmitted positrons on the small scintillation detector. Each time a crystal plane was aligned along the incident beam direction, the reduced multiple scattering within the crystal resulted in a peak in the detector signal. A typical scan is shown in Fig. 2. We obtained a map of the crystal by plotting the coordinates of the measured peaks, as shown in Fig. 3. After obtaining the crystal map, the deflection magnet was energized, the scintillation detector removed, and the photon detector installed.

The encapsulated intrinsic-germanium photon detector (manufactured at Lawrence Livermore Laboratory) is 0.9 cm square by 0.7 cm thick. The detector has high efficiency for photoelectron conversion for photon energies below ≈ 150 keV. Detector electronics included a charge-sensitive preamplifier (room-temperature FET), spectroscopy amplifier, and pulse-height analyzer. The energy scale was calibrated and the energy resolution (2.0 keV FWHM at 60 keV) determined by use of standard radiation sources.

The 0.5-cm diam, 3.0-cm thick photon collimator downstream from the deflection magnet served to limit the field of view of the detector to the central portion of the crystal, minimizing the possibility of bremsstrahlung from the thick outer rim of the crystal

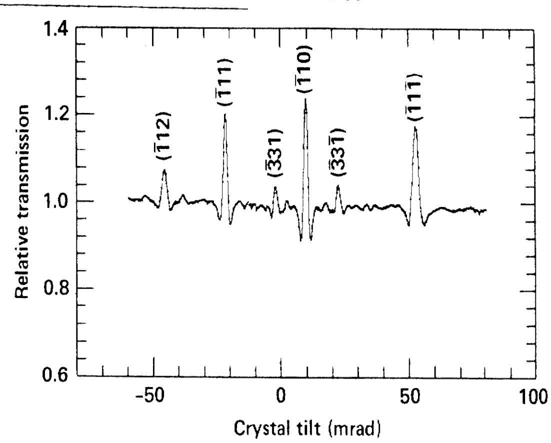

Fig. 2. Forward-positron transmission as a function of crystal orientation about the horizontal goniometer axis. The orientation about the orthogonal axis was fixed at 47.4 mrad from the <110> axis for this scan.

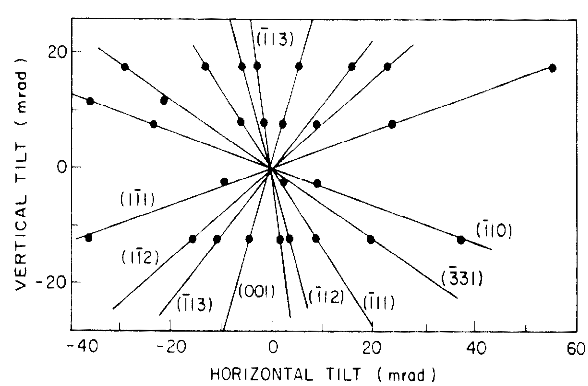

Fig. 3. Map of the silicon crystal. The points represent the goniometer coordinates at which a planar channeling condition was observed. The Miller indices of the observed planes are given.

contributing to the signal, and limiting the effective positron beam to approximately that for which the divergence was measured. The count rate at the detector also was reduced by approximately an order of magnitude by this collimator, which allowed measurements to be made at nearly full beam intensity.

Results

Spectra for the photon energy range from 10 to

600 keV were taken for numerous crystal orientations. We found that within statistical errors these spectra were indistinguishable provided that the angle between the beam and a major channeling direction was ≳ 2 - 3 mrad. Several of these featureless spectra were summed to provide a "random" bremsstrahlung spectrum against which to compare the spectra obtained for the various channeling conditions.

In Fig. 4 we show the ratios of the spectra obtained for (110), (111), and (100) planar, and <110> axial channeling to the random spectrum. The peaks seen in the energy range 30 to 50 keV in Figs. 4a, b, and c are the channeling radiation. In Table I we tabulate the measured energies of the peaks along with the energy range calculated for the anharmonic oscillator approximation.[4] The agreement is good. The largest single factor contributing to the measured linewidth (also given in Table I) is the Doppler spread resulting from the beam divergence in the crystal plane. The measured divergence was 3 mrad x 9 mrad, with the larger component nearly along the (110) crystal plane.

In the case of (110) planar channeling, the measured enhancement of the channeling radiation above the bremsstrahlung is ≈ 1.5. For the present beam divergence the expected enhancement is ≈ 4.

For the case of <110> axial channeling, shown in Fig. 4d, a feature can be seen in the energy range where planar channeling radiation was observed. This feature probably results from positrons scattered out of the axial channel and into planar channels. Additional theoretical and experimental work is needed to understand other aspects of the axial spectrum; in particular, the broad enhancement that appears in the vicinity of 100 keV.*

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* A classical calculation of the radiation spectrum using a Monte-Carlo calculation of the channeling trajectories is being pursued.[7] Preliminary results agree qualitatively with the observed axial spectrum.

Table I. Spectral features of channeling radiation

Plane	γ	E_γ(calc.)[a] (keV)	E_γ(expt.) (keV)	Linewidth (%)
(110)	99	33 to 38	36.5 ± 1.0	≈ 20
(110)	111	38 to 44	42.5 ± 0.5	24
(111)	111	29 to 35	35.3 ± 0.5	26
(100)	111	46 to 51	46.7 ± 0.5	18

[a]See Ref. 4.

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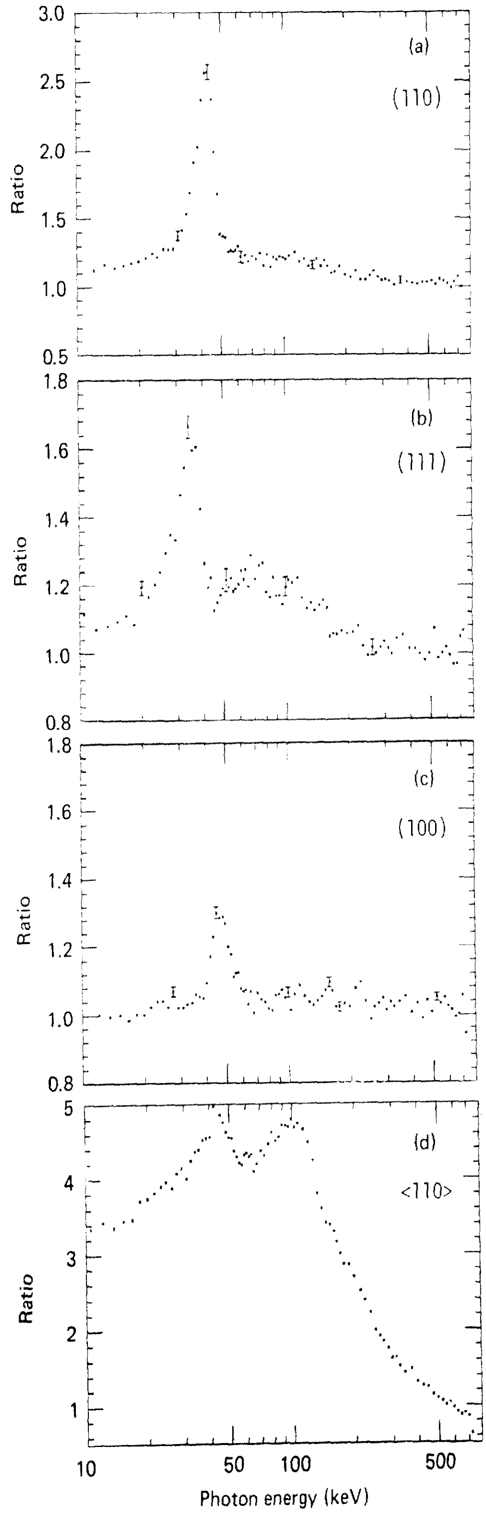

Fig. 4. Ratios of the channeling spectra to a smoothed version of the "random" spectrum: (a) (110) planar/random; (b) (111) planar/random; (c) (100) planar/random; (d) <110> axial/random.

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