Radiation from the Channeling of 10-GeV Positrons by Silicon Single Crystals

N. A. Filatova, V. M. Golovatyuk, A. N. Iskakov, I. M. Ivanchenko, R. B. Kadyrov, N. N. Karpenko, T. S. Nigmanov, V. V. Palchik, V. D. Riabtsov, M. D. Shafranov, E. N. Tsyganov, I. A. Tyapkin, and D. V. Uralski
Joint Institute for Nuclear Research, Dubna, U.S.S.R.

and

A. Forycki, Z. Guzik, and J. Wojtkowska
Institute for Nuclear Research, 05-400 Swierk, Poland

and

R. A. Carrigan, Jr., and T. E. Toohig
Fermi National Accelerator Laboratory, Batavia, Illinois 60510

and

C. Carmack, W. M. Gibson, I.-J. Kim, and C.-R. Sun
State University of New York at Albany, Albany, New York 12222

and

M. D. Bavizhev, N. K. Bulgakov, and N. I. Zimin
Tomsk Polytechnical Institute, Tomsk, U.S.S.R.

and

I. A. Grishaev, G. D. Kovalenko, and B. I. Shramenko
Kharkov Physical-Technical Institute, Kharkov, Ukraine 108, U.S.S.R.

and

E. I. Denisov and V. I. Glebov
Kurchatov Institute of Atomic Energy, Moscow, U.S.S.R.

and

V. V. Avdeichikov
V. G. Khlopin Radium Institute, Leningrad, U.S.S.R.
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An investigation has been carried out of the radiation emitted by 10-GeV positrons planar channeled in perfect single crystals of silicon. The radiation is found to be narrowly peaked in direction and energy as compared with normal bremsstrahlung radiation, consistent with theoretical predictions. Strong evidence is found for structure not resolved in previous experiments, particularly at angles near the critical angle for channeling where the radiation exhibits a marked periodic structure.

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Kumakhov[1] has predicted a type of radiation due to channeling which is specifically different from ordinary bremsstrahlung, coherent bremsstrahlung, and transition radiation. This radiation arises from transitions between bound states of the channeled particles in transverse momentum space. In the center of mass of the particle the energy of such transitions is in the range of up to a few kiloelectronvolts (depending on the target crystal, direction, and the velocity of the particle) but is Doppler shifted to much higher energy in the laboratory frame. This radiation has been detected in experiments performed by Miroshnichenko *et al.*,[2] Alguard *et al.*,[3] and Andersen and Laegsgaard.[4] The present experiment extends those investigations to show evidence for detailed structure in channeling radiation spectra for positrons at high energy.

In order to investigate the radiation due to channeling, the apparatus used to establish the bending of the trajectories of channeled particles by perfect single crystals[5] was moved from the extracted proton beam at the 10-GeV Dubna synchrophasotron to a 10-GeV electron/positron beam at the 76-GeV Institute for High Energy Physics (IHEP) accelerator at Serpukhov. The apparatus was redesigned to include a cesium iodide spectrometer for photon identification and measurement, and a secondary particle spectrometer for electron/positron identification and measurement. The revised experimental layout is shown in Fig. 1.

Sources of background radiation were eliminated as much as possible by minimizing the amount of radiating material in the beam and introducing weak magnets to separate upstream photon background sources so that background photons passed outside the aperture of the photon spectrometer. Drift-chamber module DC2 is a low-pressure (150 Torr), low-mass chamber contributing only 6×10^{-4} of a radiation length to the background radiation.

The beam is derived from a modified targeting system in the internal beam of the IHEP accelerator. Photons from π^0 decay emerging at an angle of 2.5 deg to the circulating beam are converted by a radiator placed outside the accelerator. The measured hadron contamination in the beam is less than 0.5%. The positron beam intensity is 10^5 per 10^{12} protons on the production target.

For the experiment reported here, scintillation counters S1–S3 and veto counters A1–A3 formed the event trigger. The drift-chamber modules were used to record the position coordinates of the positron. Positron identification was provided by the lead-glass Cherenkov counter array. The momentum of the positron is measured using the analyzing magnet M3. The energy of photons originating in the crystal was measured in the CsI photon spectrometer. The CsI was protected by a lead shield and surrounded by anticounters. These anticounters were also used to form a muon trigger for continual calibration of the CsI. The CsI detector consisted of a cylindrical crystal with a diameter of 150 mm and a length of 230 mm, approximately 13 radiation lengths. The spectrometer was calibrated with Cs, Co, and Po-Be sources. The resolution of the detector, obtained by unfolding the calibration spectra, is around 3% in the region of 1 MeV and is expected to be approximately 1% in the region of 100 MeV. The most probable energy loss of minimum-ionizing muons was calibrated against the radiation sources.

The silicon crystal used in the experiment was a disk of approximately 22 mm diam and 0.5 mm thickness. A circular section of 18 mm was etched to a thickness of 90 μm. A guard ring of solid-state counters was mounted with the crystal in the goniometer. The crystal was cut normal to the $\langle 111 \rangle$ axis within 0.2 deg. It was prealigned by reflecting laser light from the polished surface. The axis was then determined relative to the beam direction by rotating the crystal in the goniometer to find the peak in the number of γ counts. For the measurements reported here the $\langle 111 \rangle$ axis was oriented 0.5 deg horizontally relative to the beam direction, to eliminate axial channeling, while the (110) plane was horizontal and aligned to the beam direction.

All events were recorded which produced a photon of energy greater than 5 MeV in the CsI detector and a positron signal in the lead-glass array. To eliminate events due to the low-energy tail of the incident positron beam, the minimum energy of the positron was required to be greater than 8 GeV. For each event the incident angle relative to the (110) plane, the photon energy, and the secondary positron energy were determined.

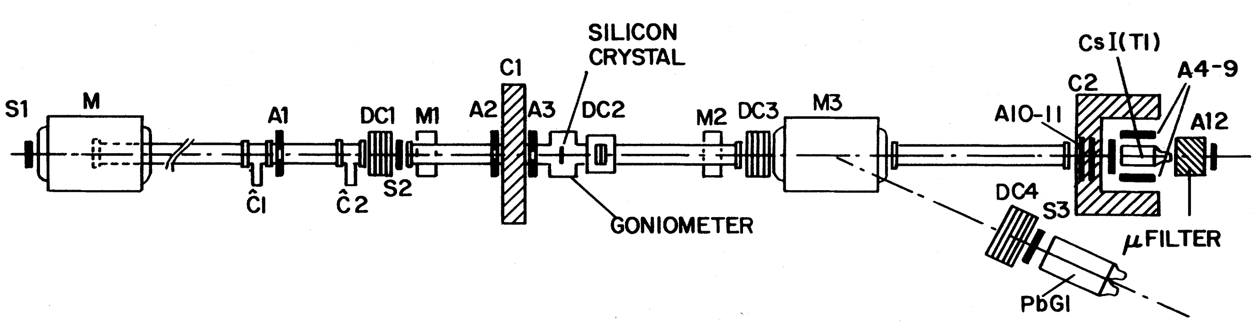

FIG. 1. Experimental apparatus. S1–S4 are the trigger counters while A1–A12 are the vetoes. DC1–DC4 are drift-chamber modules. M and M1–M3 are magnets for calibration and background elimination. C1 and C2 are threshold Cherenkov counters.

Figure 2 presents the spectral density of the radiation (normalized for one incident positron) as a function of the photon energy for all events lying within 20 μrad of the (110) plane. A line consistent with the apparatus resolution has been fitted through the data to guide the eye. For 10-GeV positrons in silicon the critical angle for channeling in the (110) plane is about 65 μrad, so that the events in Fig. 2 are well within the channeling regime. Superimposed on the experimental distribution is a theoretical prediction using the Kumakhov approach. In addition a curve is included that has been fitted through the 10-GeV data on diamond from the experiment of Miroshnichenko *et al.* with the energy axis properly scaled to transform from diamond to silicon. The bremsstrahlung spectrum for an amorphous aluminum radiator is also shown. The radiation length for aluminum is only about 1% different than the silicon radiation length.

The data are in reasonable agreement with the channeling prediction: specifically, the radiation due to channeling is of the order of 50 times more intense than ordinary bremsstrahlung radiation, it is much more narrowly peaked in energy, and the energy of the principal peak near 50 MeV corresponds closely to the Kumakhov prediction. This energy is calculated on the basis of the full Kumakhov theory using the nondipole calculation necessary at extremely relativistic energies.

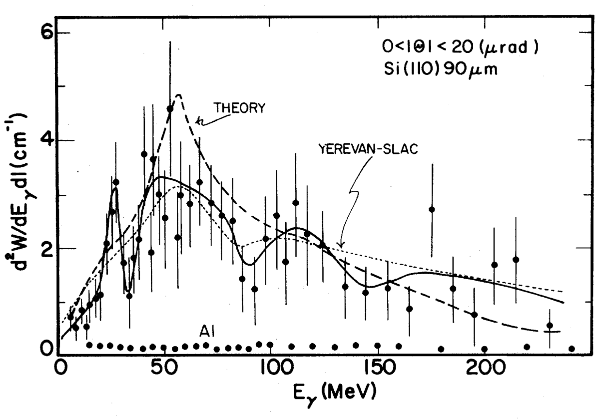

FIG. 2. Spectral density of channeling radiation due to positrons incident on the silicon crystal in the angular range $0<\theta<20$ μrad, well within the critical angle. The solid line is a curve consistent with the resolution placed through the experimental data to guide the eye. The dashed line is a theoretical calculation. The dotted line represents the data of Miroshnichenko *et al.* on a diamond renormalized to silicon. Points are measurements of ordinary bremsstrahlung on an amorphous aluminum sample.

The arguments for this treatment are summarized in Wedell's review article.[6] The absolute rate also agrees with the theory.

Below 50 MeV the data reported here are distinctly different from both the Kumakhov theory and the data of Miroshnichenko *et al.* There is

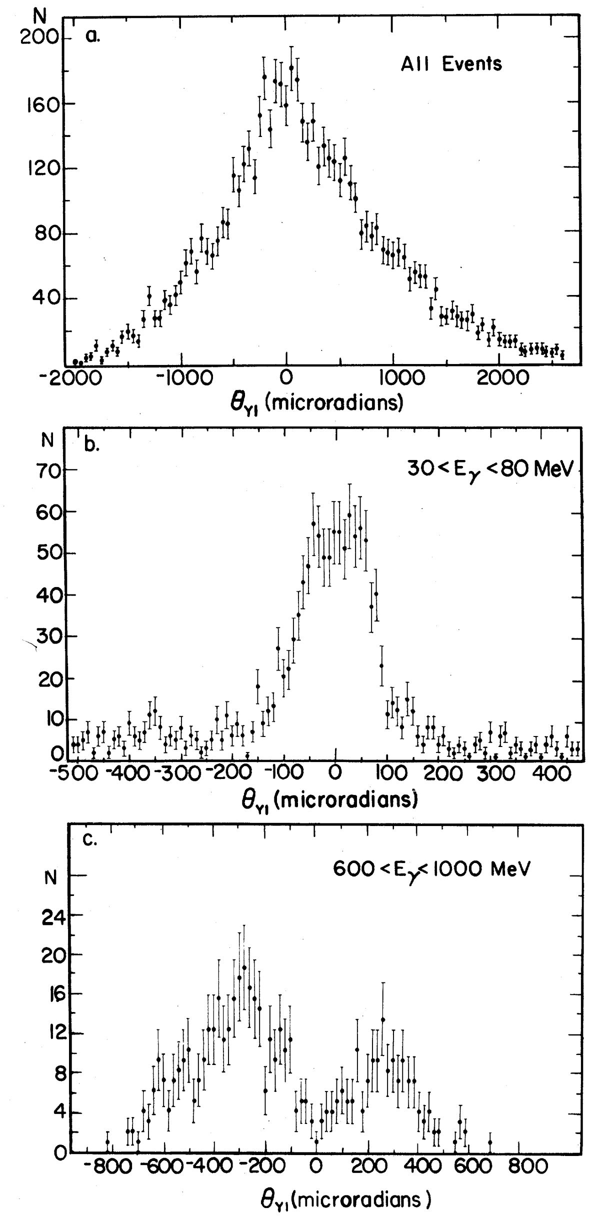

FIG. 3. Incident angular distribution for positrons (a) within the aperture of the spectrometer, (b) producing a photon in the peak region $30<E<80$ MeV for channeling radiation, and (c) producing a photon in the range $600<E<1000$ MeV corresponding to typical bremsstrahlung energies. (Note that the range of angles differs for each curve.)

evidence for a narrow, statistically significant peak in the spectral energy distribution in the vicinity of 25 MeV.

The dependence of the radiation probability (for an arbitrary scale) on the incident direction of the positrons relative to the (110) plane is illustrated in Figs. 3(a)–3(c). Figure 3(a) shows the angular dependence for all incident particles detected in the spectrometer. The distribution is seen to be on the order of 1000 μrad corresponding to the angular divergence of the incident positron beam. Figure 3(b) presents the angular distribution for those positrons producing a photon in the region of the prominent peak of Fig. 2, $30 < E < 80$ MeV. The distribution has a width $\sigma = 65$ μrad, comparable to the critical angle and centered about the (110) plane. The flat distribution in Fig. 3(b) may be a hint that excitation at very small angles is suppressed since otherwise one would anticipate a more Gaussian-shaped curve. In any event it is evident that events in the peak of the photon spectrum are strongly correlated with positrons incident within the critical angle for channeling.

Figure 3(c) shows the incident angular distribution for events with $600 < E < 1000$ MeV, well away from the peak of Fig. 2. These events are seen to be correlated with positrons incident at angles larger than the critical angle. These photons are consistent with bremsstrahlung production. Bremsstrahlung is strongly reduced for particles in the channeling regime because the particles do not pass close to nuclear centers.

At ultrarelativistic energies higher harmonics are generated, particularly for trajectories near the critical angle.[6] Such events appear to give rise to a qualitative difference in the spectral energy distributions between Figs. 4(a) and 4(b). Figure 4(a) does not include the critical angle, while Fig. 4(b) does include the region near the critical angle. Lines consistent with the apparatus resolution are fitted through the data to guide the eye. Although the statistical uncertainty precludes detailed examination, the apparent periodic structure is consistent with the harmonic structure predicted by Kumakhov.[6] It should be noted that this structure is qualitatively different from the spectral structure observed at lower energies in the studies of Alguard *et al.*[3] and Andersen and Laegsgaard[4] which were attributed to transitions between discrete bound states for the channeled positrons or electrons. At very high energies, as in the present case, the density of states in the potential becomes so high

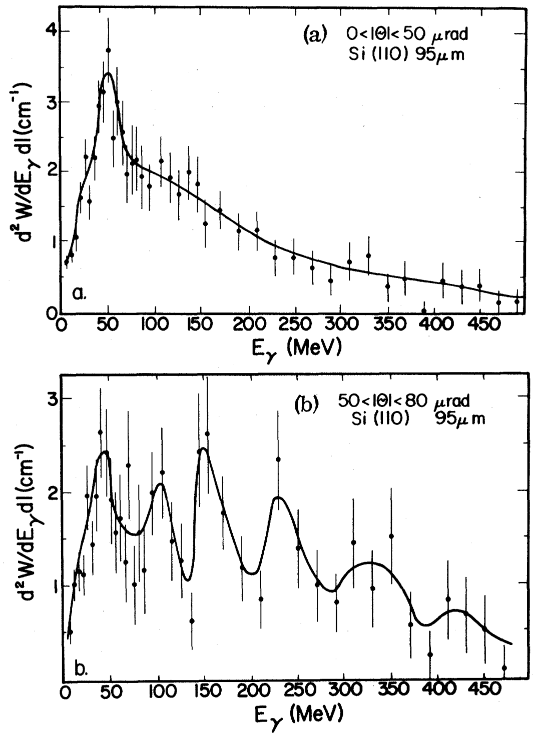

FIG. 4. Spectral density distribution for photons produced by positrons whose incident angles (a) lie inside the critical angle, and (b) include the region near the critical angle. (Solid lines are curves to guide the eye.)

that observation of transitions between discrete levels is precluded.

Further studies are underway to investigate these effects and to get more information on the origin of the sharp peak at 25 MeV.

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[6]See, for instance, R. Wedell, Phys. Status Solidi (b) 99, 11 (1980). This article contains a complete review of earlier work on channeling radiation.

Bifurcation Universality for First-Sound Subharmonic Generation in Superfluid Helium-4

Charles W. Smith, Manu J. Tejwani, and Dale A. Farris
Department of Physics and Astronomy, University of Maine, Orono, Maine 04469
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Measurements are presented which show that below the superfluid transition, the generation of first-sound subharmonics in the low-megahertz range quantatively follows the Feigenbaum universal convergence. In addition, by using ion-trapping techniques the physical nature of the onset of the first bifurcation sequence is identified as the threshold for the generation of quantum vortex line, not the threshold for the production of macroscopic classical turbulence, i.e., acoustic cavitation.

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The response of driven nonlinear systems has been investigated by an enormous number of experimental techniques. Recently such studies have included Rayleigh-Benard experiments,[1] couette flow,[2] optically bistable laser cavities,[3] acoustic cavitation noise,[4] charge-density waves,[5] pinning dynamics of dislocation lines,[6] and nonlinear discrete electronic circuits.[7] These systems generate output signals rich in spectral detail. Generally one is interested in how the frequency content of the output signals varies as some driving parameter is changed. Typically, driven nonlinear systems exhibit (1) harmonic generation, (2) subharmonic generation (which displays onset thresholds but may or may not show period doubling), (3) ultraharmonic generation (harmonics of the subharmonics), and at a sufficiently large value of the driving parameter, (4) a transition to a noisy, chaotic or turbulent regime.

The recent theory by Feigenbaum[8] concerning the discovery of certain universal properties in period-doubling bifurcations of iterated one-dimensional maps has catalyzed a search for analogous universal behaviors in experimental nonlinear systems. He has shown that for systems which lead to a transition to chaotic behavior via a sequence of period-doubling bifurcations, an ordered set of values of the driving parameter, λ_n, for which bifurcations occur, converges to a universal number δ, where $\delta=(\lambda_{n+1}-\lambda_n)/(\lambda_{n+2}-\lambda_{n+1})=4.669\ldots$. In addition, the ratio of the amplitudes of the Fourier components of adjacent fully developed bifurcated subharmonics scales by $\mu=6.57$ or $10\log_{10}\mu=8.2$ dB, again a universal number, independent of the details of the nonlinear system. As a result of this expected commonality, a rather large literature is emerging which describes many nonlinear systems exhibiting subharmonic routes to chaotic behavior. However, it must be emphasized that to date only three types of experiments quantitatively show the Feigenbaum period-doubling bifurcation universalities. These are Rayleigh-Benard experiments, couette flow experiments, and nonlinear discrete electronic circuits.

This paper presents the results of measurements of the finite-amplitude first-sound response of liquid helium-4, a system known to exhibit an acoustic subharmonic spectrum.[9] Above the superfluid transition, $T_\lambda=2.17$ K, liquid helium behaves macroscopically as a classical liquid. One observes a very rich nonlinear response, dominated by vapor bubble dynamics of the type recently carefully documented for the case of water.[4] This includes a subharmonic route to chaos (acoustic cavitation), but does not show bifurcation of the Feigenbaum type. However, below the superfluid transition where the existence of conventional vapor bubbles is excluded by

