Observation of Channeling Radiation from Relativistic Electrons

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Radiation from 56- and 28-MeV electrons channeled along major plances or along a major axis of an 18-μm-thick silicon crystal has been observed. Unpredicted spectral peaks in the range from 10 to 130 keV were observed and resolved for planar-channeling electrons, whereas only a large low-energy enhancement was seen for axial-channeling electrons.

Relativistic charged particles channeled in a crystal have a periodicity to their motion which can result in the emission of forward-directed electromagnetic radiation of narrow linewidth. The observation of such channeling-radiation spectral peaks was first reported by us for 56-MeV positrons channeling in silicon.[1,2] In this Letter we report the first observation of sharp spectral features in the photon-emission spectrum from channeling *electrons*; in contrast, only a featureless low-energy enhancement had been reported in previous experiments.[3,4] The observation of these spectral peaks is of particular importance, both because they were not predicted theoretically and because they offer the potential promise of an intense, tunable, narrow-linewidth, polarized source of x and γ radiation.

The photon-emission spectrum from planar-channeling positrons has been described successfully by use of either a classical or a quantum-mechanical model, by assuming that the positrons are bound, between crystal planes, in the approximately harmonic potential obtained by averaging the true periodic crystalline potential over the planar coordinates[5,6]; both models predict the observed spectral peak correctly.[1] Analyses of the expected emission spectrum from axially channeled electrons also have been carried out using quantum-mechanical[7] and classical[6,8] viewpoints. In this case, the quantum-mechanical model predicts emission at discrete photon energies corresponding to spontaneous transitions between eigenstates of the electron bound to the attractive potential of the channeling string, whereas the classical model predicts an enhanced region in the low-energy photon spectrum, corresponding to the range of orbital frequencies of stable helical trajectories about the channeling axis.

The emission properties of planar-channeled electrons have received less attention. Since the attractive planar potential can support only a few bound states for the channeling electron,[9] a quantum-mechanical calculation with a realistic planar potential is imperative. Available calculations have been based either upon classical mechanics,[10] or upon an unrealistic harmonic approximation[6] to the cusplike planar potential, and do not predict the presence of unequally spaced spectral peaks.

The emitted photons should be plane polarized in a direction orthogonal to the channeling plane. The energy of the forward-emitted photons should increase rapidly with electron energy, both because of the Doppler shift and because of relativistic mass increase. In addition, like bremsstrahlung, the radiation is strongly forward peaked, with half-angle $\theta = \gamma^{-1}$. This polarization, tunability, and directionality are particularly attractive qualities for a photon source.

The electron beam for the present experiment was produced by the Lawrence Livermore Laboratory electron-positron linear accelerator; the experimental arrangement was basically the same as that for our positron experiment.[1,2,11] Briefly, the electron beam, energy analyzed to $\delta p/p = 0.0025$, impinged upon the 18-μm-thick silicon crystal [which was cut parallel to the $(1\bar{1}0)$ plane] and then was swept from the initial direction into a beam dump. The electron beam had a divergence of $\simeq 2$ mrad full width at half maximum (FWHM) estimated from the size of the beam spot viewed on a cesium iodide crystal $\simeq 5$ m downstream from the crystal.

The goniometer used in the present experiment is of the three-axis (θ, φ, ψ) variety, allowing full angular range of adjustment of the crystal with a resolution of 0.0625 mrad. As in previous experiments,[1-3,12] the crystal was aligned with the aid of positron-transmission scans. The electron beam then was tuned and the transmission scans repeated. For electrons, only an axial alignment produced dramatic changes in the forward transmission. The familiar "*W*" pattern[12] was observed with a peak-to-valley ratio of nearly 2:1. Variations in transmission of only $\simeq 3\%$ were observed for planar-channeled electrons, indicating that planar-channeling lengths are appreciably less than axial-channeling lengths, and are significantly less than the 18-μm crystal thickness.

The photon detector used in the present measurement was a 55-cm^3 coaxial Ge(Li) solid-state detector. A lead aperture, 1.27 cm in diameter, was placed in front of the detector, limiting its solid angle to 3×10^{-6} sr, and the detector and collimator were aligned along the incident beam direction. The field of view of the crystal seen by the detector was limited to a circle $\simeq 6$ mm in diameter by a copper collimator located 1.5 m downstream from the crystal. Coincidence gating was used, and the beam current was adjusted so that the total count rate did not exceed $\simeq 0.2$ counts/beam burst. The approximate average beam current for this condition was 2×10^{-11} A, a factor of more than 10^7 below the machine capability. All spectra were accumulated for a preset integrated beam current, as measured on a large plastic scintillation detector located at the beam dump.

In Fig. 1 we present the photon spectra measured for an electron beam energy of 56 MeV. The "random" spectrum shown in Fig. 1(a) represents a typical bremsstrahlung spectrum obtainable at all orientations of the crystal except those close to a planar or axial direction; Figs. 1(b), 1(c), and 1(d) are for beam directions maximizing (001), (110), and (111) planar channeling, respectively. In Figs. 2(a), 2(b), and 2(c) we have

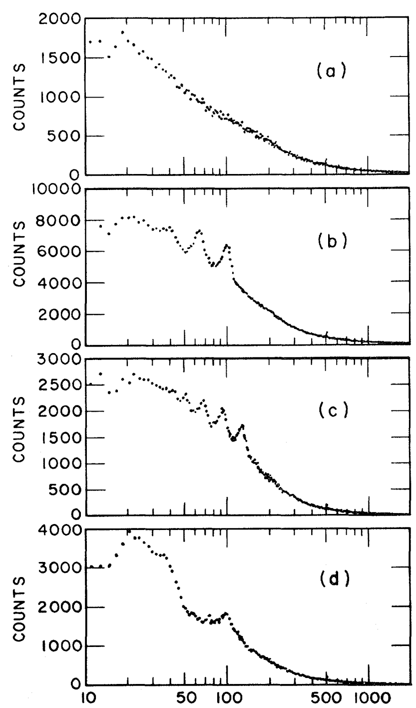

FIG. 1. Photon spectra for incident electrons of 56 MeV for (a) random orientation (not channeled); and (b) (001), (c) (110), and (d) (111) planar channeling.

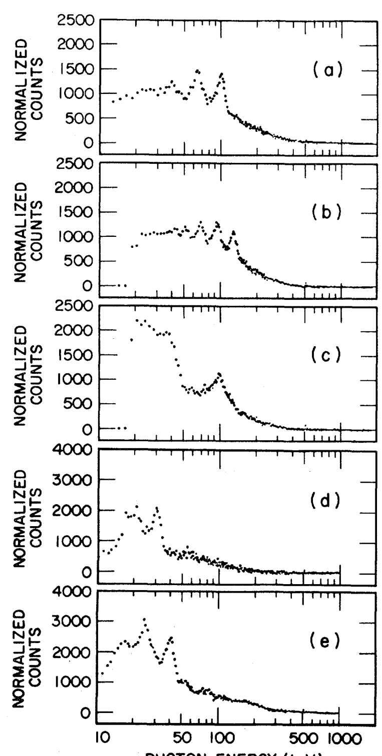

FIG. 2. Planar-channeling spectra normalized to the incident beam flux with the smoothed random spectra subtracted. For 56 MeV, (a) (001), (b) (110), and (c) (111); for 28 MeV, (d) (001) and (e) (110).

subtracted the smoothed random spectrum from each of the above planar-channeling spectra after first normalizing the spectra for equal beam charge. This procedure leaves us with that portion of the observed emission spectrum which results from channeling electrons. Similarly, we show the spectra for 28-MeV electrons channeling along the (001) and (110) planes in Figs. 2(d) and 2(e), respectively.

The energies of the observed major spectral peaks are given in Table I. Spectra taken in the same plane but at different angles relative to the $\langle 1\bar{1}0\rangle$ axis were found to exhibit the same spectral shape and peak locations in all cases studied, provided that a near-axial alignment was avoided. In addition to the tabulated peaks, a rich structure of smaller peaks is suggested by the data [e.g., see Fig. 2(e) in the energy range above 50 keV]. Our preliminary analysis, based upon a $V_0 \exp[-k|x|]$ potential,[13] where x is the distance from the plane and k^{-1} is an effective screening length, yields transition energies in reasonable agreement with the observed peaks for the (110) case. (For example, values of 128, 91, and 69 keV are obtained from the model for the first three adjacent-state transitions, with $V_0 = -25$ eV and $k = 3.6$ Å^{-1}.)

Estimates of the linewidths (FWHM) of the major peaks also are given in Table I. These linewidths were evaluated using a baseline obtained by drawing a smooth curve connecting the valleys between the peaks. There are contributions to the linewidths of each spectral peak from the Doppler shift associated with the beam divergence and from the detector aperture, and from the lifetime of the states involved in the transitions. For the present experimental conditions, the last effect dominates. From the estimated linewidths, the effective coherence lengths $2\gamma^2\beta c\tau$, where $2\hbar/\tau$ is the FWHM linewidth, have been calculated, and are included in Table I.

TABLE I. Observed spectral peaks for planar-channeled electrons.

Beam energy (MeV)	Crystal plane	Photon energy ± 2 keV (keV)	Linewidth ± 2 keV FWHM (keV)	Effective coherence length (μm)
28	(001)	31	4	0.6
	(110)	40	6.5	0.4
		25	5.5	0.5
56	(001)	99	16	0.6
		64	11	0.9
		39	8	1.2
	(110)	128	15	0.7
		94	13	0.8
		68	8	1.2
		52	5	1.9
	(111)	99	20	0.5
		37	10	1.0

In Figs. 3(a), 3(b), and 3(c) we present the measured axial spectra as ratios, taken to the corresponding unsmoothed random spectra. A large low-energy enhancement is seen, which crests somewhere in the range from 100 to 300 keV. This low-energy enhancement has been seen in previous experiments[3,4] and is presumably attributable to axial-channeling radiation,[4] but with featureless (or strongly overlapping) spectral structure. In Fig. 3(d) we show a spectrum ratio for 56-MeV electrons taken on the "shoulder" of the $\langle 1\bar{1}0\rangle$ axis, 2.7 mrad from the axis along the (001) plane, where the forward particle transmission was observed to be at its minimum value.

From Figs. 2 and 3, we see that as the energy

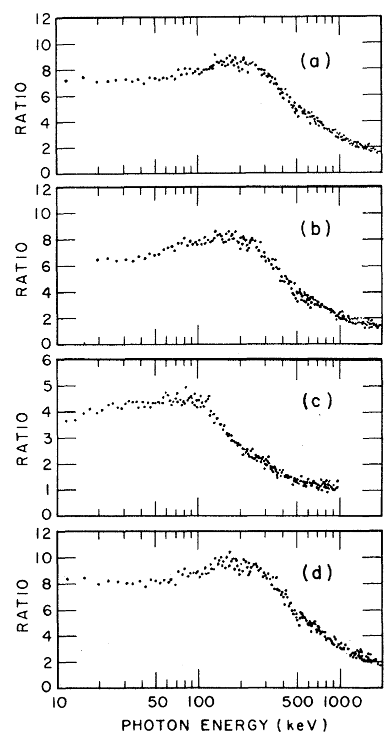

FIG. 3. (a)–(c) Ratios of the normalized axial-channeling spectra to their corresponding unsmoothed random spectra. For 56 MeV, (a) $\langle 1\bar{1}0\rangle$ and (b) $\langle 1\bar{1}1\rangle$; for 28 MeV, (c) $\langle 1\bar{1}0\rangle$. (d) The $\langle 1\bar{1}0\rangle$ shoulder spectrum for 56 MeV.

of the incident electrons is doubled, that of the channeling radiation increases at least as fast: The sharp peaks in the planar-channeling spectrum increase by slightly more than a factor of 3 and the broad enhancement in the axial-channeling spectrum increases by about a factor of 2. From these data one can infer that, in this energy range, the scaling for the planar case is somewhat slower than γ^2, and that for the axial case is about γ.

The largest enhancements relative to bremsstrahlung were observed for axial alignments, but the nearly identical "shoulder" spectrum of Fig. 3(d) casts some doubt upon a strict interpretation of the axial enhancement as channeling radiation alone. In contrast with the axial case, planar features occur only within small angles of the channeling direction. Also for the planar case, the enhancements relative to random bremsstrahlung are approximately 2:1 at 56 MeV. Since the estimated effective coherence lengths are $\simeq 1$ μm, these enhancement ratios can be expected to improve by more than an order of magnitude if a 1-μm-thick crystal were used.

In conclusion, we have observed peaks in the low-energy emission spectrum from electrons channeled in silicon. The estimated planar coherence lengths indicate that very large enhancements relative to ordinary bremsstrahlung should be achieved with thinner crystals. The existence of unpredicted spectral structure establishes that the enhancement results from correlated motion (channeling) of the electrons over a considerable distance ($\gtrsim 1000$ Å) in the lattice, and requires that a successful description of the effect must involve a quantum-mechanical treatment.

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Ultrahigh-Resolution Spectroscopy: Photon Echoes in $YAlO_3:Pr^{3+}$ and $LaF_3:Pr^{3+}$

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By using a new, delayed-heterodyne photon-echo technique, we have obtained a spectral resolving power of 1.2×10^{11}, measuring a 2.0-kHz linewidth (half width at half maximum) for the 6105-Å $^1D_2 \to {}^3H_4$ transition of $YAlO_3:Pr^{3+}$ in an external magnetic field. This appears to be the highest resolution ever obtained in optical spectroscopy. Measurements were also made on the corresponding transition of $LaF_3:Pr^{3+}$ giving a linewidth of 5 kHz. Optical free induction decay gave incorrect results (i.e., significantly broader linewidths).

The field of optical spectroscopy has witnessed a dramatic improvement in resolution since the advent of highly stable lasers, and of techniques for eliminating the effects of inhomogeneous broadening (i.e., photon echo,[1] optical free induction decay,[2] fluorescence line narrowing,[3] and

