# EFFECT OF CHANNELING OF LOW-ENERGY PROTONS ON THE CHARACTERISTIC X-RAY PRODUCTION IN SINGLE CRYSTALS*

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On entering a crystal along a direction of lattice symmetry, energetic positive ions experience a Coulomb repulsion from atoms in ordered arrays. For critical impact parameters relative to the center axes of the arrays, the particles are scattered through angles such that they become collimated along directions in the crystal where the repulsion is essentially screened out and the electron density is low. The trajectories of all others become random within a few collisions. This process of "channeling"[1] has been invoked recently to account for the orientation dependence in single crystals of the penetration of charged particles[2,3] and of the gamma-ray production by $(p,\gamma)$ reactions.[4,5]

The channeled fraction of the particle beam moves in a "free volume" of the crystal defined approximately by the envelopes of the trajectories surrounding the arrays of atoms. As long as the beam enters exactly along a crystallographic direction, it sees essentially the free channel formed by intersecting crystal planes. The "excluded volume" is bounded by envelopes of nearly rotational symmetry about such arrays, with radii of the order of the width of the Coulomb shadow behind each atom at the position of the next atom in the array, i.e., about $l\chi_c$, where, for energies of interest here, $\chi_c$ is well approximated by $(8zZ\,\mathrm{Ry}/lE_p)^{1/2}$ with $l$ being the distance in atomic units between consecutive atoms in an array, $ze$ the charge of the moving particle, $Z$ the atomic number of the crystal atoms, $E_p$ the particle energy, and $\mathrm{Ry}=e^2/2a_0$.[4] This expression is found by calculating the minimum impact parameter at one atom resulting from scattering by the preceding atom. If the particle beam enters the crystal at a small angle $\varphi$ relative to the orientation of the arrays, the surfaces formed by the trajectory envelopes are distorted, the closest approach to the atoms of the arrays now being about $l(\chi_c-\varphi)$. Since the cross section for characteristic x-ray production in a given atomic shell $n$ by heavy charged particles is large only for trajectories passing the atom at distances within the respective shell radius $a_n$, we expect the x-ray production to be small as long as $l(\chi_c-\varphi)>a_n$, and to be large if $l(\chi_c-\varphi)<a_n$. Setting for definiteness $a_n=n^2Z_n^{-1}$ in atomic units, where $Z_ne$ is the screened nuclear charge, we can estimate a critical $\varphi_n$ by setting

$$\varphi_n=(8zZ\,\mathrm{Ry}/lE_p)^{1/2}-n^2/Z_nl. \qquad (1)$$

The characteristic x-ray production by the channeled fraction of the beam should be small for $\varphi<\varphi_n$, should rise fairly sharply for $\varphi\approx\varphi_n$, and should assume a level of some high value for $\varphi>\varphi_n$.

Although clearly the model underlying Eq. (1) is a highly simplified one, it suggests that a pronounced dip in the x-ray production should be observable near $\varphi\approx 0$, it suggests the order of magnitude of the width of the dip, and predicts trends, e.g., the dependence on $n$, $Z$, and $E_p$.

Experiments were carried out to establish the existence of such dips and to investigate within the framework of the available experimental range the trend of this effect which could be compared with Eq. (1). Single crystals of aluminum and copper were cut and mounted. The target, held at room temperature, was exposed to a monoenergetic (±0.5%) beam of protons, collimated to ±0.2°, from a low-energy accelerator (located at the Law-

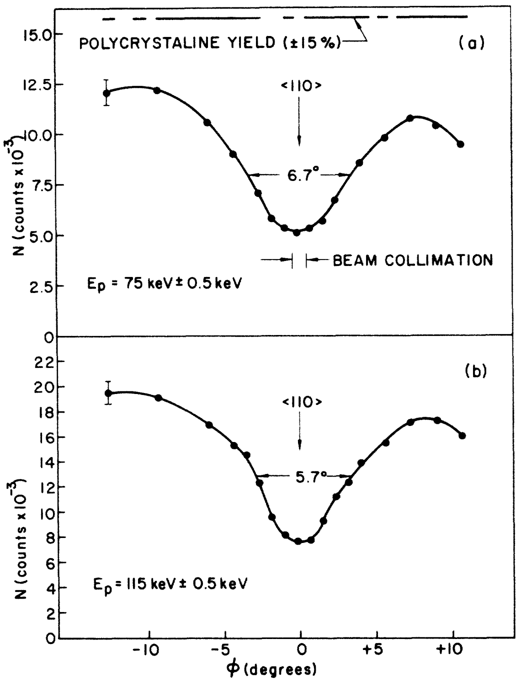


FIG. 1. Copper $L$ x-ray yield at 75 and 115 keV. Typical experimental conditions are as follows: proton current ≈ 0.1 μA; integrated current = 5 μC; detector background ≈ 200 counts. The polycrystalline yield (same for polycrystalline target and 600-grit sanded single crystal) was found to be independent of angle over the range studied. Under the present conditions the effect of x-ray absorption can be neglected.

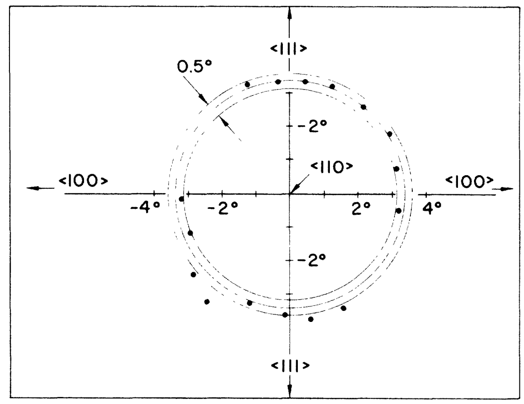


FIG. 2. Angular symmetry of half-width points. The half-width points (8000 counts) for 75-keV proton bombardment of copper show symmetry about the ⟨110⟩ direction.

rence Radiation Laboratory, Livermore) as described earlier.[6] In the range of proton energies investigated, x rays from the $K$ shell of Al and from the $L$ shell of Cu were studied.

Figure 1 shows the x-ray yield from the Cu $L$ shell as a function of the angle $\varphi$ for 75- and 115-keV protons. As summarized in Fig. 2, we found nearly rotational symmetry of the 75-keV dip at the level of the width taken to be indicative of the processes of interest here; that is, the channel in which the proton moves appears to have, to first approximation, cylindrical symmetry. The dip for the Al $K$ shell, Fig. 3, has the same general appearance as that for the Cu $L$ shell, but is somewhat narrower. Above the chosen characteristic width, asymmetries develop which may be caused by incipient effects of crystal axes of lower symmetry (higher Miller indices). It is interesting to note that the highest Cu $L$ single-crystal yields do not approach the standard thick-target yield of Cu, Fig. 1(a), indicating presumably that even at the angles of largest yield in the single crystal the proton beam does not become fully randomized.

We find agreement between the experimental widths for Al $K$ and Cu $L$, and Eq. (1) setting $z=1$ and $n=1, n=2$, respectively. Moreover, if applied to the conditions of $(p,\gamma)$ reactions, $n=0$, Eq. (1) reduces to the estimates given by Lindhard[4] and approaches the experimental values obtained by Bøgh, Davies, and Nielson[5] for Al and Si crystals.

In conclusion, the characteristic x-ray production by protons in single crystals is strongly dependent on the crystal symmetry. The effect opens promising avenues of research, since it can be studied over a wide continuous range of energies for different particles. Equation (1) may be tested in regard to its dependence on proton energy, $Z$, lattice spacing, and x-ray production cross section. The gen-

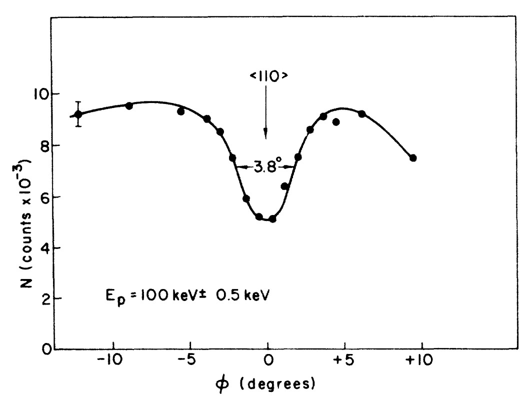


FIG. 3. Aluminum $K$ x-ray yield at 100 keV. Experimental conditions are the same as described in Fig. 1.

eral process of channeling may exhibit both temperature and lattice-defect dependences which may also be explored.

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## DISPERSION RELATIONS OF WHITE TIN*

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In this paper preliminary results are reported for the dispersion relations of white tin as determined by slow-neutron scattering. These results include the doubly degenerate transverse acoustical branch for the phonon wave vector in the [001] direction and one of the transverse acoustical branches for the [100] direction. They are important in understanding the lattice dynamics of white tin and its relationship with experimental data on specific heat, Mössbauer effect, and superconducting tunneling measurements, and tetragonal structures have not been studied previously by neutron spectrometry.

The axially symmetric lattice-dynamics model was used by Wolfram, Lehman, and DeWames[1] and DeWames, Wolfram, and Lehman[2] in an attempt to explain experimental measurements of the specific heat[3] and the Debye-Waller factor[4,5] of white tin, the latter determined from Mössbauer effect data. Disagreement between the specific-heat and Mössbauer data and the lattice model implied that at least some of the branches of the dispersion relation have lower frequencies than predicted. This problem was re-examined recently by DeWames and Lehman[6] using a modified axially symmetric model resulting primarily in a lowering of the optical frequencies. Tunneling measurements in superconducting tin[7] have established the locations of Van Hove singularities in the frequency distributions of white tin. The measurements reported here[8] indicate the source of certain of the Van Hove singularities and provide a basis for further re-evaluation of the lattice-dynamics models.

These data were obtained at the Materials Testing Reactor using the phased chopper velocity selector[9] and time-of-flight methods. With this method bursts of monoenergetic neutrons were scattered from a single-crystal sample and the scattered neutrons were sorted according to their time of flight to the scattering detectors. Peaks in the time distribution of the scattering data for a given detector were then analyzed to obtain the frequency and wave vector of the phonon involved in a given scattering process. For this work a chopper speed of 12 000 rpm was used and the 15 detector angles were each defined by single $BF_3$ detectors one inch in diameter with an active length of four inches. A flight path from sample to detectors of approximately 1.85 meters was used for measurements having the phonon wave vector in the [100] direction and was later increased to 2.4 meters for measurements in the [001] direction. The angle subtended by a scattering detector, as viewed from the sample position, was 0.79° and 0.60° for the different flight paths, respectively. The scattering-surface method[10] has been applied in analyzing the data from this experiment which closely parallels the procedure used in a previous experiment on beryllium.[11] One significant improvement in the experiment arises from the higher rotor speed used here, which gives a time resolution $\Delta t/t$ of 2% for 0.04-eV neutrons as determined from the full width at half maximum of the neutron burst at the monitor position, 2 meters from the sample. Incident neutron energies between 0.03 and 0.05 eV were used, and the sample orientation was adjusted for each data run.