DIRECTION AND ENERGY DISTRIBUTION OF CHARGED PARTICLES TRANSMITTED THROUGH SINGLE CRYSTALS*

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The discovery of the anomalous energy-loss rates of energetic protons[1,2] and helium ions[3] incident on single crystals parallel to low-index directions was soon followed by reports of similar orientation dependence of nuclear- and atomic-reactions yields.[4-6] The explanation of these phenomena through the mechanism of channeling of the incident particles between rows of atoms in the crystal[1,2,7] is not sufficiently general. This was shown by discovery of planar (as distinct from axial) symmetry in the energy loss of 3-MeV protons in passing through thin silicon crystals.[8] That work also showed for the first time that, in addition to an anomalously small energy loss, some of the particles exhibited an anomalously high energy loss. More recent work has demonstrated the quantitative dominance of planar effects in the energy loss of protons above 2 MeV in silicon crystals of 20 to 50 μ thickness.[9] The purpose of this note is to report new observations from a detailed study of the energy loss of 5-MeV protons incident on low-index planes in silicon crystals. These results show that (1) transmitted particles with anomalously high energy loss have a strikingly different dependence on both the incidence and emergence angle than particles with anomalously low energy loss; (2) particles transmitted most nearly parallel to the planar direction exhibit a specific energy loss that depends on the characteristics of the plane; and (3) multiple coulomb scattering plays an important role in the observed anisotropy.

Particles incident on a single crystal in a direction sufficiently far from low-index crystal planes have an energy-loss spectrum expected for an amorphous sample. This is called the "normal" distribution, and deviations from this spectral shape are ascribed to the effects of the crystalline structure. In any given measurement some particles are essentially unaffected by the lattice. Therefore, to obtain the energy distribution of particles which are affected by the lattice, the normal or randomly scattered particles must be subtracted. In the absence of information on the fraction of the beam behaving in this normal or random manner, we have assumed we could separate the normal particles from those affected by the lattice by normalizing the spectrum in question to have the height of the "normal" spectrum at the peak energy of the normal spectrum and then subtracting the normal spectrum from the normalized spectrum. The difference spectrum obtained in this way represents a lower limit to the fraction of particles affected by the lattice. While the normalization is somewhat arbitrary, this procedure provides a convenient method of separating those particles which have lost less energy than normal (low-loss component) and those which have lost more energy than normal (high-loss component) and to study their systematic behavior.

By using a $\langle 110\rangle$ oriented sample tilted at 10° to the particle beam, the different planes which intersect at the $\langle 110\rangle$ axis were studied by rotating the crystal about that axis. The dependence on incidence angle relative to the plane for the low- and high-loss components are shown in Fig. 1 for the $\{111\}$, $\{110\}$, and $\{100\}$ planes. In each case, the abnormal-loss

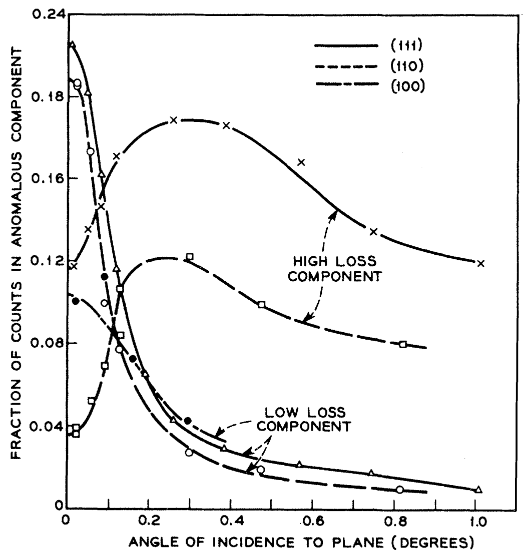

FIG. 1. Fraction of the particles incident on a 50μ silicon crystal which are in the low-energy-loss component and the high-energy-loss component as a function of the incident proton beam direction relative to the {100}, {110}, and {111} planes.

component was obtained by the subtraction method indicated above. Any high-loss component associated with the {100} planes was below the detection limit of these measurements.

A number of features of the angular distribution of Fig. 1 are of interest: (1) The magnitudes of the anomalous energy-loss components for the different planes appear to be related to the spacing and atomic density in the planes. Both the low- and high-loss components are higher for the dense {111} plane and lowest for the most closely spaced and least dense {100} plane. (2) The low-loss component first decreases rapidly with a half-width equal to the divergence of the incident beam. At incidence angles greater than about 0.2°, the low-loss component varies more slowly, in good agreement[10] with the expected decrease in multiple coulomb scattering through the indicated angle. (3) The high-loss component for the {111} and {110} planes shows an initial rise followed at large angles by a slow decrease, again suggestive of multiple coulomb scattering.

We have also measured simultaneously the angular and energy distribution of particles emerging from the crystal for incidence exactly along the {111} and {110} planes. Previous observations for particles incident along axial directions in silicon crystals[11,12] showed marked angular structure with high intensity in the direction of planes in the crystal. In the present experiments scanning measurements were made by moving a semiconductor detector, collimated to 1-mm diameter, in the plane perpendicular to the beam at a distance of 90 centimeters from the 50 micron-thick silicon crystal. The incident proton beam (4.85 MeV) was collimated to a spot size of 1.6 mm on the crystal with a half-angle of divergence of about 0.15°. The measured angular distribution is shown in Fig. 2(a). The contours correspond to the total particle intensity in arbitrary units. The incident-beam direction is indicated by X. The most striking feature of this distribution is the relatively rapid decrease in intensity even along the plane, in contrast to the long "star arms" observed in measurements in which the beam direction is along a crystal axis.[11,12] A possible explanation for this difference is the strong scattering of beam particles into planar directions by the dense atom rows when incidence is along a crystal axis.

Again, a simple subtraction of the normal spectrum was used to show the dependence of the intensity of the high- and low-loss components on the emergence angle from the thin crystal. Such angular distributions were taken across the {111} plane at emergence angles corresponding to the circles shown on Fig. 2(a). The results are shown in Fig. 2(b). Since the incident direction is along the plane, the high-loss component is relatively small, as Fig. 1 shows, and is furthermore scattered through a large range of angles. Therefore, the number of these particles which reach the detector is very small. This makes the detailed angular dependence of this component somewhat uncertain. However, the increase and subsequent decrease with increasing emergence angle are clearly seen. By changing the incidence angle to enhance the high-loss component, scanning measurements can be used to study this component in detail, and the results of such measurements, as well as further details of the present experiments, will be discussed in a more complete account of this work.

The energy spectrum of the transmitted particles depends strongly on their emergence angle with respect to the incident-beam direction and is also dependent on the particlular crystal plane involved. Figure 3 shows the

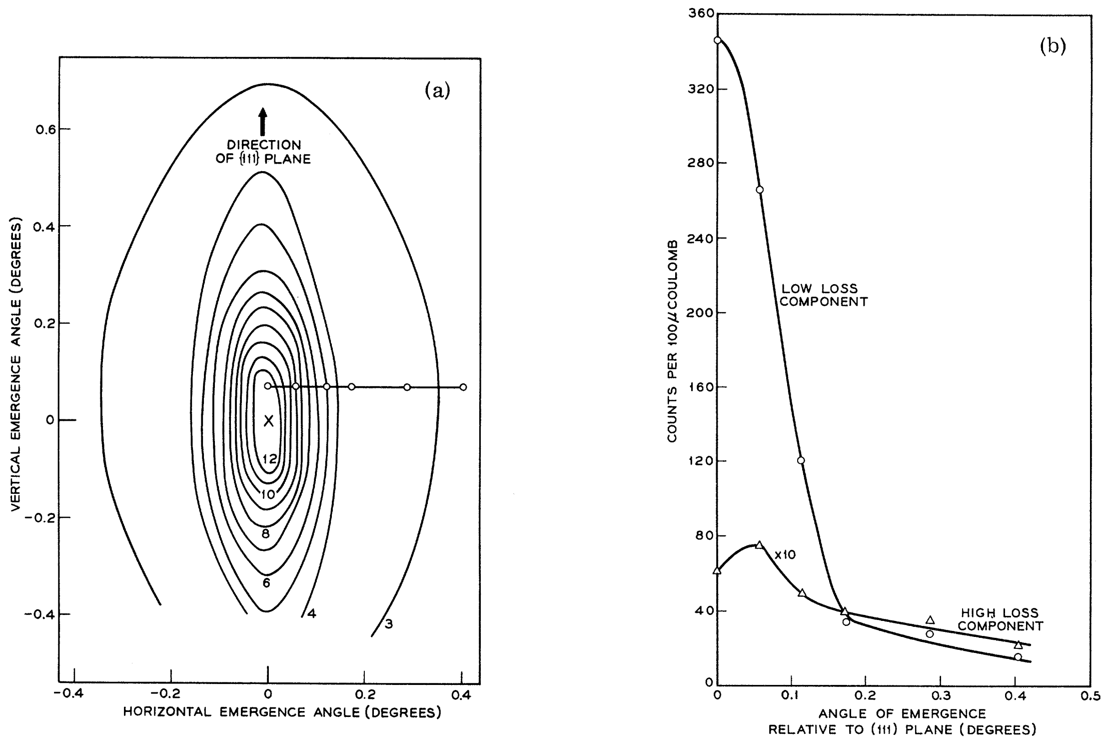

FIG. 2. (a) This shows the relative intensity (in arbitrary units) observed with a small (1-mm-diameter) semiconductor detector placed to intercept particles emerging from a 50μ silicon crystal at the angles indicated. The angles are relative to the direction of the incident 4.85-MeV proton beam which was directed exactly along a {111} plane. The circles indicate positions at which energy spectra were measured to obtain the curves of (b). (b) This shows the relative intensity of particles in the low-energy-loss component and high-energy-loss component as a function of the emergent proton direction relative to the {111} plane for beam incidence directly along the {111} plane.

spectrum for particles emerging directly along the {111} plane [corresponding to position X in Fig. 2(a)] and is compared to the normal spectrum (obtained by rotating the crystal away from low-index planes) and to the incident-beam spectrum (obtained by removing the crystal). The spectra are all measured for the same number of incident-beam particles. In this measurement, the incident beam was collimated to 1-mm spot size on the thin crystal.

The spectrum of particles emerging exactly along the beam and parallel to the {111} plane shows an almost complete absence of "normal" particles. Most of the particles emerging in this direction are those suffering least energy loss and smallest deflection.[13] It is seen that these particles exhibit a very specific energy loss with an energy dispersion little changed from that observed for the incident beam. The {110} plane shows a similar but broader single peak shifted to lower energy (4.54 MeV). As the scanning detector is moved from the beam direction the intensity of the sharp single peak drops rapidly, the peak broadens and shifts to lower energy, and a second peak at the normal energy-loss position appears.

The origin of the low-loss component observed in these measurements is consistent with channeling of incident particles between planes in the crystal. Some of the theoretical aspects of such planar channeling are discussed in the accompanying Letter.[10] The observed dependence of this component on incidence angle (Fig. 1) and emergence angle [Fig. 2(b)] indicates that for 5-MeV protons the half-angle of acceptance for channeling is less than 0.1°. The origin of the high-loss component is less clear. The large incidence angle (~0.30) (Fig. 1) at which this component is a maximum and the slow decrease for still larger incidence angles discounts channeling of the particles between planes in large amplitude oscillations because the distance of approach to the lattice atoms becomes too small to support the necessary

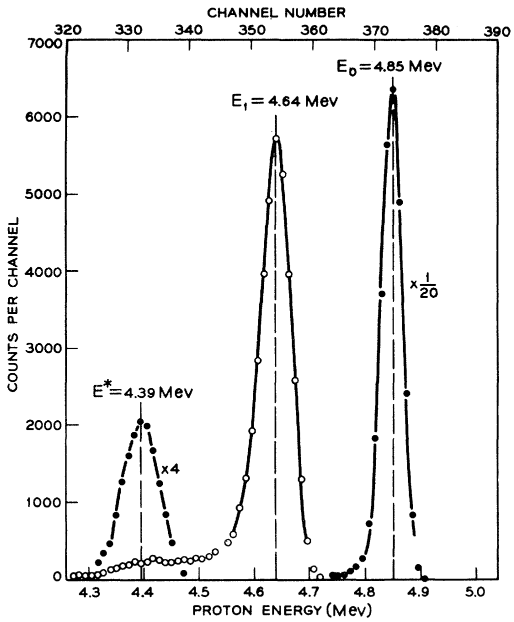

FIG. 3. Energy spectra measured with a 1-mm-diameter semiconductor detector for the incident proton beam (most probable energy E_0 = 4.85 MeV); for particles transmitted in the beam direction through a 50μ-thick silicon crystal oriented with the beam directed exactly along a {111} plane (most probable energy E_1 = 4.64 MeV), and with the crystal oriented with the beam directed far from any low-index planes (most probable energy E^* = 4.39 MeV). All three spectra are for the same number of incident protons.

correlated scattering. Multiple scattering in the planes is suggested[10] as the source of this effect.

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[1]R. S. Nelson and M. W. Thompson, Phil. Mag. 8, 1677 (1963).

[2]G. Dearnaley, IEEE, Trans. Nucl. Sci. 11, 243 (1964).

[3]T. C. Madden and W. M. Gibson, IEEE, Trans. Nucl. Sci. 11, 254 (1964); Bull. Am. Phys. Soc. 9, 493 (1963).

[4]E. Bøgh, J. A. Davies, and K. O. Nielsen, Phys. Letters 12, 129 (1964).

[5]M. W. Thompson, Phys. Rev. Letters 13, 756 (1964).

[6]W. Brandt, J. M. Khan, D. L. Potter, R. D. Worley, and H. P. Smith, Phys. Rev. Letters 14, 42 (1965).

[7]J. Lindhard, Phys. Letters 12, 126 (1964).

[8]C. Erginsoy, H. E. Wegner, and W. M. Gibson, Phys. Rev. Letters 13, 530 (1964).

[9]B. R. Appleton, C. Erginsoy, H. E. Wegner, and W. M. Gibson (to be published).

[10]C. Erginsoy, following Letter [Phys. Rev. Letters 15, 360 (1965)].

[11]W. M. Gibson, C. Erginsoy, and H. E. Wegner, Bull. Am. Phys. Soc. 10, 43 (1965).

[12]J. P. Schiffer and R. E. Holland, Bull. Am. Phys. Soc. 10, 54 (1965).

[13]A "channeling peak" has also been observed for protons transmitted through thin germanium crystal by A. R. Sattler and G. Dearnaley, Phys. Rev. Letters 15, 59 (1965).

ANISOTROPIC EFFECTS IN INTERACTIONS OF ENERGETIC CHARGED PARTICLES IN A CRYSTAL LATTICE*

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Directional effects have been observed in electronic, atomic, and nuclear interactions accompanying the passage of charged particles through a crystal lattice.[1-6] Related effects have been demonstrated when charged particles are emitted from a single-crystal source[7,8] or emerge from a single crystal after suffering large-angle Rutherford scattering.[9] In previous theoretical discussions[1,10] only the influence of atom rows in the crystal on particle trajectories incident at small angles to them has been emphasized. Recent experiments show that the observed effects do not necessarily depend on the interaction of particle trajectories with atom rows. All effects occur, although to a lesser degree, when the incident beam is parallel to low-index crystal planes.[3,11-13] Furthermore, planar symmetry is observed by particle trajectories over much larger solid angles than axial symmetry, and planar effects