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ANISOTROPIC ENERGY LOSS OF LIGHT PARTICLES OF MeV ENERGIES IN THIN SILICON SINGLE CRYSTALS*

C. Erginsoy and H. E. Wegner
Brookhaven National Laboratory, Upton, New York

and

W. M. Gibson
Bell Telephone Laboratories, Murray Hill, New Jersey
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Recent experiments[1,2] show that the ionization loss of a beam of fast light particles passing through a thin Si single crystal is strongly dependent on orientation. When the beam enters the crystal along one of the low-index crystal axes, the energy spectrum of the transmitted particles differs markedly from a Gaussian distribution and has a broad "shoulder" towards the high energies. Dearnaley[1] suggests that this effect is due to the correlated small-angle collisions between the penetrating particles and the lattice atoms. As a result of such collisions the particles are deflected away from the vicinity of nuclei (hence from regions of high electron density) and "channeled" along the crystal axes where the electron density is low. Such a mechanism was previously proposed by Nelson and Thompson[3] to account for the enhanced transmission of 75-keV protons in thin Au foils. No quantitative treatment of the degree of anisotropy to be expected from "channeling" has been given so far. The purpose of this Letter is to report new experimental evidence indicating that (i) the anisotropy of energy loss is characteristic of the low-index symmetry planes of the crystal and shows up strongly along crystal axes where such planes intersect, (ii) the fraction of the transmitted beam with energies in the "tail" or "shoulder" of the distorted spectrum is relatively insensitive to the collimation of the incident beam, and (iii) in addition to the distortion towards high energies there is also an increase in the energy straggling at the low-energy end of the spectrum.

An explanation based on correlated small-angle deflections is supported by very recent observations[4] on the dependence of macroscopic nuclear cross sections of (p,n) and (p,γ) reactions on orientation. Our evidence on energy loss favors the hypothesis that for fast light particles a mechanism of correlated deflections from atoms lying in low-index symmetry planes is essential to the phenomenon, rather than that of channeling along low-index atom rows. This latter process was predicted by machine calculations[5] and appears to be operative in the case of heavy ions of keV energies.[6,7] Some evidence for "interplanar channeling" with light ions near 50 keV in Cu and Au was obtained by Nelson and Thompson[3] from reflection data. More theoretical work is needed to clarify both processes.

A beam of 3-MeV protons (stable to ±1 keV) from the Brookhaven Van de Graaf accelerator was scattered elastically from a target of gold and collimated within a half-angle of divergence of about 0.05° on a 1-mil thick single crystal of silicon cut normal to the ⟨111⟩ axes. The crystal was prepared as a diffused-junction particle detector, using phosphorus diffusion and planar etching techniques described elsewhere.[2] A goniometer allows the adjustment of the angle of the plane of the crystal with respect to the beam direction and also the rotation of the crystal in its plane. The angular adjustments in the system were reproducible to ±0.1° by direct read-out of vernier scales and the accuracy of the goniom-

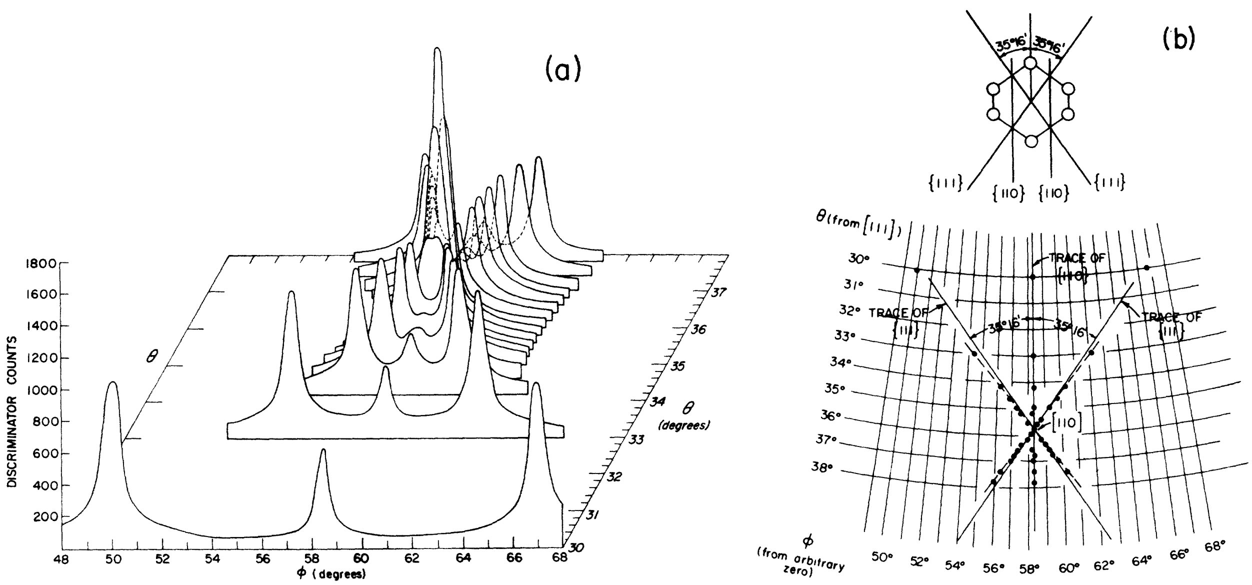

FIG. 1. Discriminator counts are shown in (a) as a function of azimuthal angle θ (measured from the [111] axis) and the rotation angle φ (measured from an arbitrary zero). (b) shows the distribution of angles θ and φ for which discriminator counts reach maxima (indicated by solid circles). The loci of such points are seen to be the {111} and {110} sets of planes. The small deviation of the dotted curves from straight lines is due to the projection of a spherical surface on a linear scale.

eter in terms of backlash and other mechanical errors was approximately ±0.02°.

In a preliminary experiment with a 4-mil thick silicon crystal mounted in the goniometer, it was established that the ionization yield of the crystal for complete stopping was independent of orientation. This is also the result obtained by Dearnaley[1] and Madden and Gibson.[2]

The region of beam directions around the [110] axis of the crystal was then studied in detail with the 1-mil crystal as absorber mounted in the goniometer. The particles transmitted through this crystal were stopped by the 4-mil crystal in which they lost all their energy. The energy distribution of the transmitted particles was obtained by means of a multichannel analyzer which measures the amplitude distribution of the ionization pulses in the 4-mil crystal. A pulse-height discriminator was adjusted to count pulses above the electronic noise of the system. A second discriminator was set to count pulses corresponding to transmitted particle energies exceeding the upper edge of the Gaussian spectrum of a "no-symmetry" orientation of the thin crystal. Figure 1(a) shows the counts in the second discriminator (per 10 000 counts in the first) as a function of the orientation of the thin crystal. The angular coordinates θ and φ are defined in Fig. 2. The discriminator counts show maxima, not only when the beam direction coincides with the [110] axis (single high peak at center) but also when the beam direction lies in one of the symmetry planes of the crystal. The peaks in the discriminator counts have widths of the order of 1° at their base and 0.6-0.7° at half maxima. These are larger than the width of

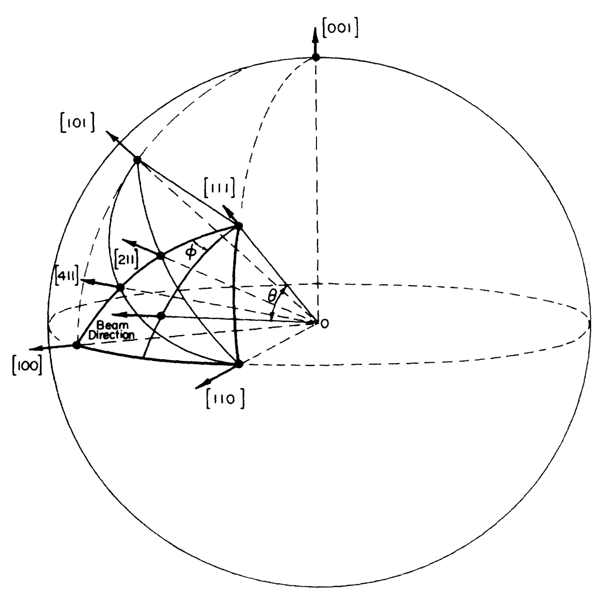

FIG. 2. Polar and azimuthal angles defining the orientation of the crystal with respect to the incident beam direction.

the incident beam (~0.1° full width). Figure 1(b) shows that the planes of symmetry involved are {110} and {111}. The energy spectra of the transmitted protons for beam directions lying in such planes are shown in Fig. 3(a).

The neighborhood of the [110] axis was further scanned by rotating the crystal at an angle of tilt $\theta = 35.8°$. Figure 3(b) shows the energy spectra for different angles of rotation φ, including the highly distorted spectrum corresponding to the

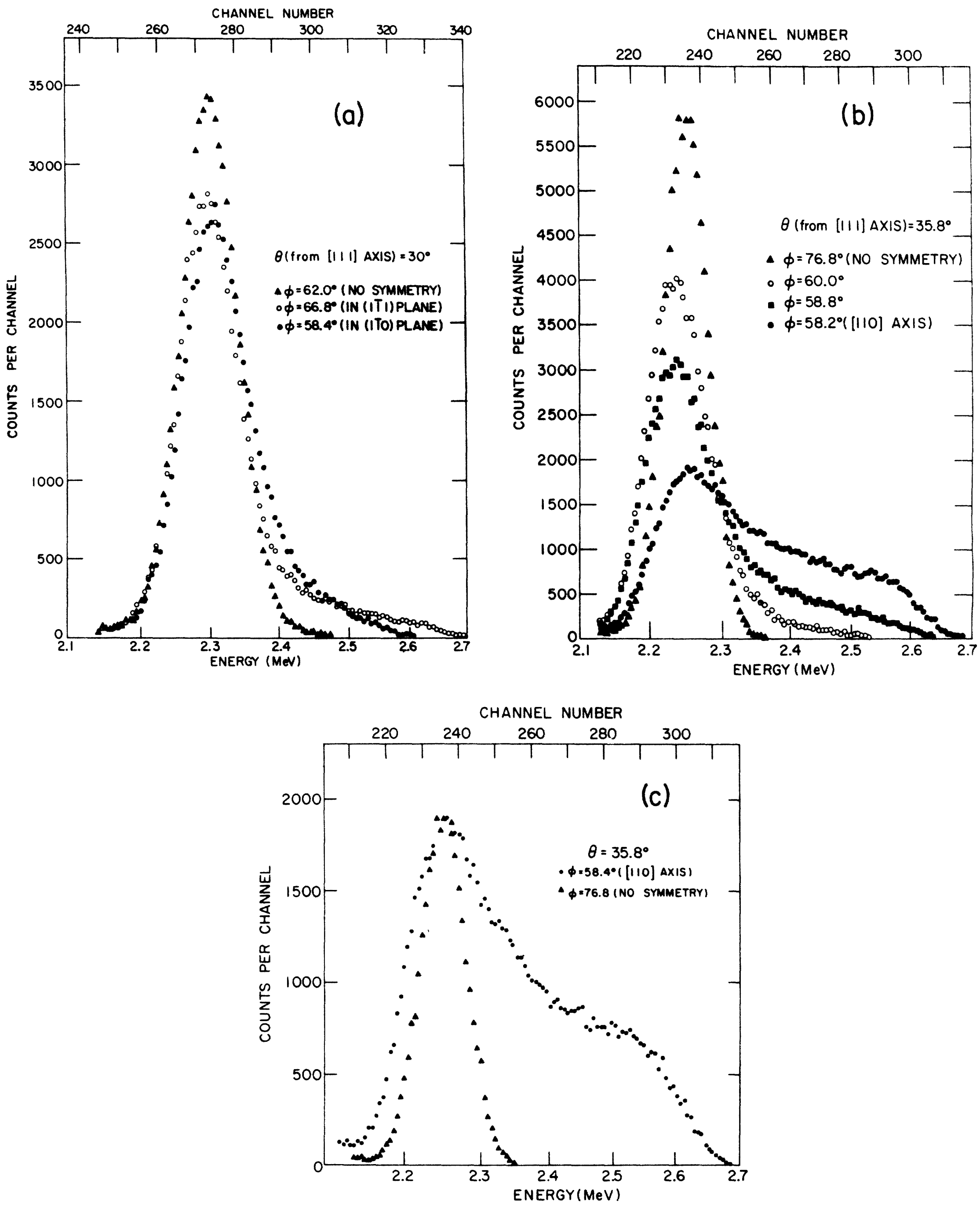

FIG. 3. Energy spectra of transmitted protons for different beam directions. Spectra in (a) and (b) are normalized to equal area in each figure. (c) shows the spectra for the [110] axis and for a "no-symmetry" direction, normalized to equal peak height to illustrate the distortion at the low-energy end as well as the "shoulder" towards high energies.

[110] axis. Two features of these spectra are noteworthy. First, some high-energy "tail" is seen also when the beam lies in the closely spaced {100} planes, as shown by the spectrum for $\varphi = 60°$. Secondly, the energy distribution at the low-energy end of the spectra is somewhat broader than the Gaussian distribution corresponding to a "no-symmetry" direction. This is seen clearly in Fig. 3(c) where the spectra for $\varphi = 58.4°$ ([110] axis) and $\varphi = 76.8°$ (no symmetry) are normalized to the same peak height.

We have also carried out an experiment at the Brookhaven cyclotron, using 30-MeV He^3 particles and the 4-mil crystal as absorber. The most probable energy loss was approximately 4 MeV. For the beam in the $(1\bar{1}0)$ plane about 10% of the transmitted particles lost 2-3 MeV, while about 2% lost only 1-2 MeV. Experiments at these high energies are now in progress and further results will be reported elsewhere.

In discussing the observed anisotropy we want to distinguish between three parameters: (i) anisotropy coefficients, (ii) angular widths, and (iii) energy shifts. Some comments will be made on each.

(i) Anisotropy coefficient F. – This can be defined as the fraction of the transmitted beam with energies in the "tail" or "shoulder" of the distorted spectrum. Table I shows F obtained from spectra in Figs. 3(a) and 3(b) for directions in the symmetry planes but away from the [110] axis. The "isotropic" component is taken as symmetrical about the peak energy.

F is the highest for the {111} planes which have the most closely packed structure and presumably are the most effective in providing the correlated deflections to the particle trajectories. The closely spaced {100} planes which show the smallest F have the most open structure. It must be noted that F is rather small in all planes. It is unlikely that the random scattering from the small amounts (~ few tens of ppm) of impurities and the thin (~250 Å) layer of gold on the crystal can account for the smallness of F.

Table I. Anisotropy coefficient F in the low-index symmetry planes.

Plane	F
$(1\bar{1}1)$	0.13
$(1\bar{1}0)$	0.10
(001)	0.05

Thermal vibration amplitudes of atoms in the lattice may have an important limiting effect on F. Since these are of the order of 0.1 Å for silicon at room temperature and, therefore, comparable to the collision impact parameters, it is possible that only a small fraction of the penetrating beam may become subject to the correlated set of small-angle deflections.

We have observed that F is rather insensitive to small deviations (~0.2°) of the beam direction away from the planes. Considering that our initial beam was narrow (~0.05° half-angle), this would indicate that the initial collimation has little effect on F within a half-angle of 0.25°. This margin is presumably dependent on the energy of the beam.

(ii) Angular widths. – Figure 1(a) shows that anisotropy is observed within a range $\Delta\varphi$ of rotation angles, which are of the order of 1.5-2° for the symmetry planes crossed. In terms of actual angles in the crystal these widths are $\Delta\Omega = 2\theta\tan(\Delta\varphi/2) \cong 1\text{-}1.3°$. These widths are large compared with the full width of the incident beam (~0.1°).

(iii) Energy shifts. – Energy loss to ionization and excitation consists of two components: a loss due to impact-type collisions between the penetrating particle and an electron, and the distant resonance-type momentum transfers. The equality of these two components (equipartition rule) at the high-energy limit has been stated by Bohr[8] and recently proved rigorously for the case of an electron gas by Lindhard and Winther.[9] It follows from this rule that if the average energy loss for a nonsymmetry direction of the beam is $\bar{E}$, the minimum loss for a particle whose trajectory has been correlated (few close impact-type collisions) approaches $\bar{E}/2$. This applies, of course, in the limiting case of the infinitely thin crystal. Nevertheless, we see that the energy shifts in the distorted spectra obtained are within this limit.

Regarding the distortion at the low-energy end of the spectra in Figs. 3(b) and 3(c), we have no explanation for this at the present time.

Details of experiments with crystal directions other than the [110] and with particles of different energies will be given elsewhere. Methods of preparing "thin" particle counters in which orientation effects are minimized will also be treated in another publication.

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18-cm SPECTRUM OF OH†

H. E. Radford
National Bureau of Standards, Washington, D. C.
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The detection of interstellar OH by its 18-cm absorption spectrum[1-3] has created a need for improved laboratory measurements of the spectrum. Earlier measurements of the line frequencies, although invaluable for locating and identifying the interstellar spectrum in the first place, are too coarse to use in analyses of the observational results. An experimental accuracy of about one part per million in the rest frequencies is required for evaluation of Doppler shifts, and measurements to this accuracy are reported here.

The spectrum consists of four electric dipole transitions within the Λ-type doublet structure of the molecular ground state. The line frequencies are approximately 1612, 1665, 1667, and 1720 MHz (Mc/sec), with expected relative intensities of 1:5:9:1. In a weak magnetic field, such as the earth's field, each of the two stronger lines ($\Delta F=0$) splits into a normal Zeeman triplet, consisting of one π component ($\Delta M_F=0$) and two oppositely shifted σ components ($\Delta M_F=\pm1$). The same field splits each of the two weak lines ($\Delta F=\pm1$) into three π components and six σ components; this is illustrated by Fig. 1, which is a recording of the 1612-MHz line made in the earth's magnetic field. These splitting patterns are not quite symmetrical about the line positions at zero field, the chief reasons being the small difference between the molecular magnetic moments of the upper and lower Λ-type doublet levels, and the presence of quadratic

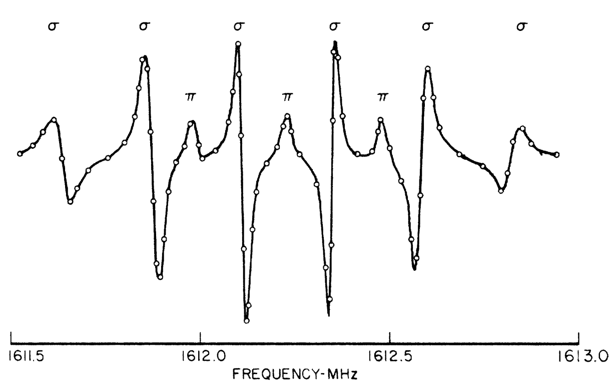

FIG. 1. Point-by-point recording of the 1612-MHz line of OH, split by a static magnetic field of 0.36 gauss. The relative orientations of the microwave electric field, static magnetic field, and magnetic modulation field have been chosen so as to excite both π and σ transitions, although with unequal intensities.

Zeeman shifts. Both of these effects are small, typically 1 kHz or less in the earth's field; they may be calculated reliably, and introduce no uncertainty in the determination of zero-field frequencies.

Like the earlier work of Ehrenstein, Townes, and Stevenson,[4] the present measurements were made by the method of microwave absorption in a flowing gas in which OH radicals were generated continuously. Freed from the search problem of the earlier work, however, we have used a highly sensitive superheterodyne cavity spectrometer, rather than a spectrometer of the