[2]J. Itoh and Y. Kamiya, J. Phys. Soc. Japan 17B, 512 (1962).
[3]T. Haseda, R. Miedema, H. Kobayashi, and E. Kanda, J. Phys. Soc. Japan 17B, 518 (1962).
[4]S. C. Mathur and A. Mookherji, Bull. Am. Phys. Soc. 10, 254 (1965).
[5]K. Okada, M. I. Kay, D. T. Cromer, and I. Almodovar, to be published.
[6]H. Kiriyama, Bull. Chem. Soc. Japan 35, 1199 (1962).
[7]E. Sawaguchi, G. Shirane, and Y. Takagi, J. Phys. Soc. Japan 6, 333 (1951).
[8]G. Shirane, E. Sawaguchi, and Y. Takagi, Phys. Rev. 84, 476 (1951).
[9]Yu. Ya. Tomashpol'skii and Yu. N. Venevtsev, Fiz. Tver. Tela 6, 2998 (1964) [translation: Soviet Phys.-Solid State 6, 2388 (1965)].
[10]V. A. Bokov, S. A. Kizhav, I. E. Myl'nikova, and A. G. Tutov, Fiz. Tver. Tela 6, 3038 (1964) [translation: Soviet Phys.-Solid State 6, 2419 (1965)].

ANISOTROPIC ENERGY LOSSES IN A FACE-CENTERED-CUBIC CRYSTAL FOR HIGH-ENERGY ^{79}Br AND ^{127}I IONS*

S. Datz, T. S. Noggle, and C. D. Moak
Oak Ridge National Laboratory, Oak Ridge, Tennessee
(Received 4 June 1965)

Multicomponent beams of Br and I ions from the Oak Ridge tandem accelerator,[1] with energies up to 80 MeV have been used to study crystal orientation effects on energy losses in thin gold single crystals. Channel effects were predicted theoretically by Robinson and Oen[2]; they have been observed with 75-keV protons transmitted through gold,[3] and by range measurements with low-energy heavy ions.[4,5] Evidence has been found for channeling effects with (p,γ) and (p,n) reactions and in studies of yields of x rays induced by proton bombardment.[6-8] Other observations with fast light particles in Si have been reported by Dearnaldy,[9] Erginsoy, Wegner, and Gibson,[10] and Shiffer and Holland.[11]

For the experiments reported here, Au single crystals were prepared by evaporation and epitaxial growth upon cleaved rock-salt faces. The crystals were formed with a (100) face parallel to their surfaces and were 1.1 mg/cm^2 (0.57 μ) thick, as determined by α-particle energy-loss measurements and by weighing. Following removal from their rock-salt substrates, they were mounted for rotation about a fixed axis in the surface plane. Two rotations, one about a [100] axis and the other about a [110] axis, were studied. The angular position error was ±0.1°. The [100] axis rotation allowed alignment of the [001] and the [110] directions with the incident beam, while the [110] axis rotation permitted alignment with the [001], [112], and the [111] crystal directions. It should be noted that in both rotations low-index crystal planes were parallel to the beam at all goniometer settings. As in earlier work,[1] Br and I negative ions were accelerated in the first stage of the tandem accelerator, stripped of some of their electrons, and stripped further during acceleration in the second stage. The resulting high-energy continuous spectrum of particles was passed through a 90° magnetic analyzer which gave a beam consisting of a series of accurately known energies. Incidence of this beam onto a Si surface-barrier detector produced the pulse-height spectra shown in Figs. 1(a) and 2(a). The procedure was to measure the effects upon each peak in these spectra produced by the insertion of a crystal in various orientations. The collimator arrangement consisted of the target, 3 mm in diameter followed by a 1-cm diameter aperture at a distance of 10 cm, followed by the 2-cm-diameter detector at a distance of 5 cm from the aperture. In earlier experiments with polycrystalline absorbers, the only effects observed were simple peak shifts without appreciable shape distortions. Earlier dE/dx measurements on polycrystalline samples[12] have been employed to calculate estimated normal energy losses corresponding to the thickness of the specimens used in the present experiments, and these are shown in the figures.

The spectrum of Fig. 1(c) illustrates the effects produced when the [001] crystal direction was aligned to a ^{79}Br beam. The energy losses for the various groups are characterized by single peaks. The losses are less than corresponding normal (polycrystalline) losses for a foil of this thickness. Although the peaks are asymmetric, the fraction of particles with normal energy loss was less than 0.1. Almost

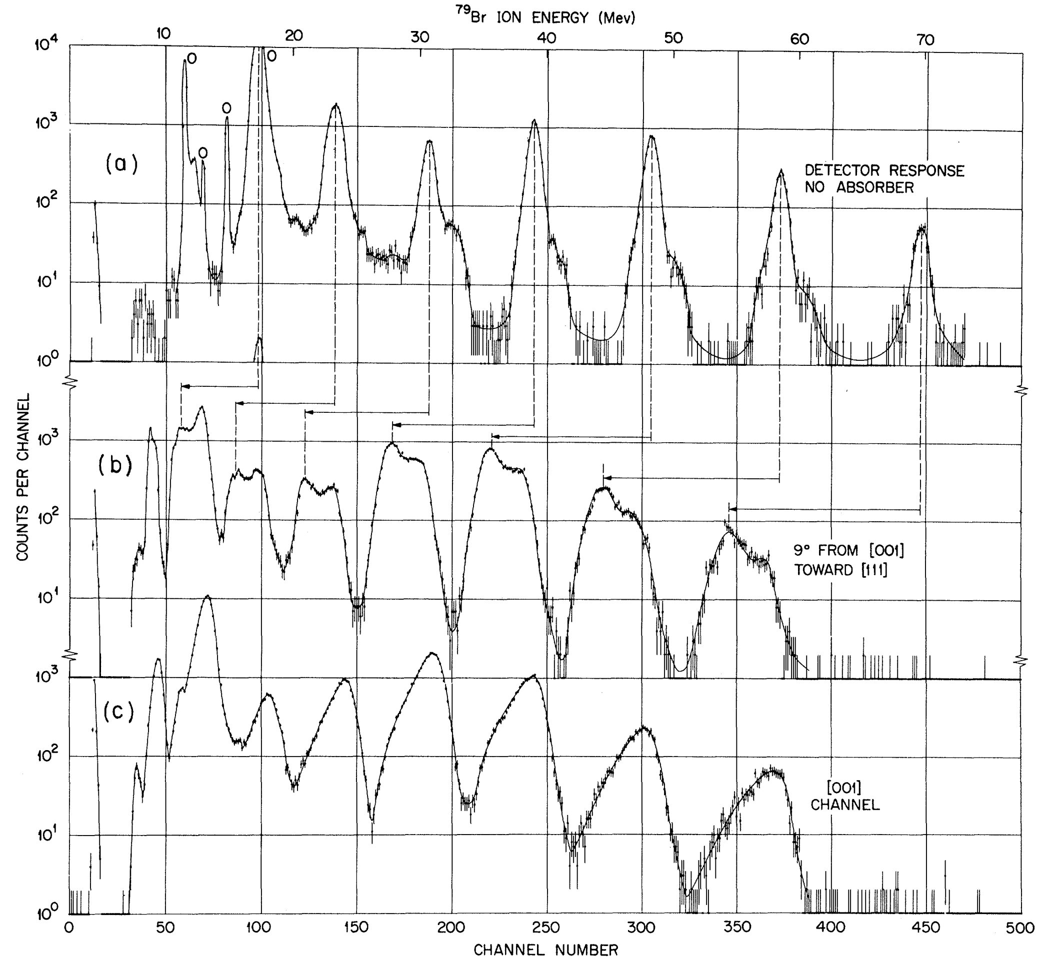

FIG. 1. ^{79}Br pulse-height spectra obtained with (a) no absorber, (b) an Au single-crystal absorber rotated 9° about a [110] axis in the (100) surface toward [111], and (c) with the [001] axis in line with the ion beam. The shifts indicated by the arrows drawn from the peak positions on (a) show the expected energy loss in a polycrystalline Au sample of the same thickness. The peaks labeled O are due to oxygen-ion impurities.

identical patterns have been observed for bombardment in the available low-index directions, i.e., [110] and the [112] directions. For the case of the [111] direction, the spectra were unusable because of excessive sample thickness due to the oblique angle.

The spectrum of Fig. 1(b) was obtained with the crystal rotated 9° about a [110] axis from the [001] direction; in this case the (110) planes were parallel to the beam. The spectrum consists of double peaks, one set of which corresponds to the normal energy losses. This spectrum is typical of all those taken at angles corresponding to planar channels. In these cases the relative populations vary with energy, the normal components becoming predominant at high energy. Since there is a slight uncertainty in the rotational alignment about a planar axis, this energy dependence may reflect a variation in the channel acceptance angle with energy. Thus these results may give at least qualitative verification to arguments of Lindhard[13] which indicate an expected $(v)^{-1}$ dependence for channel acceptance angle.

Some corresponding spectra obtained for ^{127}I ions are shown in Fig. 2. Once again single peaks of reduced energy loss occur for axial channel directions [Fig. 2(c)]; for planar channels [Fig. 2(b)] double peaks appear corresponding to reduced energy loss and normal energy loss.

For the experiments reported here, two axes of rotation were not available simultaneously. Without rotation around two axes, small mis-

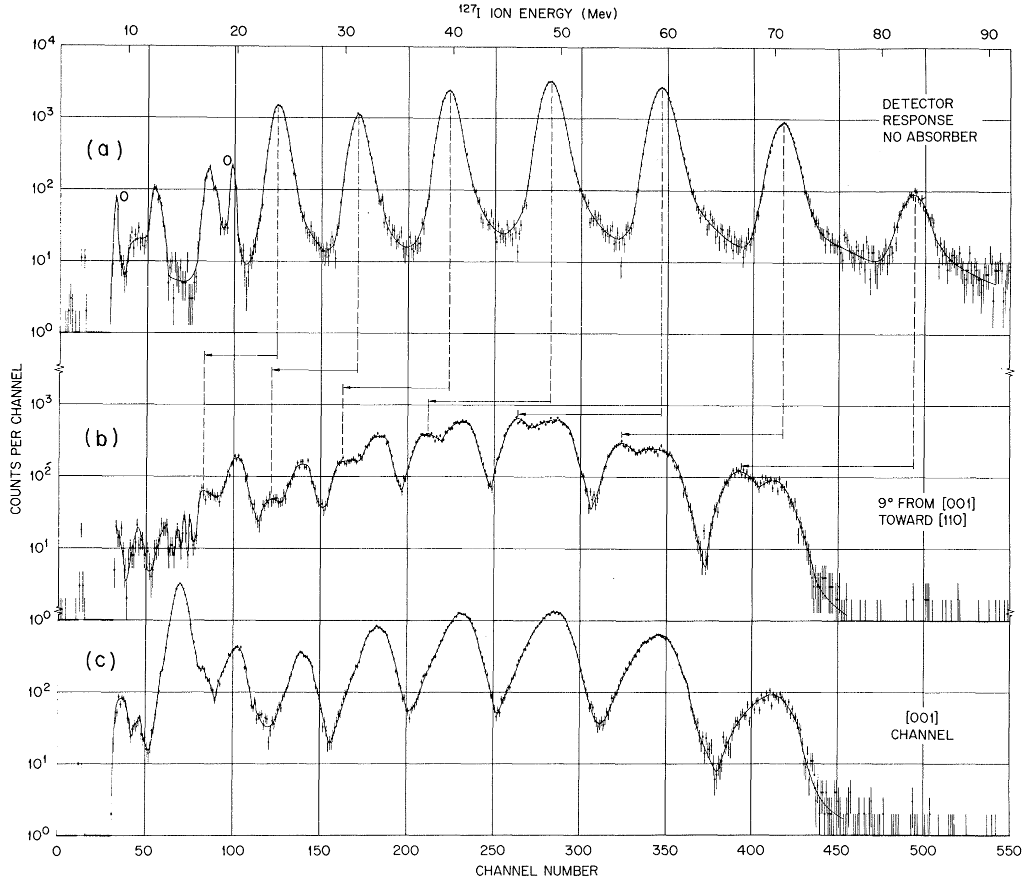

FIG. 2. ^{127}I pulse-height spectra obtained with (a) no absorber, (b) an Au single-crystal absorber rotated 9° about a [100] axis in the (100) surface toward [110], and (c) with the [001] in line with the ion beam direction.

alignments could not be corrected. Although these misalignments are thought to be less than 0.1°, several spectra have indicated that even these small errors might affect the relative populations of channeled and unchanneled groups. It will be necessary to perform rotations around two axes in order to obtain the detailed structure of channel acceptance angles. In spite of the possible misalignment, it is noteworthy that in the cases studied where planar channeling was involved a major portion of the ions were channeled. As can be seen from the relative peak heights for a given energy group in Figs. 1(b) and 2(b), the fraction of the ions which are channeled decreases with increasing ion energy. For direct incidence along a low-index crystal axis, the fraction undergoing normal loss is too small to be measured accurately at any of the incident energies; at angles slightly off axis (i.e., 0°30′) a normal loss component became observable which increased with increasing energy. These observations suggest a positive channeling mechanism as opposed to a simple transparency model and indicate that the probability of channeling decreases with increasing transverse momentum of the incident ion. Moreover, the fact that two distinct groups were observed, rather than a continuum of energy losses, implies that most of the channeled particles were channeled almost immediately upon entering the crystal and remained in channels during the remainder of their trajectory through the solid. Channeling of ions involves correlated collisions with rows of atoms which steer the ions on paths with reduced probability of low-impact parameter events; however, the effective size of the "strings"[13] of atoms, in this energy range, is too small to confine a particle to a single channel. Thus, in a low-index crystal axis direction, movement of the particle to adjacent channels is essentially unhin-

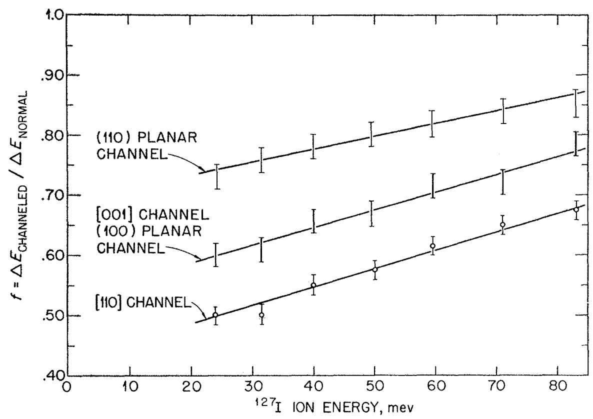

FIG. 3. Fractional energy loss for ^{127}I ions for several channel directions in Au versus incident-ion energy.

dered. Interplanar movements are more restricted because wandering is limited to only one direction.

Although the trajectory of the particle is controlled by nuclear collisions, the energy loss suffered by the ions in this energy range is primarily due to electronic stopping, and the decreased energy loss associated with channeling therefore reflects the lower average electron density encountered by the channeled particle. Detector resolution in these experiments was insufficient to allow observation of the detailed structure and shape of the channeled and unchanneled groups of ions; however, in most cases the two groups were easily separable and a set of numbers called the channel energy-loss fraction ($f = \Delta E$ channeled/ΔE normal) was derived from the data. The energy-loss fraction for ^{127}I ions in various channels is plotted against incident energy in Fig. 3. The values all lie between 0.5 and 0.85, show a slow rise with energy, and seem to have lower over-all values for broader channels. Planar channels seem to give the same energy loss as axial channels of the same restricting dimension. It is also noteworthy that the energy-loss fraction in planar channels did not change when the effective crystal thickness was changed by 40% by rotation about an axis in the surface, in accord with the assumption that the particles are channeled early and remain channeled. The fact that the values are larger than those recently measured for protons and α particles is perhaps caused by the fact that the ions are not bare nuclei but have electrons which spend part of their time in dense regions alongside the channels, while the fact that the values are not constant with energy may indicate that the ion charge states are not following the same schedule which they would follow in amorphous solid matter.

---

*Research sponsored by the U. S. Atomic Energy Commission under contract with the Union Carbide Corporation.

[1]C. D. Moak, J. H. Neiler, H. W. Schmitt, F. J. Walter, and G. F. Wells, Rev. Sci. Instr. 34, 853 (1963).

[2]M. T. Robinson and O. S. Oen, Bull. Am. Phys. Soc. 7, 171 (1962); Appl. Phys. Letters 2, 30 (1963); Phys. Rev. 132, 2385 (1963).

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

[4]G. R. Piercy, F. Brown, J. A. Davies, and M. McCargo, Phys. Rev. Letters 10, 399 (1963).

[5]H. Lutz and R. Sizmann, Phys. Letters 5, 113 (1963).

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

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

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

[9]G. Dearnaley, IEEE, Trans. Nucl. Sci. 11, 249 (1964).

[10]C. Erginsoy, H. E. Wegner, and W. M. Gibson, Phys. Rev. Letters 13, 530 (1964); Bull. Am. Phys. Soc. 10, 43 (1965).

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

[12]C. D. Moak and M. D. Brown, Phys. Rev. Letters 11, 284 (1963).

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