DETERMINATION OF INTERATOMIC POTENTIALS AND STOPPING POWERS FROM CHANNELED-ION ENERGY-LOSS SPECTRA*

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Structure has been observed in the energy-loss spectrum of 60-MeV ^{127}I ions and 3-MeV α particles channeled in gold single crystals. The explanation of this structure has been found to lie in the nature of transverse oscillations of the particles in the channels. The energy losses associated with given wavelengths and amplitudes allow a mapping of the stopping power in the channel and should permit the direct determination of interatomic potentials.

In a previously reported experiment[1,2] surface-barrier solid-state detectors were used to measure the energy loss suffered by high-energy (20-80 MeV) ^{79}Br and ^{127}I ions upon passing through oriented, thin single crystals of gold. It was found that, for incidence in low-index crystal directions, almost all the ions suffered energy losses which were significantly lower than those entering in a random direction. Low-index crystal planes were also shown to be effective in channeling. In another experiment,[3] in which time-of-flight techniques were used to improve the energy resolution, detailed angular scans were made across planar channels. Additional sharp energy-loss groups were discovered between the normal and lowest energy-loss components. Reports of channeling experiments with protons and α particles from other laboratories[4,5] contained no evidence of similar structure in the energy-loss pattern.

For the experiments reported here, a beam of 60-MeV ^{127}I ions was passed through a thin Au crystal and into a magnetic analyzer. The Au single crystal, ca. 5400 Å thick, was mounted in a goniometer, which permitted rotation about two orthogonal axes; mosaic spread across the usable area of the crystal was ca. 0.2°. The original beam divergence was 0.05°; the acceptance angle of the analyzer was 0.02°; the resolution of the magnetic analyzer, fitted with a position-sensitive detector, was $\Delta E/E = 2\times10^{-3}$.

The energy spectrum obtained for beam incidence parallel to the (111) plane, with the crystal tilted 40° with respect to the (100) face, is shown in Fig. 1(a). The peak is sharp on the high-energy side but decreases more gradually with only minor undulations on the low-energy side. Figure 1(b) shows the pronounced structure obtained when the crystal is rotated 0.5° perpendicular to the plane. The observed peak positions did not vary with angle of incidence, α_0. Since structure had not previously been reported with light ions, our experiment was repeated with a beam of 3-MeV α particles. Although the instrumental resolution was poorer, the spectra (Fig. 2) clearly show the same general features. The suggestion that the structure is due to charge-state fluctuations is eliminated by this α-particle experiment as well as by studies of the individual charge states of channeled iodine ions to be reported elsewhere.

The explanation of the structure reported here has been found to lie in the nature of the transverse oscillations of the particles in the channels. Consider a planar channel consisting of two parallel closely packed lattice planes. In this channel a particle of energy E experiences a repulsive force from each wall. We assume a smooth "planar potential," $\Phi(y)$,[6] where y is the distance from the midplane. The particle motion reduces to a two-dimen-

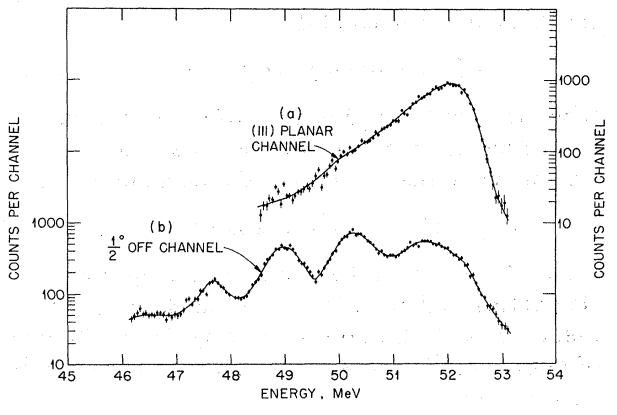

FIG. 1. Energy spectra of 60-MeV ^{127}I ions in Au single crystals obtained with a 7000-Å thick Au single-crystal absorber. (a) (111) plane aligned with beam direction, (b) (111) plane tilted 0.5° from beam direction. The normal energy loss in this crystal was ca. 16 MeV.

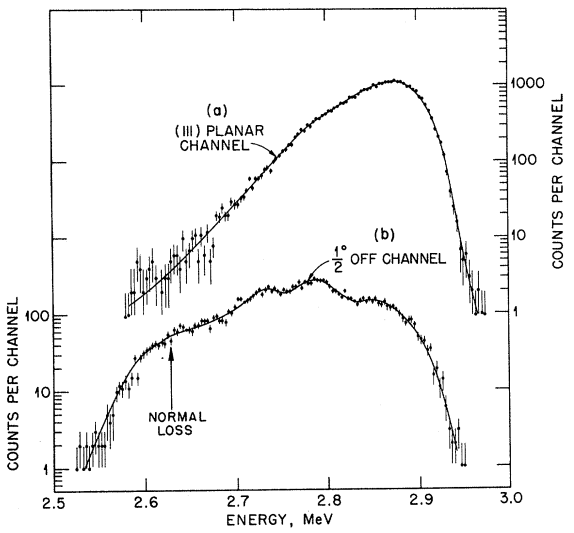

FIG. 2. Energy spectra of 3-MeV α particles obtained with a 7000-Å thick Au single-crystal absorber. (a) (111) plane aligned with beam direction, (b) (111) plane tilted 0.5° from beam direction. The energy scale is uncertain by ca. 3%.

sional problem in which the direction of incidence into the channel lies in the x-y plane. The walls are assumed to be rigid. Since for channeled particles the maximum angle between particle trajectory and axial plane is ca. 1°,[7] the x component of the velocity is assumed to be constant. Thus

$$\frac{d^2y}{dx^2} = -\frac{1}{2E}\frac{\partial\Phi(y)}{\partial y}. \tag{1}$$

To integrate Eq. (1), we can write the potential $\Phi(y)$ as a polynomial

$$\Phi(y) = \Phi(0) + a_1y^2 + b_1y^4 + \cdots. \tag{2}$$

Since (1) and (2) lead to the differential equation of an undamped anharmonic oscillator, we can write the solution in the periodic form

$$y = A_1\sin[(x-x_0)/\lambda\!\!\!^{-}] + A_3\sin[3(x-x_0)/\lambda\!\!\!^{-}], \tag{3}$$

where $A = A_1 + A_3$ is the oscillation amplitude. Neglecting higher order terms in Eq. (2), we insert (3) and (2) into (1). Setting the coefficients of $\sin[(x-x_0)/\lambda\!\!\!^{-}]$ and $\sin[3(x-x_0)/\lambda\!\!\!^{-}]$ to zero yields $A_1 \gg A_3$ and

$$\lambda\!\!\!^{-2} = a + 3bA_1(A_1+A_3)/4 = a + 3bA^2/4, \tag{4}$$

where $a = a_1/E$; $b = 2b_1/E$.

It should be emphasized that in the experiment, the detecting system was aligned with the original beam direction. A particle can, therefore, only be detected if the angle of incidence, α_0, into the channel is equal to the exit angle, α_e. This introduces conditions for the wavelength of the detected particles:

$$l = n\lambda_1, \tag{5a}$$

$$l = n\lambda_2 \pm 2|x_0|, \tag{5b}$$

where l is the channel length, n an integer, and $x_0 = \lambda\!\!\!^{-}_2\cos^{-1}(\lambda\!\!\!^{-}_2\alpha_0/A)$. For $\alpha_0 = 0$, $l = n\lambda/2$. Because the wavelength, λ, of the detected particles is quantized, their amplitude, A, is also quantized, since from Eq. (4)

$$A^2 = (\tfrac{3}{4}b)(\lambda\!\!\!^{-2} - a). \tag{6}$$

Particles with different oscillation amplitude, A, probe different electron-density regions and thus have different distinct energy losses. Since the wavelengths, λ_2, are a function of α_0, the mosaic spread of the crystal introduces an energy spread in the case of Eq. (5b) which increases with increasing α_0. Hence the discrete groups seen in Fig. 1(b) are due to the $l = n\lambda_1$ solutions. With $\alpha_0 = 0$ [Fig. 1(a)], the λ_2 peaks are still sharp enough to fill in the valleys between the λ_1 groups.

If the channel length, l, is increased a small amount, the λ chosen increases. The energy separation between the $A = 0$ group and higher order groups decreases.[8] This peak shift has been observed. In the (100) planar region, tilting the crystal parallel to the plane to give a 4% change in thickness produced the spectra shown in Fig. 3. For greater thickness, the peaks are shifted to lower energy loss with respect to the most channeled group as predicted. From these shifts, we derived a wavelength, λ, of ca. 800-900 Å for the first side group. To calculate λ we expand the planar Molière potential,[6] using the Thomas-Fermi screening length, about the channel midplane according to Eq. (2). From Eqs. (5a) and (6), we get λ = 880 Å for this group. Applying the Poisson equation to our potential, we obtain for the energy loss

$$dE/E = 2Sl[a(1+c) + 3bA^2/2], \tag{7}$$

where S is the energy-dependent stopping power in the center of the channel, and c is an apportioning factor between distant and close collisions. Assuming equipartition,[7] $c = 1$. For the experimental conditions of Fig. 1, the product $S\cdot a$, obtained by measuring the energy-loss

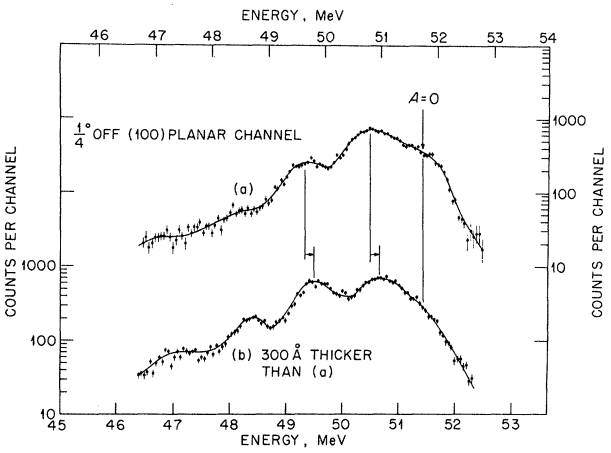

FIG. 3. Energy spectra of 60-MeV ^{127}I ions obtained with a Au single-crystal absorber; the (100) plane was tilted 0.25° from beam direction. Crystal thickness (a) 7000 Å, (b) 7300 Å. The energy scales were shifted to compensate for the thickness change.

group with $A = 0$ (for $\alpha_0 = 0$), was 486 cm^{-1}. For this case, we calculate from Eq. (5) a series of amplitudes, $A = 0$, 0.180, 0.556, 0.980 ···, Å for the observed λ_1 solutions. [The (111) channel width is 2×1.18 Å.] This leads to a set of calculated values for $(dE/E)_{calc} = 0.137$, 0.159, 0.208, 0.264, ···, which, considering the crudity of the approximations, is in reasonable agreement with the measured values $(dE/E)_{expt} = 0.137$, 0.151, 0.177, 0.203. The accuracy of these calculations can be improved by using more appropriate potential forms, such as the hyperbolic cosine, or by including more terms in Eq. (2). In some cases Eq. (1) can be solved directly by means of elliptic integrals.

The demonstration that oscillation amplitudes can be experimentally related with their corresponding energy losses suggests a number of interesting experiments. A study of the populations of the groups may indicate the form of the interplanar potentials. The energy shifts of the groups with crystal thickness will give exact numerical values for the wavelengths of different oscillation modes. Studies of energy versus angle of exit from the crystal should give exact values of oscillation amplitudes. The energy losses associated with the measured wavelengths and amplitudes allow a mapping of the stopping power in the channel. Thus, this experimental technique in conjuction with the theory should permit the direct determination of interatomic potentials and stopping powers.

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[8]For the much thicker crystal used in previous light-ion channeling studies (Refs. 4 and 5) the structure was probably too compressed to be observable.

NEW RESULTS ON THE QUESTION OF AUGER AFTEREFFECTS*

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Since Wertheim[1] reported the observation of two charge states in Mössbauer studies on cobalt oxide, other observations have been made,[2-4] which have been interpreted as further evidence that in some materials the time required to reach electronic equilibrium, following the emission of an Auger electron, can be of order of or greater than 10^{-7} sec. This evidence has been extensively quoted in the recent literature[4-7] despite reported evidence[8] that the Mössbauer effect in $Co^{57}O$ showed only one charge state. This later experiment, which appears to conflict with Wertheim's results, was only reported in an abbreviated form, and no explanation was given for the discrepancy in Wertheim's original work. While exper-