We then obtain

$$\frac{dP}{d\Omega}=\frac{e^2n}{2\pi c^3}|\hat{k}_s\times\vec{w}|^2\frac{\omega_r^{\ 2}}{(1-n\beta\cos\theta_s)^3} \qquad (5)$$

as an expression for the emitted power. From classical mechanics,

$$w^2\approx\frac{4\pi e^2}{m^2\omega_r^{\ 2}c}P_L \qquad (6)$$

gives an approximate expression for the oscillatory velocity amplitude. We insert (6) into (5) and divide by P_L, the laser power, to obtain the cross section:

$$\frac{d\sigma}{d\Omega}\approx\left(\frac{e^2}{mc^2}\right)^2\frac{1}{(1-n\beta\cos\theta_s)^3}. \qquad (7)$$

This formula shows the departure from the Thomson cross section. We have neglected factors of the order of unity. It appears that (7) is independent of the laser angle, but that is illusive. Because of (1) and the requirement that both ω_s and ω_L be in the optical region, the resonance only occurs if the laser beam is aligned close to the Cherenkov cone.

The reason for the resonance is very simple. The Cherenkov radiation process occurs because the Coulomb field of the electron is a viable radiation field in the laboratory frame. Similarly, the laser field (which would only produce small oscillations of an electron at rest) appears as a nearly electrostatic field in the electron frame. It is, therefore, able to accelerate the electron to large velocities and the electron reradiates strongly.

There are numerous factors which reduce the strength of the resonance in (7). Use of relativistic dynamics for the electron reduces the effect. Taking notice of collisions of the electron with the medium should reduce the cross section very near to the resonance, and removal of the approximation of neglecting $\vec{w}$ in the exponential of (3) should further reduce the cross section. Nevertheless, the effect may be observable.

We wish to acknowledge illuminating remarks of Dr. W. B. Thompson and Dr. T. O'Neal.

---

[1]J. D. Jackson, Classical Electrodynamics (John Wiley & Sons, Inc., New York, 1962), p. 497.

DIRECT OBSERVATION OF CHANNELING IN bcc IRON FILMS*

C. J. Andreen,† E. F. Wassermann, and R. L. Hines

Northwestern University, Evanston, Illinois

(Received 4 April 1966)

In a recent Letter[1] we reported about transmission of 13-keV D^+ ions in single-crystalline fcc gold films. The results showed that the transmitted intensities in the beam direction are high in low-index directions or along low-index planes. The ions are believed to be channeled between the atom rows and planes in the crystal.[2] We found that the channeled intensities are correlated with calculated transparency values A_{hkl}, the area per atom along the direction $\langle hkl\rangle$, given by $A_{hkl}=\mathrm{const}\,\rho_{hkl}^{-1}$ where ρ_{hkl} is the number of atom rows per unit area.[3] A good agreement exists between the strongest five peaks and low-index directions calculated by Robinson and Oen[3] to be the most open channels in fcc crystals.

In this Letter we report the direct observation of channeling in a bcc structure. We compare the results with those obtained on gold films in our previous investigations and show that planar channeling plays an important role. Penetration distributions of ^{125}Xe ions in bcc tungsten have been obtained earlier.[4] The anomalous long-range "tails" in the curves are interpreted as being due to channeling. However, these authors do not discuss the distinction between directional and planar channeling.

Single-crystal α-iron films are used in our investigations. The films are grown by ultrahigh-vacuum (10^{-8} Torr) deposition of iron onto hot rocksalt substrates. Growing techniques similar to those described by Matthews[5] and Shinozaki and Sato[6] are used. The film thickness is measured with a quartz crystal microbalance. The epitaxial relation between the films and the substrates as seen in an electron microscope is that the (001) plane of iron is parallel to the (001) plane of the rocksalt. The

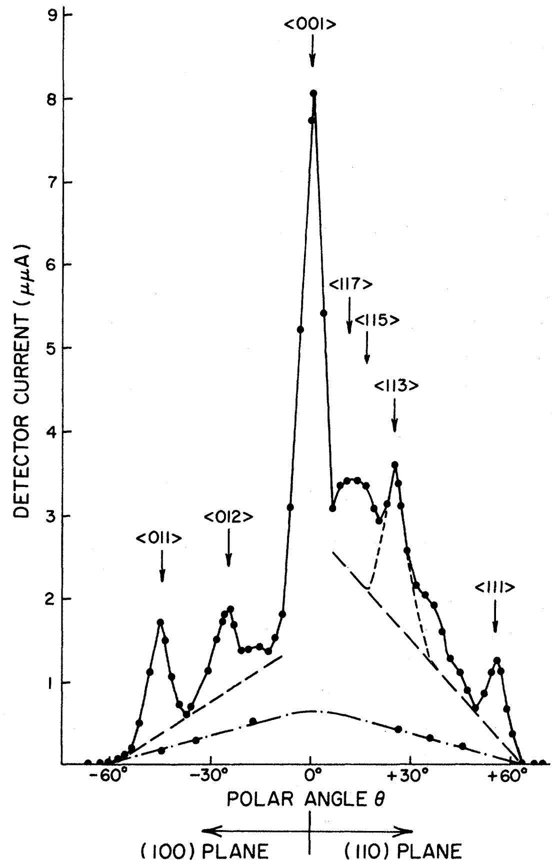

FIG. 1. Transmitted currents of D^+ ions in the beam direction through a 1000-Å-thick α-iron film are shown as a function of film orientation. The film normal is ⟨001⟩. Arrows point to the angles for low-index directions in the (100) and (110) planes. Dashed lines indicate the separation of directional and planar contributions. The dot-dashed line represents transmitted intensities in high-index planes. Incident ion current is 10^{-9} A. Incident ion energy is 15 keV.

films are picked up on 3-mm-diameter Cu grids and mounted in a goniometer. With the goniometer, the foil normal can be inclined to a polar angle θ with respect to the beam direction, and the foil can be rotated about its normal through an azimuthal angle φ. A mass-separated D^+ ion beam is used for the bombardment. Details about the apparatus and the goniometer geometry have been described earlier.[1,7]

Figure 1 shows the channeled intensities in the beam direction in a (100) and a (110) plane for a 1000-Å-thick iron film. The D^+ ions have an energy of 15 keV. The incident ion current is 10^{-9} A. Because of the film orientation the ⟨001⟩ direction appears at $\theta = 0$, the intersection between the two planes. In the (100) plane, peaks are found in directions corresponding to the channels ⟨011⟩ and ⟨012⟩. In the (110) plane we find channels in the ⟨111⟩, ⟨113⟩, ⟨115⟩, and ⟨117⟩ directions. The smooth background shown by the dot-dashed line in Fig. 1 is obtained from measuring the intensity in high-index planes. In these planes the foil acts like a polycrystalline film with random orientation. Similar curves are obtained from measurements on randomly oriented iron films.

Table I. Most-open channel directions ⟨*hkl*⟩ as found experimentally are shown for fcc[a] and bcc structures. A plus sign refers to resolved peaks and a minus sign to directions where no resolved peaks are seen. The parentheses indicate that the ⟨012⟩ direction has a relatively low intensity.

⟨*hkl*⟩	bcc	fcc
001	+	+
011	+	+
111	+	−
012	+	(+)
112	−	+
013	−	+
113	+	−
114	−	+
015	−	+
133	+	−
115	+	−
117	+	−

[a]See Ref. 1.

In Table I we list 12 low-index directions in increasing order of the sum $h+k+l$. Directions for which resolved peaks are found are marked with a plus sign. No peaks have been seen in directions marked with a minus sign. Table I shows clearly that most of the peaks present in one structure are absent or unresolved in the other. This fact proves that the channeled intensities are closely related to the lattice structure and therefore gives strong support to the transparency model discussed by Robinson and Oen.[3] Their transparency values (expressed by the row densities ρ_{hkl}) suggest a certain order among the channel directions. The order is different for fcc and bcc structures. For both structures we do obtain the first five most open channels. The peak intensities, however, do not give the expected order because of an unknown dependence on effective foil thickness. The most striking difference between the fcc and bcc structures occurs for the two directions ⟨112⟩ and ⟨013⟩. In gold[1] both directions are very pronounced while they are hardly visible at all in iron.

Figure 2 shows the transmitted intensities as a function of azimuthal angle φ for a constant value of $\theta=45°$. Peaks at $\varphi=10°$ and $\varphi=100°$ correspond to $\langle 011\rangle$-type channels. The shoulders on each side of these maxima belong to the channels of the type $\langle 133\rangle$. At $\varphi=55°$ and $\varphi=145°$ no low-index directions are expected from theory. The high peaks at these angles must, therefore, be due to channeling in (110) planes. The total intensities in Fig. 1 thus also have to contain planar contributions. For $\theta=+49°$ and $-37°$ only very high-index directions exist, and we expect only planar channeling at these points. Using these minima and observing the fact that the width at half-maximum is roughly constant for all peaks, we can find the planar part on top of which the directional contributions appear. The separations are done in Fig. 1 (dashed lines). It can now be seen that the (110) plane is more transparent than the (100) plane, which is expected from calculated values of interplanar spacings.

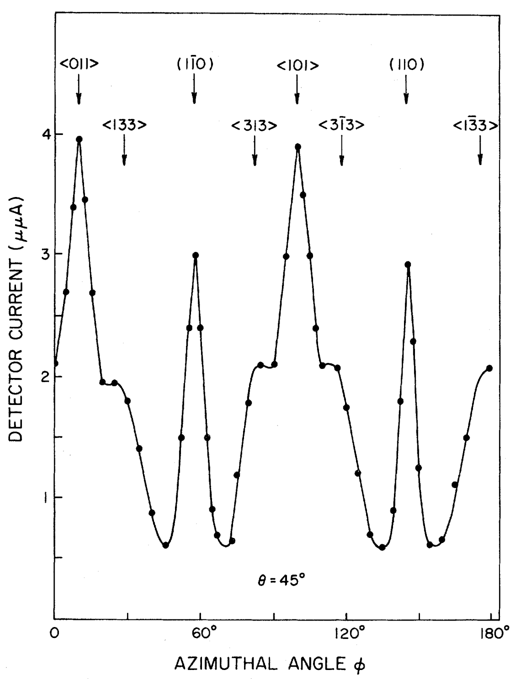

FIG. 2. Transmitted current of 15-keV D^+ ions in the beam direction in a 1000-Å α-iron film is shown as a function of azimuthal angle φ. The polar angle is $\theta=45°$. Arrows point to the angles for the indicated low-index directions and planes. Incident ion current is 10^{-9} A.

No sign of the next important plane (112) is found. This means that in our experiment only the two most important planes (110) and (100) show planar channeling. In directions where these planes intersect ($\langle 111\rangle$, $\langle 011\rangle$, and $\langle 001\rangle$), the net effect of several planes has to be considered. So far we do not know exactly how this could be done; but a calculation based on an estimated hard sphere radius of $0.06a$, where a is the lattice constant for gold, gives a maximum correction of about +20% for the planar contribution indicated in Fig. 1 in the $\langle 011\rangle$ direction. In the $\langle 001\rangle$ and $\langle 111\rangle$ directions the upward shift is much smaller.

The energy loss of the ions in the iron films can be determined by a 90-deg energy analyzer. For the $\langle 001\rangle$ channel this energy loss is found to be about 50%. Energy losses for other directions are higher.

Provided that the D^+ ion energy is kept constant, a comparison between peak widths for iron and gold films of the same thickness can be made. We find that the channel peaks are broader in iron than in gold. H^+, D^+, He^+, C^+, O^+, and Ne^+ ions have been used for channeling experiments in gold foils. It is found that the peak width increases when the mass ratio between the target and the bombarding particle decreases. The data on iron agree with this relation.

Radiation damage reduces the peak intensities because the channels are blocked by displaced atoms. By looking at the films in an electron microscope after bombardment, the damage can also be observed as a high density of defect clusters.

---

*Research supported by U. S. Atomic Energy Commission.

†Present address: Department of Physics, Chalmers University of Technology, Gothenburg, Sweden.

[1]C. J. Andreen, R. L. Hines, W. Morris, and D. Weber, Phys. Letters 19, 116 (1965).

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

[3]M. R. Robinson and O. S. Oen, Phys. Rev. 132, 2385 (1963).

[4]B. Domeij, F. Brown, J. A. Davies, G. R. Piercy, and E. V. Kornelsen, Phys. Rev. Letters 12, 360 (1964).

[5]J. W. Matthews, Appl. Phys. Letters 7, 225 (1965).

[6]S. Shinozaki and H. Sato, J. Appl. Phys. 36, 2320 (1965).

[7]R. L. Hines and R. Arndt, Phys. Rev. 119, 623 (1960).