ANOMALOUS PENETRATION OF HEAVY IONS OF keV ENERGIES IN MONOCRYSTALLINE TUNGSTEN

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Recent experimental studies[1,2] have shown that the range distribution of heavy ions in single crystals of aluminum and of copper are dependent upon the crystallographic orientation of the target with respect to the direction of the incident ions and that the penetration can be very much greater than is observed in amorphous solids. Theoretical studies[3-6] predict that moving ions can become channeled along the more open crystallographic directions; the qualitative agreement between theory and experiment suggests that such channeling does indeed occur.

We have now extended the experimental studies to monocrystalline tungsten, which has a bcc structure in contrast to Al and Cu which are fcc. The experimental techniques were similar to those used previously in experiments with polycrystalline W.[7] Single crystals of W were bombarded with a beam of radioactive ions. For ion energies less than 40 keV, an ultrahigh-vacuum ion gun, capable of operating at 10^{-10} mm, was used; this enabled the crystals to be cleaned before bombardment by heating to 2400°K, thereby removing the surface oxide and other contaminants. At higher energies, where the presence of a few atomic layers of oxide on the surface is not so critical, the bombardments were carried out in an electromagnetic isotope separator as in our earlier work. After bombardment, thin uniform layers of the crystals were dissolved by anodizing the chemical stripping, and the radioactivity of the crystals was measured after removal of each layer.

By plotting the residual activity against the thickness removed, the integral range distributions were obtained, as shown in Fig. 1. Figure 1 shows the ranges of 40-keV ^{125}Xe ions in W along four main directions: ⟨100⟩, ⟨110⟩, ⟨111⟩, and ⟨112⟩. The observed crystallographic effects are even larger than those found previously in Al; furthermore, the results are in qualitative agreement with the theoretical prediction[4] for bcc lattices, i.e., the ⟨100⟩ and ⟨111⟩ are the most favored directions for channeling and the ⟨110⟩ and ⟨112⟩ are less favored. This contrasts with the fcc structure, where both theory and

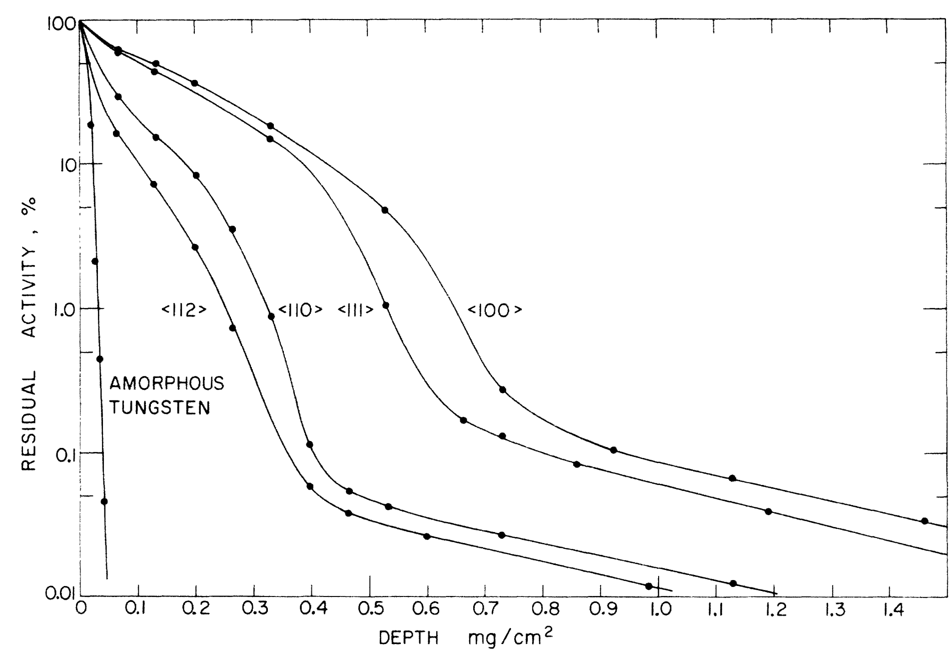

FIG. 1. Integral penetration distributions for 40-keV ^{125}Xe in tungsten. (Note that 1 mg/cm^2 is equivalent to 0.52 micron.)

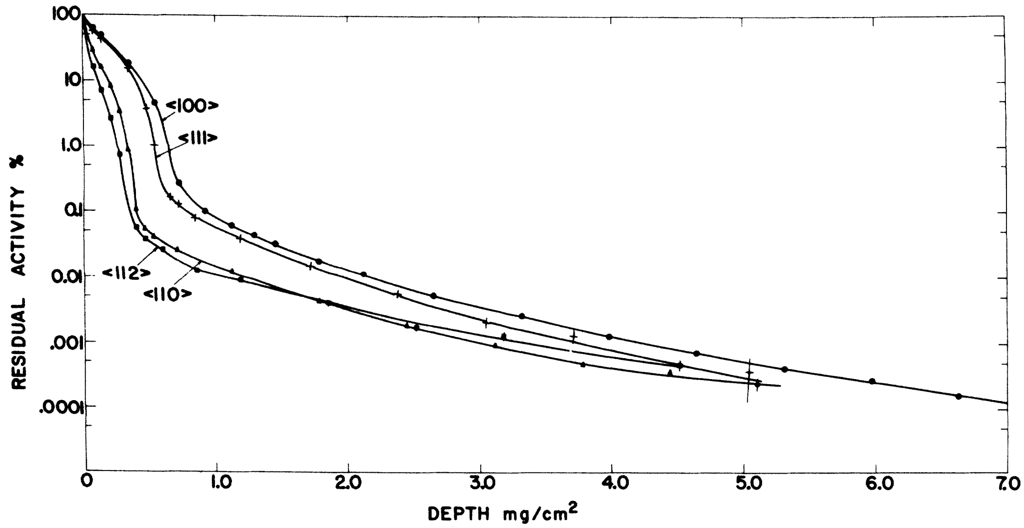

FIG. 2. Penetration curves of Fig. 1 extended to larger depths.

experiment find ⟨110⟩ the most favored and ⟨111⟩ one of the less favored. The curve labeled "amorphous tungsten" is an experimental result for the range in amorphous WO_3,[7,8] corrected approximately for the effect of oxygen. This curve, with a median range of 15 $\mu g/cm^2$, is typical for heavy ions in the absence of crystallographic effects.

Figure 2 represents the same data on an extended depth scale. It shows that, in addition to the main distributions occurring up to depths of a few hundred $\mu g/cm^2$, there is in each case a small, much more penetrating, component hereinafter referred to as the "tail" of the distribution. Two supplementary experiments have verified that these tails are not caused by a part of the surface becoming immune to the anodizing-stripping process, but are indeed due to atoms buried at the depths indicated: (i) The β activity (actually conversion electrons) and the γ activity were measured independently after each layer was removed. Buried atoms give a lower β/γ ratio due to self-absorption of the electrons. By calibrating with absorbers of known thickness, we established a mean depth of ~0.5 mg/cm^2 for the Xe atoms in the tails, in good agreement with

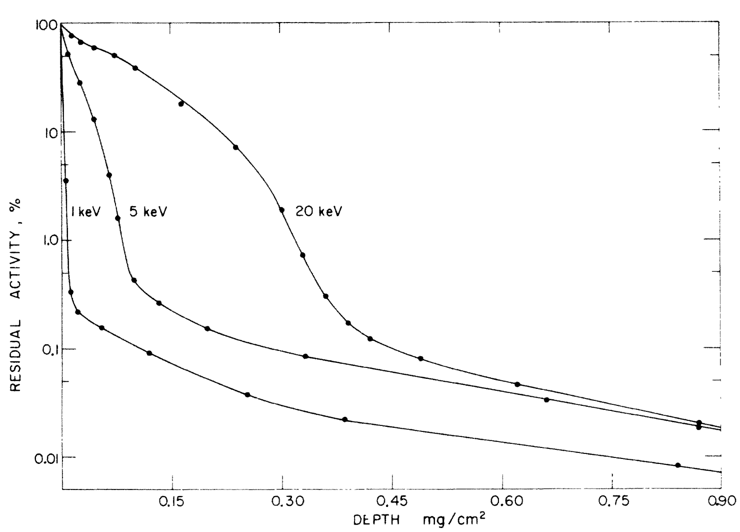

FIG. 3. Integral penetration distributions for ^{133}Xe along the ⟨100⟩ direction at various incident energies. (1 mg/cm^2 is equivalent to 0.52 micron.)

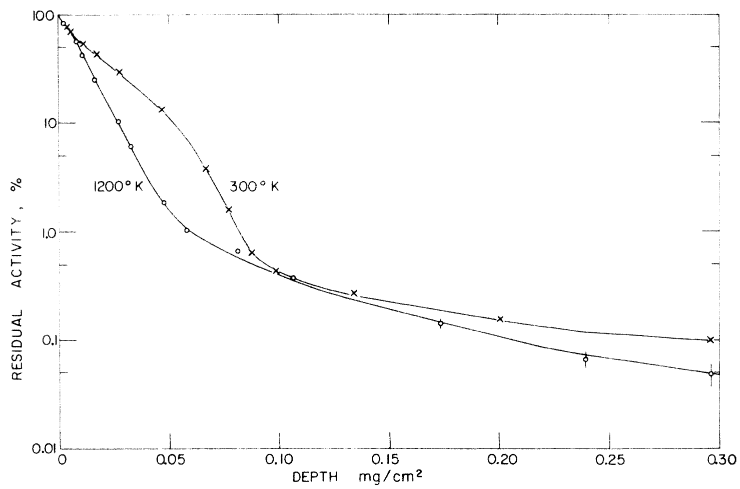

FIG. 4. Effect of lattice temperature on the penetration of 5.0-keV ^{133}Xe along the ⟨100⟩ direction.

that calculated from Fig. 2. (ii) Measurements of the conversion line shapes in a β spectrometer also confirmed that the tails are due to deeply buried atoms. The conversion lines are broadened by self-absorption and calibrations are available[9] that relate the linewidth to the depth of the embedded ^{125}Xe. Again, a value of ~0.5 mg/cm^2 was obtained.

We have established the following properties of these tails. (a) They persist for ion bombardment energies as low as 1 keV; the fraction of the incident beam contributing to the tails decreases slightly with decreasing energy, but the half-thickness at a given depth remains constant (see Fig. 3). (b) Since a 1-keV ion can penetrate several thousand atom layers, the rate of energy loss must be very small. (c) The crystallographic direction of ion incidence has a marked effect on the fraction contributing to the tail, but once again the half-thickness is almost unaffected. (d) Preliminary experiments have shown that a similar tail occurs for other noble gas ions (^{41}Ar, ^{85}Kr) and for alkali metal ions (^{24}Na, ^{86}Rb) in tungsten. (e) Channeling (i.e., the main part of the range distribution) is decreased considerably (Fig. 4) when the target is held at 1200°K during the ion bombardment. This effect agrees qualitatively with the computer studies of Robinson and Oen.[4] The tail of the distribution, on the other hand, is unaffected by the increased temperature.

The lack of temperature effect and the observed shape of the distributions indicate that these extremely penetrating tails are not the result of ordinary diffusion. Also, if the target is heated to 1200°K after bombardment, we find that the range distribution is identical to that observed in room-temperature experiments, again confirming that ordinary diffusion is not significant in these experiments. The possibility of some special type of diffusion process, which occurs rapidly even at room temperature but which is restricted to atoms located in certain special positions, e.g., along a dislocation line, is also open to doubt, since this would mean that the different single crystals of tungsten all have the same high density (~10^{11} cm^{-2}) of dislocation lines, preferentially oriented parallel to channel directions.

An interpretation of the observed features of the anomalous penetration, based on collisional excitation and autoionization of the channeled atom, has been suggested by Erginsoy[10] to whom we are indebted for a most interesting discussion.

Full details of our channeling experiments in tungsten will be presented in a forthcoming publication.

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ANOMALOUS PENETRATION OF RARE GAS ATOMS IN LATTICE CHANNELS*

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In the preceding Letter[1] evidence is given for large penetrations, of the order of several microns, in the various low-index channels of a single crystal of tungsten, by a small fraction of an incident beam of rare gas atoms. This constitutes the penetrating "tail" of the range distribution, the main part of which has been predicted by machine calculations based on the elastic model[2,3] and observed in recent experiments.[4,5] The purpose of this Letter is to show that the elastic model of channeling cannot explain the observed large penetrations and also to account for the observed slopes in the tails.

The percentage residual activity plotted in the curves of reference 1 is the percentage of atoms penetrating to depths greater than a given value. It is significant that the tails in Fig. 2 continue with nearly constant or slowly decreasing slopes with depth, but do not show a sharp downward bend, as would be expected near the maximum penetrations.[6] This suggests that the maximum penetrations are larger than the depths so far investigated. More experiments for determining the actual maximum penetrations with low-energy ions (less than 1 keV) would be of great value.

If the slowing down were elastic, the initial fractional energy loss $\Delta E/E_0$ per collision along a channel axis would be given in the impulse approximation[6] by

$$\Delta E/E_0 = 1/(2N_c L_{\max}), \qquad (1)$$

where N_c is the number of collisions per unit length along the channel axis and $L_{\max}$ is the maximum penetration for a beam of energy E_0. For Xe in W, assuming $L_{\max} = 10^4$ Å (probably an underestimate) for $E_0 = 5$ keV, we obtain $\Delta E/E_0 = 4\times10^{-5}$ for the ⟨100⟩ channel where $N_c = 1.27$ Å^{-1}. It is difficult to postulate an interatomic potential between a neutral Xe and a W atom at the impact parameter concerned (1.58 Å for the ⟨100⟩ channel axis) which will account for such a small energy loss per collision. For instance, the Thomas-Fermi statistical potential gives[7] $\Delta E/E_0 = 3.8\times10^{-3}$ for these conditions. Conversely, $L_{\max}$ corresponding to this last value would be only 102 Å.

Since the losses in the channels appear to be too small to stop any of the perfectly channeled atoms in the range of observed depths, the tails of the distribution would, in the absence of an additional stopping mechanism, be flat except for a sharp downward bend at the maximum penetration end. The observed insensitivity of the slope of the tails to channel type (Fig. 1), to energy E_0 (Fig. 3), and to temperature (Fig. 4) strongly indicates that this stopping mechanism, which removes an approximately constant fraction of the atoms in the penetrating tail over the range of observed depths, is not one of gradual slowing down (elastic or inelastic) in the channels. We suggest that when a straight channel section becomes distorted in the strain field of a lattice defect (impurity atom, interstitial, vacancy or dislocation line), the channeled atom suffers a wide deflection and is stopped rapidly by further large-angle collisions within a short distance. Such a process would be independent of channel type, energy, or temperature. The mean free path for these events is approximately given by

$$\Lambda = 1/(N\sigma) = 1/(N\pi\rho^2), \qquad (2)$$

where N is the volume concentration of defects and σ is the cross-sectional area presented by the strain field of effective radial range ρ. Assuming $N = 10^{18}$ cm^{-3} and $\rho = 4\times$lattice constant $= 12.6$ Å, we obtain $\Lambda = 2000$ Å, which agrees well with the observed half-widths of the tails. Since the density of defects in the path of channels is likely to fluctuate, the "tails" obtained in different irradiations will not be exactly reproducible.

The reason why perfectly channeled atoms are able to move in the straight channel sections with very little energy loss is not at present understood. The possibility of inelastic processes in