Range Measurements in Oriented Tungsten Single Crystals (0.1–1.0 MeV). II. A Detailed Study of the Channeling of K^{42} Ions

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In this paper the mechanism of channeling of K^{42} ions in monocrystalline tungsten is investigated. The influence of various parameters—ion energy, crystal direction, surface oxide thickness, misorientation, lattice temperature, and bombardment dose—has been studied. It is found that: (i) the over-all range distribution is rather sensitive to all these parameters; (ii) the maximum range R_{max} depends only on the ion energy and crystal direction; (iii) planar channeling exists down to the lowest energy studied (70 keV); (iv) the critical angle for channeling is about 3° at 500 keV and decreases slowly with increasing energy. In all cases, the crystals have been oriented with respect to the ion beam to ±0.1°, by means of wide-angle scattering of protons. An attempt is made to correlate the results for these fairly slow heavy ions with Lindhard's theoretical treatment of the motion of charged particles in a crystal lattice, and with the experimental studies on fast light ions.

INTRODUCTION

THIS paper is the second of two dealing with range measurements in oriented tungsten single crystals. In the preceding paper,[1] the emphasis was on *energy losses* of channeled heavy ions. Range distributions were measured for several different projectiles in the energy region 0.1–1.0 MeV along the ⟨100⟩ and ⟨110⟩ directions, in order to obtain information on the electronic stopping power. The main characteristic of these range distributions in tungsten is that, unlike the lower-energy work,[2] they consist of two peaks—one close to the surface and one deep below the surface [see Fig. 1(b), Ref. 1]. The first peak agrees well with the amorphous range; it is attributed to particles that have been scattered out of the incident beam on entering the crystal—i.e., by violent collision with the atomic rows. The second peak possesses a sharp falloff on the more penetrating side, which led us to introduce the concept of a *maximum range* (R_{max}). It was suggested that this deeper peak consists of particles that have maintained a channeled trajectory over most of their path and that R_{max} could be attributed to the most perfectly channeled portion. It was further shown in Paper I that, throughout this energy region, R_{max} approximates very closely an $E^{1/2}$ dependence characteristic of electronic stopping. However, although electronic collisions may dominate the *stopping* of a channeled ion, it can be shown that only the nuclear collisions provide the necessary *steering* action.[3] In this paper we make a detailed study of the channeling mechanism of a heavy ion of 0.1–1.0-MeV energy in tungsten. Measurements have been made along the ⟨100⟩, ⟨111⟩, and ⟨110⟩ directions and in the {110} planes.

In earlier experiments on heavy-ion channeling at low energies,[4] the crystal orientation was not precise enough to provide quantitative information (as was shown in Fig. 4, Ref. 5). With the improved orientation technique now available,[6] we are able to study the channeling process in a more quantitative way. Potassium has been selected for this purpose because, of all the projectiles investigated in Paper I, it exhibits the most pronounced channeling properties. A partial explanation for this fact is that the electronic/nuclear stopping-power ratio for potassium is particularly high compared to other ions (Fig. 5, Paper I), and so the scattering effect (due to nuclear stopping) is less important. However, chromium has a similar electronic stopping power (and Z_1 value), and yet does not show nearly as pronounced a channeled peak as potassium; the reason for this difference in channeling behavior is not understood. In this connection it might also be noted that, of the target crystals used to date, tungsten appears to have by far the best channeling properties, as revealed from range measurements. This may be due partly to its almost oxide-free surface. Moreover, the electronic stopping observed along preferred directions in tungsten is much higher than in the other crystals studied (e.g., it is more than twice the value observed in gold[7]); this must also be a contributing factor.

The most important parameters are the ion energy and the crystal direction. Both these parameters have been varied in the present investigation in order to study their effect on the characteristic features of the double-peaked range distribution; a qualitative discussion of the directional dependence is given. Also, the importance of a surface oxide layer is examined by anodizing the crystal to form different oxide thicknesses.

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[1] L. Eriksson, J. A. Davies, and P. Jespersgaard, previous paper, Phys. Rev. **161**, 219 (1967). Referred to as Paper I.

[2] E. V. Kornelsen, F. Brown, J. A. Davies, B. Domeij, and G. R. Piercy, Phys. Rev. **136**, 849 (1964).

[3] J. Lindhard, Kgl. Danske Videnskab. Selskab, Mat.-Fys. Medd. **34**, No. 14 (1965).

[4] See Refs. 7–12 of Ref. 1.

[5] J. A. Davies, L. Eriksson, and P. Jespersgaard, Nucl. Instr. Methods **38**, 245 (1965).

[6] J. U. Andersen, J. A. Davies, K. O. Nielsen, and S. L. Andersen, Nucl. Instr. Methods **38**, 210 (1965).

[7] F. Brown, G. C. Ball, D. A. Channing, L. M. Howe, J. P. S. Pringle, and J. L. Whitton, Nucl. Instr. Methods **38**, 249 (1965).

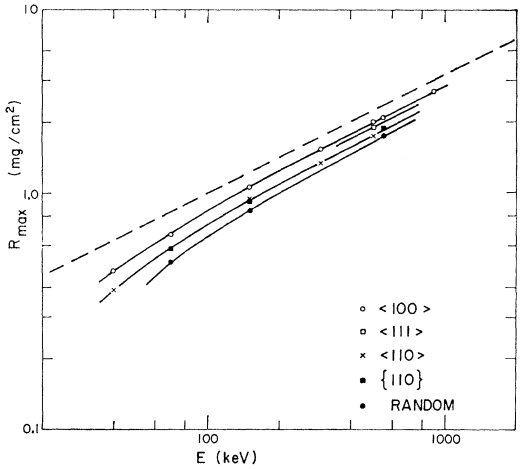

FIG. 1. Energy dependence of R_{max} for K^{42} ions in tungsten single crystals of various orientations. The dotted line depicts an $E^{1/2}$ dependence, characteristic of electronic stopping.

Several recent experiments[6,8–10] have studied the influence of the crystal lattice on the motion of energetic protons and alpha particles. One striking feature in these experiments and in the corresponding theory[3] is the existence of a well-defined critical angle for channeling.[11] In this paper, experimental estimates of the critical angles for channeling of 0.1–1.0-MeV K^{42} ions in tungsten are obtained.

In the earlier work, Kornelsen *et al.* observed a marked decrease in the amount of channeling of 5-keV xenon ions (Fig. 10, Ref. 2), when the tungsten crystal was held at 1200°K during the bombardment. In order to study the temperature effect under more favorable channeling conditions, we have also measured range distributions along the ⟨111⟩ direction with the crystal at 525°K during bombardment.

Finally, in order to investigate the dose dependence of the double-peaked distributions, a few range measurements have been performed in a crystal that had been deliberately prebombarded with one of the stable K isotopes.

EXPERIMENTAL TECHNIQUE

The experimental technique has been fully described in Paper I. All measurements reported in this paper have been performed with the crystals aligned to within a few tenths of a degree with respect to the incident beam; this alignment was achieved by means of the proton wide-angle scattering technique.[6,8]

[8] E. Bøgh and E. Uggerhøj, Nucl. Instr. Methods **38**, 216 (1965).

[9] J. A. Davies, J. Denhartog, and J. L. Whitton, Phys. Rev. (to be published).

[10] B. Domeij, Arkiv Fysik **32**, 179 (1966).

[11] In this paper, channeling is not restricted to what Lindhard (Ref. 3) defines as "proper channeling" (in which the particle has such a small transverse momentum that it cannot overcome the barrier to a nearby channel), but rather is used to include all steered trajectories in which violent collisions are avoided.

RESULTS AND DISCUSSION

A. Dependence on Ion Energy

The maximum range R_{max} is physically the most significant, and experimentally the best-defined parameter in the observed range distributions. As discussed in Paper I, R_{max} is almost exactly proportional to $E^{1/2}$; this $E^{1/2}$ dependence is again illustrated in Fig. 1, using K^{42} ions of 70–900-keV energy. As can be seen, a ⟨100⟩ direction has the greatest maximum range; it was therefore selected for studying the energy dependence of the range distribution.

The observed distributions can be split into three parts: A, B, and C, as defined in Fig. 2(a) [for typical experimental curves see Fig. 1(b), Paper I]. A represents that fraction of the beam undergoing essentially "random" stopping throughout its path, C is the fraction that remains channeled for its entire path (or at least a major part of it), and B is the intermediate fraction that, although initially channeled, gradually becomes scattered into a random direction during the slowing-down process.[12] Amorphous ranges R_{am} for potassium ions were presented in Paper I, Sec. 3; it was noted that, because of scattering effects, the first peak in a single-crystal range distribution does not always coincide with the amorphous range. In the case of potassium, however, R_{am} can be measured rather accurately, and therefore the area A is defined as twice the fractional loss of activity at R_{am}. (These A values will be used in Subsec. D to deduce the critical impact parameter r_{min} for channeling.)

The distinction between areas B and C is less well understood. Presumably, the scattering effects that contribute to B might also contribute to the left slope of the channeled peak. The significance of peak C will be discussed in Subsec. B. It can be seen from Fig. 2(b) that, within experimental errors, the width ΔR at half-height increases linearly with R_{max}: in the ⟨100⟩ direction, $\Delta R = 0.082 + 0.105\ R_{max}$ (mg/cm²).

The most probable range R_{prob} of the channeled peak does not have a simple physical interpretation and so will not be discussed here; the channeled peaks are markedly asymmetric [see Fig. 1(b), Paper I], and their sharp cutoff makes R_{max} more significant than R_{prob}. The energy dependence of R_{prob} for K^{42} ions along the ⟨100⟩ was shown in Fig. 4, Paper I.

We interpret $(B+C)$ as the total fraction of particles starting out with a channeled trajectory. We note [Fig. 2(c)] that B is almost independent of energy, whereas $(B+C)$ increases slowly with energy; consequently, the probability of a particle remaining channeled throughout most of its path must also increase somewhat with energy. This energy dependence, how-

[12] For *light* particles it has been shown that a small part of the incident beam can have a trajectory resulting in an abnormally high energy loss. This component, however, is not observed in our measurements, probably because it is smeared out by multiple scattering effects.

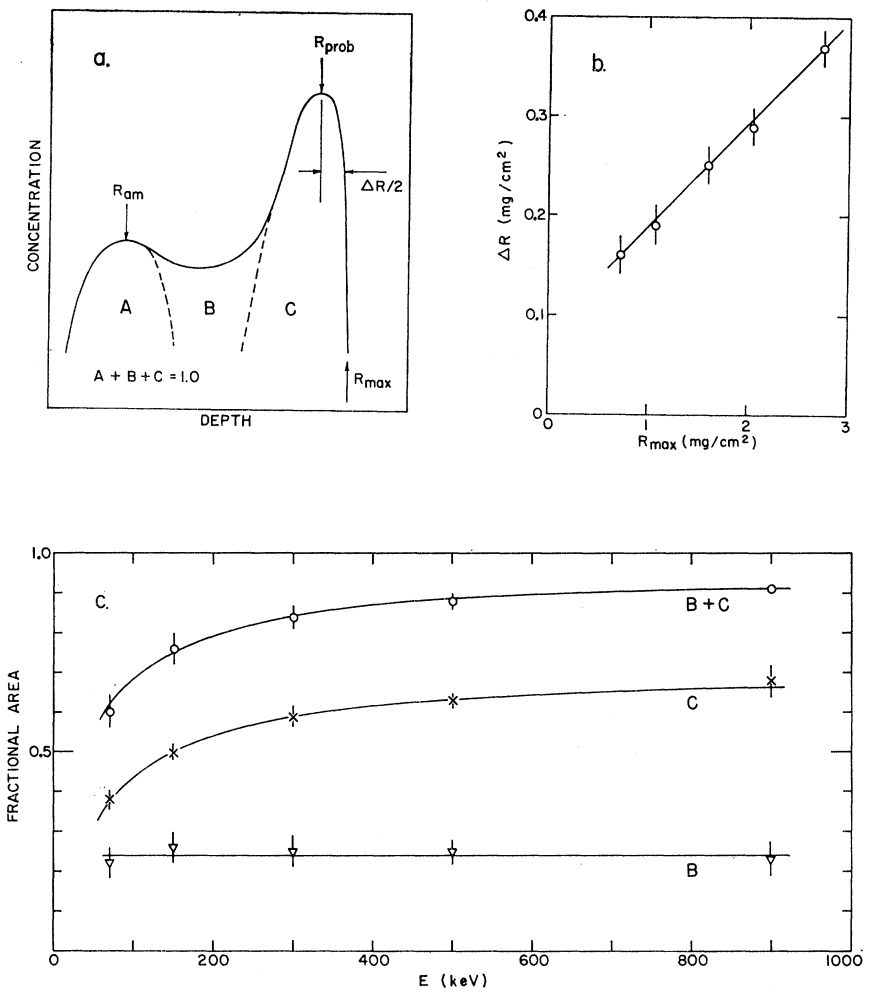

FIG. 2. Energy dependence of the differential distribution of K^{42} ions along the ⟨100⟩ direction in tungsten: (a) characteristic parameters of a channeled distribution; (b) the half-width ΔR of the channeled peak versus R_{max}; (c) the energy dependence of B, C, and $B+C$ [as defined in (a)].

ever, is not very large, except perhaps at the lowest energies.

B. Dependence on Crystal Direction

Maximum ranges versus energy have been measured for the ⟨100⟩ and ⟨110⟩ directions and for the {110} planes. As shown in Fig. 1, the curves are essentially parallel in a log-log plot with a slope close to 0.5, indicating the predominance of electronic stopping in the slowing down of a channeled ion (as discussed in Paper I). The maximum ranges at 500 keV are given in Table I, together with a value for the ⟨111⟩ direction. A qualitative comparison between these values, based on estimated mean electron densities along the channels, will be given later in this section.

The range distribution in the {110} plane was measured at 70, 150, and 550 keV. In each case the crystal was deliberately oriented (by means of the Rutherford scattering technique) to a random orientation within the {110} plane, i.e., one that did not coincide with any minor axis. Typically, the crystal was tilted 5°–10° away from the closest main axis, ⟨100⟩ or ⟨111⟩. For comparison, the range distribution was also measured with the crystal tilted the same amount to a random direction. Figure 3 compares the results at 550 keV. The distribution in the ⟨100⟩ direction is also included.

The maximum range in the most close-packed plane (i.e., the {110}) is very nearly the same as in the ⟨110⟩ direction, but is significantly shorter than in the most close-packed ⟨100⟩ and ⟨111⟩ directions (Fig. 1). About 12% of the beam remains channeled within the plane at 550 keV. It is not possible to attribute such a high fraction to scattering into a preferred axis; hence, we are observing a true planar channeling. It should be noted that, even in the random case, roughly 1% of the particles become channeled. This is probably due to scattering into one or more of the major *planes*, as the probability of being scattered 5°–10° into the acceptance cone of a main axis is much too small to account for the observed effect.

It can be seen from Fig. 3 that the probability of a particle being scattered out of a channeled trajectory is much higher in the planar case than along the ⟨100⟩ direction. At 500 keV the probability of remaining

TABLE I. Channeling properties for 500-keV K^{42} ions in tungsten, lattice spacing $l=3.16$ Å.

Crystal direction	⟨100⟩	⟨111⟩	⟨110⟩	{110}
R_{max} (mg/cm²)	2.02	1.91	1.75	1.77
Percentage C of particles in channeled peak	63%	75%	8%	11%
Half-width ΔR (mg/cm²) of channeled peak	0.29±0.02	0.14±0.01	...	...
Probability $B/(B+C)$ of dechanneling	0.27±0.04	0.17±0.03	0.90±0.05	0.78±0.04
Atomic spacing (d) along the surrounding rows	l	$\sqrt{3}l/2$	$\sqrt{2}l$	...
Distance from surrounding rows to channel axis	$l/2$	$\sqrt{2}l/3$	$\sqrt{3}l/4$	...
Number of surrounding rows	4	3	4	...
Relative mean electron density along midchannel[a]	1.00	1.10	1.26	1.57

[a] Reference 14.

channeled beyond 80% of R_{max} is only 0.092±0.008 in the {110} plane; the corresponding number for the ⟨100⟩ axis is 0.60±0.04. A similar difference between planar and axial channeling has been observed for 10–30 MeV C, O, and Cl ions in tungsten crystals,[9] and also for lighter particles at MeV energies (see Fig. 8, Ref. 6).

Piercy *et al.*[13] found no evidence of a planar effect for 40-keV Kr^{85} in the {111} plane of an aluminum crystal. This, perhaps, is not too surprising; their crystal alignment was certainly no better than ±1°, and even along the main ⟨110⟩ axis they observed that the fraction of particles penetrating beyond 80% of R_{max} was less than 0.005. In our experiments, planar channeling is clearly detectable down to the lowest energy studied, viz. 70 keV. The planar effect has also been observed with P^{32} ions—a projectile that in comparison to K^{42} has fairly poor channeling properties.

We will now consider how the characteristic parameters of a channel affect the range distribution.

Table I compares the experimental values of the maximum range R_{max}, the percentage of particles in the channeled peak, the half-width of the channeled peak, and the probability of dechanneling for 500-keV K^{42} ions in the various main axes and in the {110} plane. The table also gives, in terms of the lattice spacing l, the spacing of the atoms in the atomic rows surrounding the channel and the distance from the atomic rows to

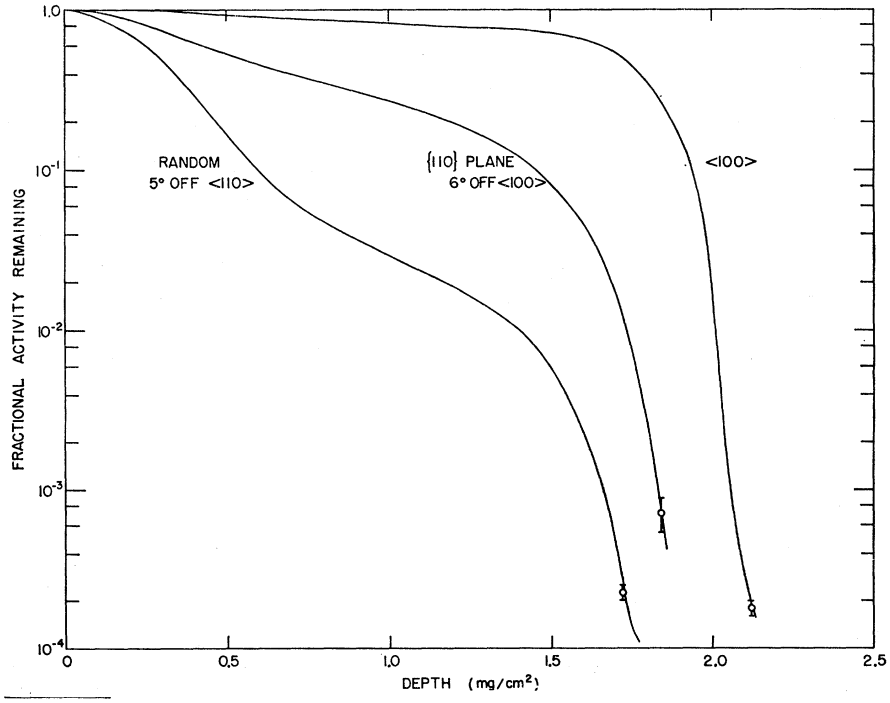

FIG. 3. The integral range distribution of 550-keV K^{42} ions along the {110} plane in tungsten. Distributions along the ⟨100⟩ direction and along a typical random direction are included for comparison.

[13] G. R. Piercy, M. McCargo, F. Brown, and J. A. Davies, Can. J. Phys. **42**, 1116 (1964).

the midchannel axis, the number of rows constituting the channel and, in relative units, the estimated mean electron density along the midchannel. Electron densities have been calculated[14] by means of Lindhard's standard potential.[3]

The oscillating Z_1 dependence in Fig. 7, Paper I, clearly demonstrates that R_{max} does *not* bear a simple quantitative relationship to the mean electron density $\bar{\rho}$ along the midchannel, and also that the difference in R_{max} between various directions is unusually small for potassium ions. Nevertheless, Table I shows that the R_{max} values decrease as $\bar{\rho}$ increases.

Particles can be prevented from remaining channeled by several mechanisms. We have already noted that if a particle enters the crystal within a certain critical impact parameter r_{min} of a close-packed row (or plane), it will immediately be removed from the aligned beam. The fraction of particles [A in Fig. 2(a)] scattered in this way will thus be given by $N\times d\times\pi r_{min}^2$, where N is the number of tungsten atoms per unit volume and d is the atomic spacing along the particular close-packed row. Within experimental error, the proportionality to d is fulfilled for the crystal axes investigated, yielding a value of $r_{min}\sim 0.45$ Å at 500 keV.

Region A in Fig. 2(a) may also contain a few particles that were initially channeled but have then been rapidly scattered out of the aligned beam. This contribution, of course, cannot be measured, but the relative areas of A and B indicate that no more than 3–4% are involved, hence the r_{min} value given above is at most about 15% too high. The critical impact parameter will be discussed in more detail in Subsec. D.

As a measure of the steering, or rather the lack of steering, we consider the probability $B/(B+C)$ of a channeled particle being scattered out of the aligned beam (i.e., becoming dechanneled) during its slowing down. These values are also included in Table I; within experimental error, we observe a linear dependence on d. As several different scattering processes are involved, and as the effects are cumulative over the whole slowing-down process, a quantitative discussion will not be attempted. It is interesting to note, however, that the predicted effect of thermal vibrations would also vary linearly with d.[3] Our experiments suggest that, for directions with an interatomic spacing $\gtrsim 1.5l$, the probability of a particle remaining channeled throughout most of its path is essentially zero. It is shown in subsequent sections that the rate of dechanneling is very sensitive to increased temperature, damage, misalignment, and surface contamination, as one might expect. In this connection, we may note that the difference in channeling behavior between tungsten and gold (as suggested in Paper I, Sec. 1.D) is due not only to a big difference in the *rate* of dechanneling, but also to a difference in the path lengths (i.e., the R_{max} values) over which dechanneling can occur.

[14] H. E. Schiøtt (private communication).

The integral range curves in the ⟨100⟩ and the ⟨111⟩ directions intersect twice—around the 0.3 and the 10^{-3} levels.[15] The first of these intersections is the more significant one, and arises from the fact that, although the number of channeled particles is higher in the ⟨111⟩ direction, their maximum range (due to the increased electron density) is somewhat smaller than in the ⟨100⟩ direction. The other intersection at the 10^{-3} level supports the conclusion (see Sec. 4, Paper I) that the level of the so-called supertail is proportional to the number of channeled particles approaching R_{max} and therefore should be higher in the ⟨111⟩ direction. Another intersection (around the 0.7 level) had been observed in *some* of the previous runs,[2] but is not significant in the present work. It was probably an artifact arising from the less precise orientation available at that time.

The shape of the channeled peak, especially in the ⟨111⟩ direction, agrees qualitatively with simplified considerations based on Lindhard's "string theory."[3] In this picture, the width of the peak arises mainly from the fact that the channeled particles do not all enter the crystal exactly at the center of the channel, and hence acquire some transverse kinetic energy. Such particles encounter a somewhat larger average electron density, and hence a slightly larger stopping power than the perfectly channeled ones. Scattering effects also may contribute significantly to the observed width on the slope closer to the surface: For example, a potassium ion injected at 500 keV in the ⟨100⟩ direction could be scattered out of the channel after slowing down to ~100 keV, and yet would still end up within the observed channeled peak.

It can be shown that, for perfectly channeled particles (i.e., those moving exactly along the midchannel axis), neither the electronic straggling nor the nuclear straggling (see Sec. 2, Paper I) is large enough to produce a relative peak width greater than 1%. Since the observed width even for the ⟨111⟩ distribution is at least 8%, it is evident that the straggling contribution from the perfectly channeled particles is negligible.

C. Surface Oxide Effect

Figure 4 shows integral-range curves for 500-keV K^{42} ions in the ⟨100⟩ direction, obtained with progressively thicker anodic oxide films on the surface. The curve at 0 V is a reference curve with a "clean" surface (i.e., $\lesssim$10 Å of oxide). Curves at 10 and 20 V correspond, respectively, to about 100 and 200 Å of amorphous WO_3. The effect of the surface oxide layer is appreciable, but is not as drastic as at lower energies (see Fig. 12, Ref. 2). The 100 and 200 Å layers transmit 99.2 and 97.7% of the total beam; however, the total number of channeled particles $(B+C)$ in the underlying W decreases from 88% for the reference curve to 58 and 30%, respectively, in the oxidized crystals. At the same

[15] See Ref. 1, Fig. 1(a) and Ref. 2, Figs. 3 and 4.

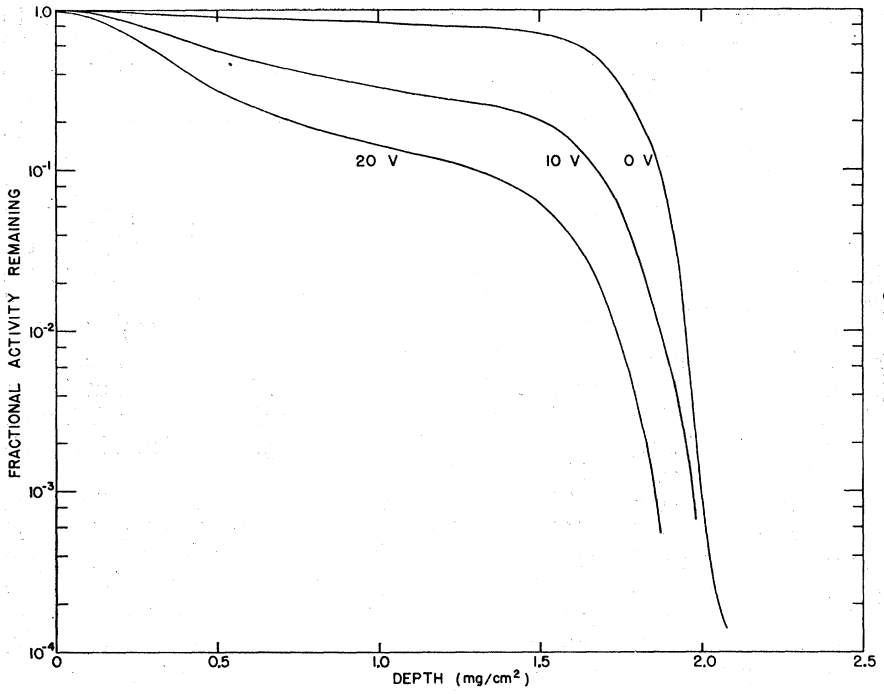

FIG. 4. The influence of a surface oxide layer on the integral distribution of 500-keV K^{42} ions along the ⟨100⟩ direction in tungsten. Anodizing voltage: 0, 10, and 20 V. (Note the resulting oxide layer has a thickness of ~10 Å per V.)

time, the number of particles C in the channeled peak is reduced from 63 to 23 and ~8%, respectively. These experiments show that, even after traversing roughly 60 molecular layers of WO_3, a significant fraction of the beam is still within the acceptance cone for channeling.

In Fig. 4, no correction has been made for the energy loss in the surface oxide layer. The observed small decrease in R_{max} corresponds, almost exactly, to the value predicted for the energy loss in traversing the amorphous oxide layer, thereby confirming that, although the range distribution is markedly perturbed by surface contamination, the maximum range is virtually unaffected.

At these higher energies, it is evident that normal vacuum conditions (in which the surface oxide layer is roughly 10 Å thick) should be sufficient for most purposes.

D. The Critical Angle for Channeling

It is not obvious how a critical angle should be deduced from our experimental results (see Refs. 6, 8–10). However, a rough estimate of this quantity for a heavy ion in the energy range 0.1–1.0 MeV is of considerable interest, not only for comparison with theoretical predictions,[3] but also to give information on the degree of alignment necessary in order to study directional effects with low-energy heavy-ion beams.

One way of estimating the critical angle is to use the information given in Fig. 2. We have identified the fraction of particles in region A as the fraction being scattered from the aligned beam on entering the crystal, and therefore undergoing random stopping. As was discussed in Subsec. B, this enables the minimum impact parameter r_{min} for channeling to be obtained. The results for the ⟨100⟩ direction are shown in Fig. 5(a). For protons and other light ions, the distance of closest approach is typically of the order of the Thomas–Fermi screening distance (~0.1 Å in W), but for the slower heavy ions used here, the r_{min} values are considerably larger.

The scattering angle ψ, corresponding to an impact parameter r_{min}, can be estimated most conveniently through the equation $E\psi^2 = U(r_{min})$, using Lindhard's continuum potential $U(r)$.[3] Figure 5(b) gives ψ as a function of energy, together with the critical angle ψ_2 predicted by Lindhard.[3] The experimental errors shown in Fig. 5(a) do not include any correction for those particles that, although initially channeled, are rapidly scattered out of the aligned beam and are stopped within region A. As noted in Subsec. B, this might cause at most a 15% decrease in the values of r_{min}; the corresponding increase in ψ would be less than 4%. Values of ψ and ψ_2 for the ⟨111⟩ direction at 500 keV have also been included in Fig. 5(b).

An independent method of estimating the critical angle is to investigate the amount of multiple scattering required to reduce the total number of channeling particles $(B+C)$ by a factor of 2. The anodic oxide measurements in Subsec. C form a basis for such an analysis; they indicate that at 500 keV about 140 Å of amorphous WO_3 is required. Assuming that the multiple scattering introduced by the surface oxide layer is almost entirely due to the tungsten atoms, and

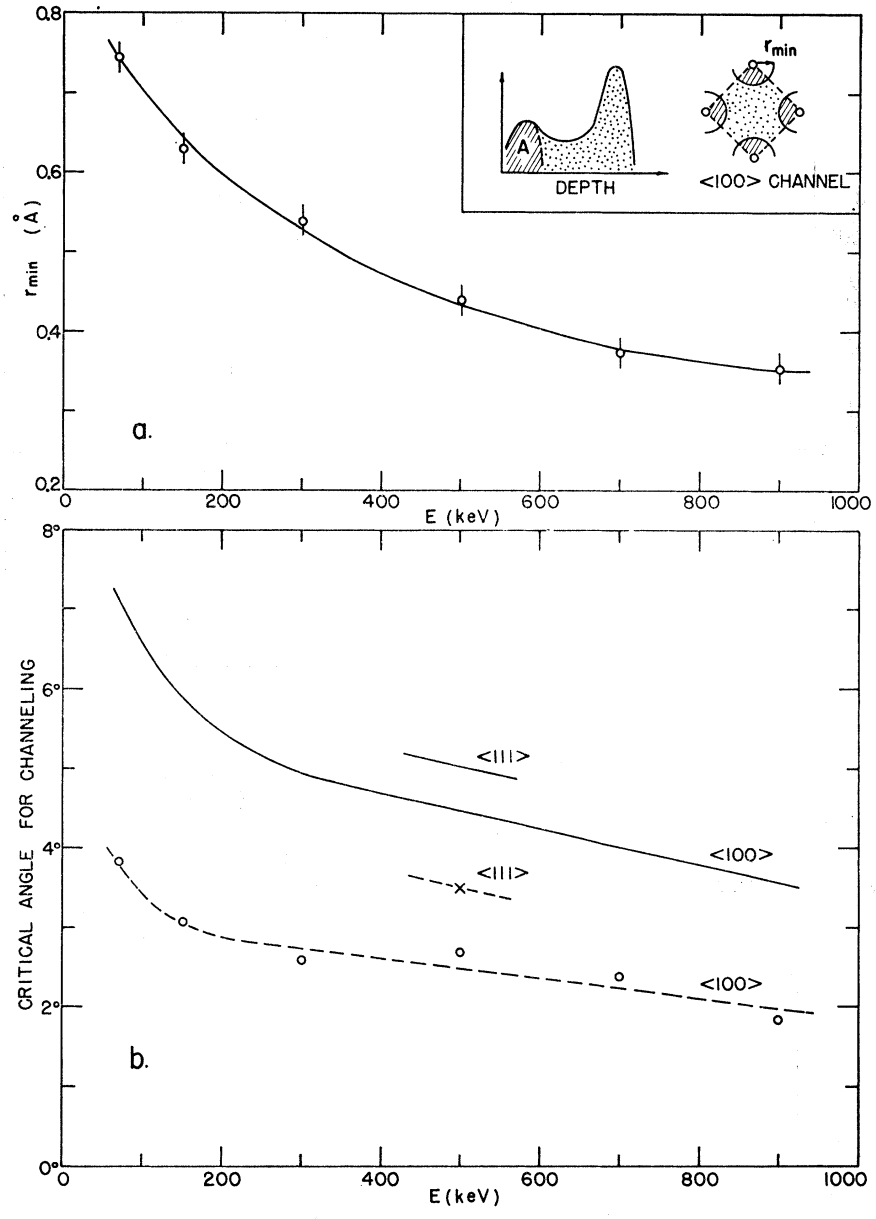

FIG. 5. (a) Experimentally derived values of r_{min} versus energy for K^{42} ions incident along the ⟨100⟩ direction in tungsten. r_{min} is obtained by equating the area of the shaded circular regions on the insert to the measured values of A. (b) The energy dependence of the critical angle ψ: O, experimental values derived from the condition $E\psi^2=U(r_{min})$. $U(r)$ is the continuum potential according to Lindhard. The solid line depicts the critical angle ψ_2 predicted by Lindhard (Ref. 3) for the ⟨100⟩ direction. At 500 keV, values are also given for the ⟨111⟩ direction.

applying an r^{-2} potential[16] to estimate the angular width of the Gaussian distribution, we obtain a multiple scattering angle of $4°\pm0.5°$. This also agrees reasonably well with the experimental and theoretical results given in Fig. 5(b).

The most direct way to obtain the critical angle is to measure a series of range distributions with the crystal tilted at different angles, but this would be an extremely time-consuming experimental procedure. A few such experiments at 500 keV indicate a critical angle of 2°–2.5° for reducing the number $(B+C)$ of channeled particles by a factor of 2.

[16] J. Lindhard, M. Scharff, and H. E. Schiøtt, Kgl. Danske Videnskab. Selskab, Mat.-Fys. Medd. **33**, No. 14 (1963).

In summary, we find that at 500 keV the critical angle for channeling along the ⟨100⟩ direction is of the order of $3°\pm1°$, and that, over the energy region studied, this critical angle decreases only slowly with increasing energy. Both the magnitude of ψ and its weak energy dependence agree roughly with theoretical predictions.

E. Dependence on Increased Temperature

Figure 6 shows the effect of increased temperature on the differential range distribution of 500-keV K^{42} ions in the ⟨111⟩ direction. The number of particles C in the channeled peak at 525°K is about a factor of 2 less than that at room temperature—due, presumably,

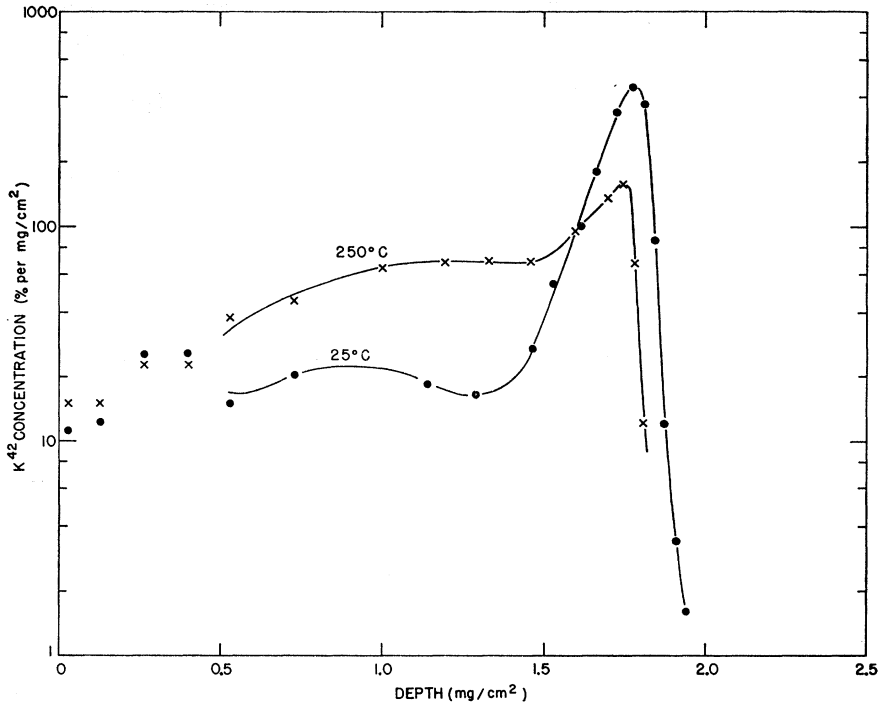

FIG. 6. The influence of target temperature on the range distribution of 500-keV K^{42} ions along the ⟨111⟩ direction in tungsten.

to the increased scattering arising from the larger vibrational amplitude (the root-mean-square displacement is increased from 0.085 Å to about 0.115 Å[17]). As one might expect, there is no significant change in the fraction of particles in the random peak. Figure 6 also shows that R_{max} decreases by less than 3%, which is just about the accuracy of the experimental method. This negligible temperature effect on R_{max} is not surprising, since, as shown in Paper I, electronic stopping is the dominant mechanism of energy loss for perfectly

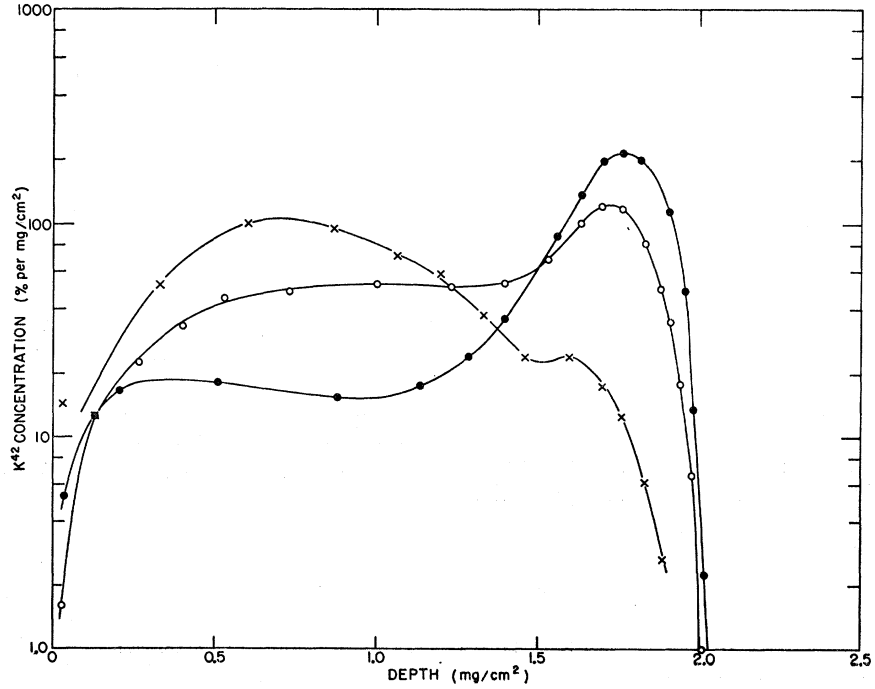

FIG. 7. The influence of prebombardment with 500-keV K^{41} ions along the ⟨100⟩ direction on the distribution of 500-keV K^{42} ions along the same direction. ○ shows the distribution for a K^{41} dose of 3×10^{15} ions/cm² and × shows the distribution for a total K^{41} dose of 3×10^{16} ions/cm². In the final case tracer (T) and stable (S) ions were injected as follows: $STSTSTS$. ● is a reference curve for trace bombardment alone.

[17] K. Lonsdale, Acta Cryst. **1**, 142 (1948).

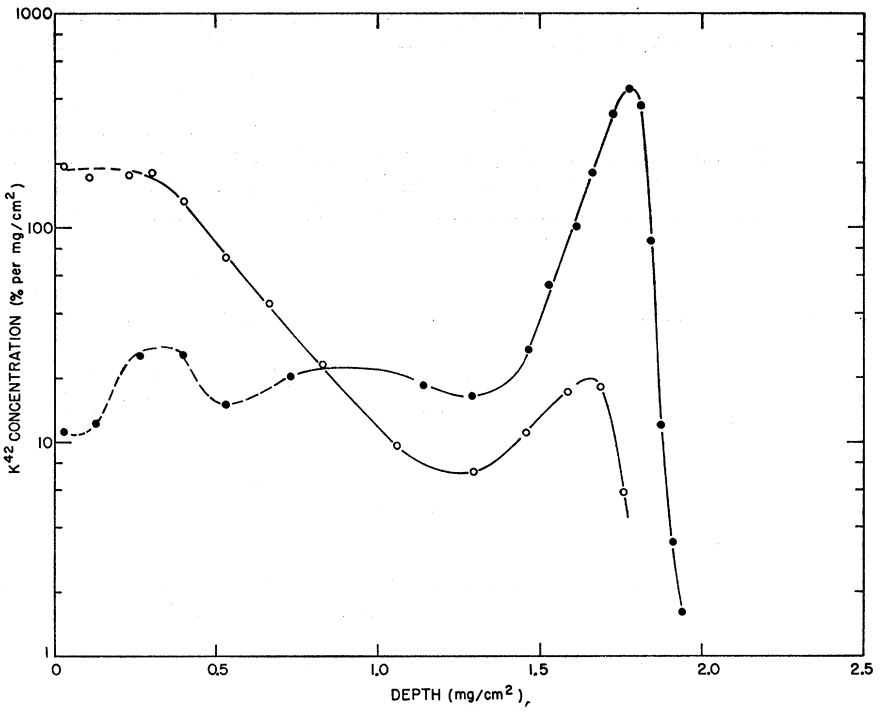

FIG. 8. The influence of a "saturation" prebombardment on the distribution of 500-keV K^{42} ions along the ⟨111⟩ direction in tungsten. About 10^{18} K^{39} ions/cm^2 were preinjected in a random direction at 150 keV (○). As a reference, the distribution for a trace bombardment (●) is also shown.

channeled particles in W. In order to establish the temperature independence of R_{max}, measurements over a wider temperature range would be desirable. Unfortunately, suitable cryogenic apparatus was not available; hence, *low*-temperature bombardments with precise orientation could not be made.

F. Dependence on Bombardment Dose

One of the most interesting aspects of these range measurements is the possibility of introducing, at a well-defined depth (0.1–3 μ) beneath the surface, a sharp distribution of foreign atoms. This feature offers interesting applications in various solid-state studies. Therefore, in order to investigate the bombardment dose at which the channeled peak starts to disappear, one of the stable isotopes (K^{41}) was injected at 500 keV in the ⟨100⟩ direction, followed by a trace bombardment of K^{42} ions at the same energy and alignment. The result is shown in Fig. 7. It is evident that, at doses up to at least 3×10^{15} atoms/cm^2, the distribution has not been drastically affected. There is still a clearly defined channeled peak containing about 40% of the injected potassium ions, and therefore corresponding to a potassium concentration of roughly 0.1 at.%.

Also shown in Fig. 7 is the distribution with a tenfold increase in dose. This bombardment was carried out in the sequence *STSTSTS*, where *S* stands for the K^{41} isotope and *T* for the radioactive tracer K^{42}. We observe that the distribution has now changed markedly. The original channeled peak contains only about 4% of the injected activity; and presumably most of this arises from the first trace bombardment stage. Hence, after a dose of $\sim10^{16}$ atoms/cm^2, only a very small fraction of the beam can still penetrate to the R_{max} region. Note, however, that the range distribution is still dominated by channeling effects, and that the most probable range of the broad peak is at least twice the amorphous range.

Figure 7 shows that R_{max} is almost independent of the prebombardment. In fact, considering the very heavy stable doses used here, the effect on the range distributions is surprisingly small.

Figure 8 shows the result of a very intense prebombardment ($\sim10^{18}$ atoms/cm^2). In this case, K^{39} ions were injected at lower energy (150 keV) and in a random direction. The K^{42} ions were then introduced at 500 keV in an aligned ⟨111⟩ direction. The region affected by this prebombardment is of the order of 1000 Å, and the dose is sufficiently high to attain a "saturation" distribution of the K^{39} atoms. It is therefore not surprising to find that the range distribution is altered drastically. However, comparison with the differentiated version of Fig. 4 shows that roughly 200 Å of amorphous tungsten oxide (or 100 Å of amorphous tungsten) is enough to produce about the same effect. This would indicate that the bombarded region is still a reasonably good crystal, and that therefore most of the radiation damage has annealed out at room temperature; it would also suggest that most of the injected K^{39} atoms are *not* occupying interstitial sites as was also concluded in the earlier work by Kornelsen *et al.*[2] Furthermore, if we correct for the increased stopping power

of the damaged surface region, we again find that R_{max} is almost unaffected by the prebombardment.

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Channeling in Diamond-Type and Zinc-Blende Lattices: Comparative Effects in Channeling of Protons and Deuterons in Ge, GaAs, and Si†

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The energy losses of ions channeled through GaAs, Ge, and Si were compared. The average number of electrons per atom participating in the stopping of channeled particles is about the same for elemental Ge and partially ionic GaAs. The number of electrons per atom participating in the stopping of channeled hydrogen ions is less for Si than for Ge or GaAs. Axial and planar channeling are discussed. The energy losses of axial channeling appear to be characterized by the energy losses of the plane having the largest interplanar spacing in the axial intersection. A much larger fraction of the incident beam undergoes channeling when the beam is incident along an axial intersection than when the beam is along a plane of the intersection. Comparison of energy losses of H^+ and D^+ shows that the mass dependencies of the minimum energy losses in channeling can be correlated simply with a velocity-dependent function. Velocity is, therefore, the important parameter in the slowing down of channeled ions within a given host lattice. The analyses of the data give evidence that an equation of the same form as the Bethe equation accounts for the minimum energy losses of channeled particles.

INTRODUCTION

THIS paper describes a study of energy losses of protons and deuterons channeled by single-crystal Ge, GaAs, and Si, and shows the importance of directional effects on the interaction of incident charged particles with solids. Until recently, theories of energy loss, while adequate for amorphous solids, did not account for the orientation dependence of charged-particle interactions with crystalline solids. These directional effects of crystal lattices on charged particles are proving to be a useful tool for probing crystalline solids. Applications of these phenomena and techniques are already being extended to semiconductor devices such as solid-state detectors, solar cells, and ion implantation. An earlier paper reported our initial observations of channeling in Ge.[1] A preliminary account of the comparison of the energy losses of channeling for Ge, GaAs, and Si has already been given.[2]

The term channeling has been applied to the anomalous penetration of energetic charged particles along low-order crystal axes and planes. Channeling was predicted in computer calculations of ion ranges by Robinson and Oen[3] just before this anomalous behavior was discovered experimentally by Davies and his group.[4] Although the work was initially confined to low energies, below 100 keV, a similar behavior was discovered when the experiments were first extended to MeV energies by Dearnaley.[5] More recently, comprehensive theories of channeling by Brice,[6] Lindhard,[7] and Erginsoy[8–11] discuss mechanisms of channeling in some detail. A partial list of references for some earlier work on channeling is found in Ref. 1.

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[1] A. R. Sattler and G. Dearnaley, Phys. Rev. Letters **15**, 59 (1965).
[2] A. R. Sattler, Bull. Am. Phys. Soc. **11**, 230 (1966).
[3] M. T. Robinson and C. S. Oen, Phys. Rev. **132**, 2335 (1963).
[4] G. R. Piercy, F. Brown, J. A. Davies, and M. McCargo, Phys. Rev. Letters **10**, 399 (1963).
[5] G. Dearnaley, IEEE Trans. Nucl. Sci. **NS11**, 249 (1964).
[6] D. K. Brice, Phys. Rev. (to be published); D. K. Brice and A. R. Sattler, Bull. Am. Phys. Soc. **11**, 177 (1966).
[7] J. Lindhard, Kgl. Danske Videnskab. Selskab, Mat.-Fys. Medd. **34**, No. 14 (1965).
[8] C. Erginsoy, Phys. Rev. Letters **15**, 360 (1965).
[9] C. Erginsoy, B. R. Appleton, and W. M. Gibson, Bull. Am. Phys. Soc. **11**, 176 (1966).
[10] H. A. Fowler and C. Erginsoy, Phys. Letters **24A**, 390 (1967).
[11] C. Erginsoy, Bull. Am. Phys. Soc. **12**, 80 (1966).