RANGE PROFILES OF LOW ENERGY (100 TO 1500 eV) IMPLANTED ^3He
AND ^4He IN TUNGSTEN; ^{34}II 21 ANALYSIS AND DISCUSSION

by

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August 1980

Report #4108

Issued by

The Materials Science Center

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Prepared for

THE U.S. DEPARTMENT OF ENERGY UNDER CONTRACT

No. DE-AC02-76ER03158.

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RANGE PROFILES OF LOW-ENERGY (100 to 1500 eV) IMPLANTED ^3He and ^4He
ATOMS IN TUNGSTEN: II. ANALYSIS AND DISCUSSION[†]

by

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ABSTRACT

The identifiable sources of possible systematic error in the measurement of the mean range ($\bar{x}$) and the straggling (Δx) of the ^3He and ^4He range profiles, reported on in the previous paper (Amano, Wagner and Seidman 1980: Part I) were modeled mathematically and the resulting expressions numerically evaluated. The evaluations showed that these possible sources of systematic error were not of significant magnitude to affect the range parameters $\bar{x}$ and Δx . The role of the transfer of energy, either indirectly or directly, from the incoming beam of helium ions to those helium atoms that had already been implanted was also considered as a possible source of systematic error. It was shown that there was a possibility of radiation-induced diffusion or the simple displacement of helium atoms--as a result of helium-helium collisions--at an implantation energy of 100 eV and a dose of $4 \times 10^{15} \text{ cm}^{-2}$; however, the magnitude of this effect was probably not large enough to have had a major effect on the detailed shape of the profiles. It was also demonstrated--employing a simple Monte Carlo simulation procedure--that for the sample sizes we employed in our experimental work (Part I) the integral profiles were characterized with a reasonable degree of statistical significance. The experimental results presented in Part I were compared with the calculated results of Biersack's and Haggmark's TRIM simulation program; this program was based on a Monte Carlo simulation procedure for an amorphous solid. There was qualitative agreement between the experimental and calculated values of the range parameters but not quantitative. In general, the experimental values of the dimensionless range parameters--for both ^3He and ^4He --were greater than the calculated values. The possible sources of this discrepancy were attributed to: (1) the use of the Molière interatomic potential in the TRIM program; and (2) possible low energy channeling effects along the [110] direction of tungsten. Simple expressions were given for the experimental range-energy data and the effective stopping powers of both ^3He and ^4He in tungsten in the energy range 100 to 1500 eV.

[†] This research was supported by the U.S. Department of Energy. Additional support was received from the National Science Foundation through the use of the technical facilities of the Materials Science Center at Cornell University.

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§1. INTRODUCTION

This paper is the second one in a two part series on the range profiles of low-energy (100 to 1500 eV) ^3He and ^4He atoms implanted in tungsten and chemically analyzed in situ at a constant temperature of 60 K. The previous paper (Amano, Wagner and Seidman 1980:Part I) described the experimental approach--that employed the atom-probe field-ion microscope (FIM) technique--and presented the experimental results in detail.

This paper considers two main themes. The first theme centers around the problem of sources of possible systematic errors in the measurement of the mean range ($\bar{x}$) and the straggling (Δx) values reported on in Part I. We considered this problem in some detail because of the unique experimental conditions under which the range profiles were determined. Four sources of error were identified and discussed in §2. In addition, the effect of sample size on the shape of the range profile was analyzed.

The second theme focused on a detailed comparison of the measured range parameters with values of the range parameter calculated employing Biersack's and Haggmark's (1979) Monte Carlo simulation program called TRIM (TRansport of Ions in Matter)--see §3. First, the general theoretical background for the problem of low-energy light ions implanted in a heavy target material, such as tungsten, was reviewed (see §3.1). Then in §3.2 we considered the application of the TRIM program to the case of 100-1500 eV ^3He and ^4He implanted in tungsten. In §3.3(a) the experimental results of Part I were compared with the results of the TRIM simulation program. Finally in §3.3(b) the major sources of the discrepancies between the experimental and TRIM results were discussed.

§2. DISCUSSION OF EXPERIMENTAL UNCERTAINTIES

There were four identifiable sources of possible systematic errors in the measurement of the mean range ($\bar{x}$) and the straggling (Δx) reported on in Part I. The first source was due to the hemispherical geometry of the FIM specimen. This geometry caused the measured values $\bar{x}$ and Δx to be greater than the values which would have been obtained for measurements that had employed a planar surface. The

physical reason for this was that the hemispherical envelope of the FIM specimen caused the surface to consist of a series of circular stepped-terraces (see fig. 1 and Moore 1962) rather than a single flat plane. The second source was caused by the random arrival of helium atoms from the background gas during the course of a profiling experiment. The first two systematic errors were discussed in §§2.1 and 2.2 (the detailed arguments were presented in Appendices A and B) and it was shown that neither of them significantly affected $\bar{x}$ or Δx . The third source was due to the transfer of energy, either directly or indirectly, from the incoming beam of helium ions to those helium atoms that had already been implanted; this source was discussed in §2.3 and Appendix C. The fourth source of systematic error was caused by the sputtering of the (110) tungsten surface by the helium ion beam. A simple calculation[†] showed that at 1500 eV a dose of 3×10^{15} ions cm^{-2} only sputtered a maximum of ~ 0.07 of a (110) plane. This was a negligible effect and hence it was not discussed any further. Finally, in §2.4 we discussed the effect of the finite number of helium atoms detected on the detailed shape of the integral profiles we presented in the previous paper.

2.1. Effect of the geometry of the FIM specimen on $\bar{x}$ and Δx .

The transverse straggling (Δy and Δz) is the standard deviation of a range profile in the directions perpendicular to the incident ion direction. For low-energy helium ions incident on a heavy target--such as tungsten-- Δy and Δz were expected to be greater than or equal to Δx (Ocn and Robinson 1976 a, Biersack and Haggmark 1979)^{††}. Because of the transverse straggling low-energy helium ions--incident on the (110) terraces adjacent to the central (110) plane of the tungsten specimen--were deposited within the cylindrical volume element analyzed by the atom probe technique. This effect is illustrated schematically in fig. 1 where a helium ion

[†] The sputtering data of Wehner (1962) was extrapolated linearly from 600 to 1500 eV to obtain a value of 0.036 for the sputtering yield (corrected for secondary electrons).

^{††} For 300 eV $^4\text{He}^+$ ions on tungsten the calculated TRIM value for Δx was 22 Å and $\Delta y = \Delta z = 35$ Å. The calculated shapes of the transverse range profiles were almost exactly normal.

incident on terrace 1 is seen to come to rest within the analyzed volume element, at a depth greater than it would have been deposited if it had been incident on the zeroth terrace.

The details of the model employed to estimate the magnitude of the error in $\bar{x}$ and Δx , due to the non-planar geometry of the FIM specimen, were described in Appendix A. The expression obtained for the difference between the measured ($\bar{x}$) and the actual ($\bar{x}_a$) ranges of the helium atoms implanted in the specimen was

$$\bar{x} - \bar{x}_a = \frac{nd_{110}}{2} \frac{[2R_t - (\frac{4n+5}{3})d_{110}]}{[2R_t - (n+1)d_{110}]}, \quad (A8)$$

where d_{110} is the interplanar spacing for the (110) planes, R_t the radius of the FIM specimen in the region of the (110) pole and n the number of terraces which contributed helium atoms to the measured profile. The value of R_t was always much greater than d_{110} , therefore for small n eqn. (A8) reduced to

$$\bar{x} - \bar{x}_a \approx \frac{n}{2} d_{110}. \quad (A9)$$

Tables 1 and 2 list the values of Δx , r_a , R_t , $n_{\max}$ and $\bar{x} - \bar{x}_a$ for all the ^3He and ^4He implantations reported on in Part I. Note that $\bar{x}$ exceeded $\bar{x}_a$ by at most 5% due to the terraced character of the FIM surface. Therefore, the actual standard deviation (Δx_a) of the range profile was essentially equal to Δx because of the very small difference between $\bar{x}$ and $\bar{x}_a$.

2.2. Effect of the random arrival of helium gas atoms

from the background gas

A second source of systematic error in the measurement of $\bar{x}$ and Δx was due to the random arrival of helium gas atoms at the surface of the specimen from the background gas, during the profiling procedure. In Appendix B it was shown that the error in $\bar{x}$ due to this effect is given by the equation

$$|\bar{x} - \bar{x}_a| = \frac{\xi}{(1-\xi)} |\bar{x}_c - \bar{x}|, \quad (B3)$$

where $\bar{x}_c$ is the measured mean depth of the helium atoms detected in a control run, ξ is equal to C/N , N is the total number of helium atoms detected in an irradiated specimen and C is the number of helium atoms detected in a control run. Thus ξ is a measure of the statistical noise in our measurements. In Part I we stated that under our experimental conditions a generous upper limit to ξ was 0.05.[†] Therefore eqn. (B3) reduced to

$$|\bar{x} - \bar{x}_a| = 0.053 |\bar{x}_c - \bar{x}|. \quad (1)$$

The value of $\bar{x}_c$ was governed by the inequality

$$0 < \bar{x}_c < \bar{x}. \quad (2)$$

This was due to the fact that at the start of a profiling experiment there was always a larger number of random background helium events reaching the surface of the specimen per unit time than at later times. The physical reason for this was that the background partial pressure of helium continuously decreased with increasing time during the course of a profiling experiment. Equations (1) and (2) implied that, in general, $\bar{x}$ was equal to $\bar{x}_a$ and therefore essentially no systematic error was introduced by this effect. Thus it was concluded there was no correction to Δx for this effect.

2.3. Direct or indirect transfer of energy to the implanted helium from the ion beam

The incident ion beam can transfer energy to the already implanted helium as a result of either direct or indirect processes. A direct energy transfer requires a helium-helium scattering event, while an indirect energy transfer involves the transfer of energy from a tungsten atom that has recoiled from a helium-tungsten collision. Both of these energy transfer processes may lead to a redistribution of the already implanted helium, as a result of a series of displacement events, and hence they may change the shape of a range profile. The process of radiation-induced

[†] In several control runs there were no helium atoms detected. This implied that ξ was zero for these experiments and that $\bar{x}$ equaled $\bar{x}_a$.

(simulated) diffusion can also lead to a change in the shape of the range profile of the implanted helium--this process involves a reduction in the energy required for a helium atom to migrate (Nelson 1964, Urban 1972, Urban and Seeger 1974).[†] The direct or indirect energy transfers discussed above, may have provided enough energy to reduce the migration energy of a helium atom. To obtain a measurable amount of radiation-induced diffusion also requires, of course that each implanted helium atom jumps enough times to produce a significant value of the root-mean-squared diffusion distance; that is, the magnitude of the effect should increase with increasing dose.

We found it difficult to estimate simply the role of indirect energy transfers on the magnitude of the radiation-induced diffusion effect. An extended version of the approach used by Littmark and Hofer (1980a and 1980b) to study recoil mixing or a Monte Carlo calculation should be of value in estimating the importance of indirect energy transfers for the case of a light projectile and a heavy target.

In Appendix C we have derived a first-order expression for the total probability of a helium projectile atom never hitting an implanted helium atom (Γ).^{††} The expression for Γ is given by

$$\Gamma = [1 - c_s \alpha_0^3 / (4\bar{x})]^{2f/\gamma}; \quad (C8)$$

where c_s is the dose (cm^{-2}), α_0 the lattice parameter of tungsten (3.16 Å), f is the fraction of collisions which are elastic and γ is the standard expression for the fraction of energy transferred in a head-on elastic collision [see eqn. (9)]. It is emphasized that the values of Γ calculated employing eqn. (C8) represent a lower bound, since we used an upper bound for the number of helium-helium collisions ($2f/\gamma$)--see Appendix C. Equation (C8) was evaluated for a constant^{†††} c_s of $4 \times 10^{15} \text{ cm}^{-2}$ for the extreme situations of 100 and 1500 eV incident ion energies (E_1); the

[†] Radiation-induced (or simulated) diffusion does not involve the production of a supersaturation of point defects as is required in radiation-enhanced diffusion, e.g., see Lam and Rothman (1976) for a review of the latter subject.

^{††} A value of Γ equal to unity implies that a helium projectile did not hit an implanted helium atom, while Γ equal to zero means that it struck an implanted helium atom with certainty. The model we used to estimate Γ was a worst case one.

^{†††} This value represents the average value of the total ion doses employed--see Table 1 of Amano, Wagner and Seidman (1980).

values of $\bar{x}$ were taken from Tables 2 and 3 of Amano, Wagner and Seidman (1980) and the values of f were estimated employing the TRIM program. At 100 eV the value of Γ was $\lesssim 0.28$, while at 1500 eV the value of Γ was $\gtrsim 0.7$ --for both ^3He and ^4He . This meant that at the smallest value of E_1 the probability of a direct energy transfer to the implanted helium atom was greatest. The value of Γ is a very sensitive function of c_s ; for example, for c_s equal to $3 \times 10^{15} \text{ cm}^{-2}$ at 100 eV the value of Γ was between ~ 0.1 to 0.15 and at 1500 eV the range of Γ was ~ 0.8 to 0.9 --for both ^3He and ^4He . Thus, in conclusion, there was a possibility of radiation-induced diffusion or the simple displacement of helium atoms at the lowest value of E_1 employed--and the highest values of dose--but the magnitude of the effect was probably not large enough to have had a major effect on the detailed shape of the profiles.

2.4. Effect of finite sample size on the detailed shape of the integral profiles

Due to the finite number of helium atoms detected in each run, significant variations in the shape of the range profiles were expected as a result of random statistical fluctuations. Simulated integral profiles of 300 eV $^4\text{He}^+$ ions on tungsten for 25, 50 and 100 helium atoms are shown in figs. 2 (a), (b) and (c), respectively. The simulations were performed by integrating the theoretical range profile calculated employing Biersack's and Haggmark's (1980) TRIM program and then normalizing the integral profile to obtain a graph of cumulative probability (0 to 1) versus depth. The ordinate--that is, the cumulative probability--was then scaled to 25, 50, and 100 total detected helium atoms to obtain the simulated integral profiles; they are shown as the dotted curves in figs. 2 (a), (b) and (c), respectively. The three corresponding simulated integral profiles were generated by selecting r random numbers (with $r = 25, 50$ and 100) in the span of 0 to 1 and then picking off the value of the range corresponding to each of the r random numbers from the theoretical plot of cumulative probability versus depth. The r values of the range were ordered in a sequence of increasing depth and the stepped curves in fig. 2 were then generated by incrementing the ordinate by one helium atom at each of the r ordered range values.

The simulated profiles shown in fig. 2 are typical examples and they illustrate the effect of random statistical fluctuations and finite sample size on the shape of the experimentally determined range profiles. Approximately 500 helium atoms were required for the simulated profile to exactly reflect the detailed shape of a theoretical integral profile. However, detailed comparisons of the experimental and theoretical values of the range parameters $\bar{x}$ and Δx were certainly justified for sample sizes as small as 25. In the previous paper (Amano, Wagner and Seidman 1980) we showed that the quantities $\bar{x}$ and Δx can be measured with rather small values of the standard deviation in the mean (Δx_m) and the universe standard deviation in the sample standard deviation (Δx_s), respectively.[†] Thus, in conclusion, we believe that the integral profiles were characterized with a reasonable degree of statistical significance for the sample sizes we employed.

§3. DISCUSSION

3.1. General theoretical background.

The problem of calculating the range properties of low-energy light ions implanted in heavy targets dates back to Schiøtt (1965) who showed that--for this case--the mean range of the projectile (or penetration depth) can be an order of magnitude less than the total path length of the projectile. The calculations performed by Schiøtt were based on the analytical model developed by Linhard, Scharff and Schiøtt (1963). This model assumed an amorphous solid which was infinite in extent and had a reference plane but no free surface. It is now generally accepted that there is no completely satisfactory way of including the presence of a surface in the classical analytical continuum theories of the range properties of projectiles. Recently this problem has been overcome by the application of the Monte Carlo method to simulate the range profiles of low-energy implanted ions in solids (Oen and Robinson 1976a, Biersack and Haggmark 1979).

[†] In our research on the diffusion of ^3He in tungsten (Amano and Seidman 1980a) we were able to employ, with confidence, the first four moments of the 300 eV ^3He range profile shown in fig. 8 of Part I.

Basically the Monte Carlo method is a computer simulation technique which follows, in detail, the trajectories of a large number of implanted ions--one at a time--as they lose their initial energy in a series of elastic and inelastic collisions (Oen, Holmes and Robinson 1963, Robinson and Torrens 1974) with the atoms of an amorphous target. The assumption was made that the collisions can be treated employing the binary-collision approximation. The elastic (or nuclear) scattering event was described by classical scattering theory and involved the solution, for the scattering angle, of the well-known orbit integral (Goldstein 1950) for a given interatomic potential; it was the elastic scattering event that produced a deflection of the projectile. Wilson, Haggmark and Biersack (1977) calculated interatomic potentials, from first principles, for a number of light projectiles incident on heavy targets. They showed that these interatomic potentials were best approximated by a Molière-like form. This potential appeared to be a more satisfactory one for the low-energy régime of interest than the Thomas-Fermi potential employed by Linhard, Scharff and Schiøtt (1963). Both Oen and Robinson (1976 a) and Biersack and Haggmark (1979) used the Molière (1974) interatomic potential in their computer simulation programs MARLOWE and TRIM, respectively, rather than the Molière-like potentials developed by Wilson et al. (1977).

There is no satisfactory first principles theory available, at present, to describe the inelastic energy losses for low-velocity light projectiles incident on heavy targets. In view of this situation Oen and Robinson (1976b) and later Biersack and Haggmark (1979) assumed that the inelastic energy loss (Q) was described by the equation

$$Q(p, E) = [0.045 K E_1^{1/2} / (\pi a_s)] \exp [-0.3 r_0(p, E_1) a_s]; \quad (3)$$

where p is the impact parameter in the collision, E_1 is the kinetic energy of the projectile, r_0 is the apsis of the trajectory, K is a parameter which was taken from the Linhard-Scharff (1961) theory and a_s is a screening length. The electronic stopping cross-section (S_e) associated with eq. (3) is given by

$$S_e = 2\pi \int_0^{p_c} p Q(p, E) dp; \quad (4)$$

where p_c is the maximum value of the impact parameter allowed by the particular target. At high energies eqn. (3) approaches the Linhard-Scharff stopping cross-section, that is,

$$S_e \rightarrow KE_1^{1/2} \quad (5)$$

Biersack and Haggmark (1979) employed the Firsov (1957, 1958 and 1959) screening length for a_s ; this quantity was given by

$$a_s = 0.885a_0 (Z_1^{1/2} + Z_2^{1/2})^{-2/3}; \quad (6)$$

where a_0 is the Bohr radius ($0.529 \text{ \AA}$) and Z_1 and Z_2 are the nuclear charges on the projectile and target atoms, respectively.

For the purposes of comparing our experimental data with the results of the TRIM program it was found convenient to employ the dimensionless energy (ϵ). The equation for ϵ is

$$\epsilon = \frac{M_2 E_1}{(M_1 + M_2)} \frac{Z_1 Z_2 e^2}{a_s} \quad (7)$$

where M_1 and M_2 are the masses of the projectile and target atoms, respectively, and e is the charge on an electron. The dimensionless depth (ρ) was also employed and it is given by

$$\rho = x N_d \pi a_s^2 \gamma \quad (8)$$

where x is the measured length, N_d is the number density of target atoms, and

$$\gamma = 4M_1 M_2 / (M_1 + M_2)^2 \quad (9)$$

Table 3 lists the values of a_s , ϵ and ρ values for ^3He and ^4He in tungsten; the ϵ and ρ values were calculated for E_1 equal to 1 keV and x equal to $5.22 \text{ \AA}$ (this corresponds to $1 \mu\text{gm cm}^{-2}$), respectively.

3.2. Application of the TRIM simulation program to

^3He and ^4He implanted in tungsten

We have applied Biersack's and Haggmark's (1979) TRIM simulation program and calculated all of the range properties of ^3He and ^4He implanted in tungsten. The TRIM program was used because it is extremely efficient from a computational point of view. In our laboratory the program was translated into the language called BASIC (Macrander 1980) and run on a Data General Nova 1220 computer. This Monte

Carlo program was used with the full knowledge that it does not represent an absolute standard but, at the present time, rather a reasonable theoretical model with which to compare our experimental data.

Figure 3 displays the results of a TRIM calculation of the total path length and the mean range ($\bar{\rho}$) in dimensionless units. It is seen that for both ^3He and ^4He atoms the total path length was almost a factor of ten greater than $\bar{\rho}$ at all values of E_1 (e). The differences between the ^3He and ^4He range data--both the total path length and $\bar{\rho}$ --can, to a large extent, be explained on the basis of eqns. (8) and (9). The ratio^o of the γ s for ^4He to ^3He is ≈ 1.32 ; thus 32% of the difference in the values of $\bar{\rho}$ for ^4He and ^3He is solely due to the effect of γ in eqn. (8). The remainder of the difference between $\bar{\rho}_{^4\text{He}}$ and $\bar{\rho}_{^3\text{He}}$, at constant E_1 , can be explained on the basis of the inequality[†]

$$\left[\frac{S_e}{S_n + S_e} \right]_{^4\text{He}} < \left[\frac{S_e}{S_n + S_e} \right]_{^3\text{He}},$$

where S_n is the nuclear stopping cross-section. This inequality implies that the absolute values of $\bar{x}$, Δx , etcetera will be different for ^3He and ^4He . Although the differences are expected to be small because of the small mass difference between ^3He and ^4He .

Figure 4 displays the trajectories of twenty 300 eV ^4He atoms, calculated employing the TRIM Program. The actual trajectories followed a path that moved through the lattice in three dimensions, while the exhibited trajectories were obtained by projecting the former trajectories into the plane of the paper for the purpose of this display. For this small sample size the value of $\bar{x}$ was $46 \text{ \AA}$, while for a sample size of 1000 events it was $37 \text{ \AA}$. The ion trajectories displayed in fig. 4 are reminiscent of the random walk behavior of an atom in a liquid or a gas. The reasons for this resulted, first, from the fact that M_1 was less than M_2 for ^3He or ^4He atoms on tungsten; therefore, the kinematics of the scattering process permitted backscattering--

[†] This inequality is a result of the following inequalities: (a) $(S_e)_{^3\text{He}} > (S_e)_{^4\text{He}}$; and (b) $(S_n)_{^3\text{He}} < (S_n)_{^4\text{He}}$. Inequalities (a) and (b) follow directly from the basic expression for these quantities.

that is, scattering through an angle greater than 90° in the laboratory frame-of-reference. Second was the fact that the maximum energy transferred ($T_{\max}$) to a tungsten atom was always small because of the large mass mismatch between the helium and tungsten atoms. In general, for a head-on hard-sphere two-body elastic collision $T_{\max}$ is given by

$$T_{\max} = \gamma E_1; \quad (10)$$

for ^4He and ^3He on tungsten $T_{\max}$ is equal to $0.083E_1$ and $0.063E_1$, respectively.

Thus, a large number of collisions were required for the helium atoms to expend all their initial energy. Finally, at the small values of E_1 employed the elastic scattering component was almost hard-sphere like, so that the recoil spectrum was approximately isotropic; that is, the scattering was not strongly peaked in the forward direction.

3.3. Comparison of the experimental results

with the TRIM simulation results.

(a) Comparison of the results

In this sub-section we compare the experimental results of Part I with the results of the TRIM simulation program. The comparisons were made in terms of the dimensionless parameters ϵ and ρ as defined by eqns. (7) and (8), respectively. The quantities $\bar{x}$, Δx , E_1 became ρ , $\Delta\rho$ and ϵ , respectively, in this notation.

Figure 5 is a plot of $\bar{\rho}$ versus ϵ .[†] Between $\epsilon \approx 4.6 \times 10^{-3}$ and 2.5×10^{-2} the experimental values of $\bar{\rho}$ for ^4He were slightly greater than those of ^3He in tungsten. At a value of ϵ equal to 3×10^{-3} the experimental values of $\bar{\rho}$ for ^4He become significantly greater than those for ^3He in tungsten--also see part I. These results were in qualitative agreement with the results of the TRIM calculations, in that the $\bar{\rho}$ values of ^4He were greater than those of ^3He for all values of ϵ . However, there was only quantitative agreement between the experimental and calculated $\bar{\rho}$ values of ^4He in the range $4.6 \times 10^{-3} \leq \epsilon \leq 2.5 \times 10^{-2}$; beyond $\epsilon = 2.5 \times 10^{-2}$ the experimental values of

[†] In a forthcoming paper (Amano and Seidman 1980 b) we presented the results of experiments which measured the reflection coefficients of ^3He and ^4He from tungsten surfaces as a function of ϵ in this same range.

$\bar{\rho}$ were significantly greater than the calculated ones. All of the experimental values of $\bar{\rho}$ for ^3He were greater than the calculated ones at all values of ϵ . For example, at $\epsilon \approx 4.8 \times 10^{-3}$ the experimental value of $\bar{\rho}$ for ^3He was ~60% greater than the calculated one, whereas at $\epsilon = 8 \times 10^{-2}$ the experimental $\bar{\rho}$ was ~33% greater than the TRIM value. The TRIM values of $\bar{\rho}$ or $\Delta\rho$ versus ϵ were not found to be particularly sensitive to the K value employed in eqn. (1); that is, increasing or decreasing K by 50% of the Linhard-Scharff (1961) value didn't significantly change $\bar{\rho}$ or $\Delta\rho$.

Because both S_n and S_e have significant absolute values in the range of ϵ studied we would not be justified in trying to extract either of these quantities from the data. Instead, we defined the total effective stopping ($S_{\text{total}}^{\text{eff}}$) to be given by,

$$S_{\text{total}}^{\text{eff}} = -\left(\frac{d\epsilon}{d\rho}\right) \quad (9)$$

It was denoted an effective S_{total} because of the large difference between the total path length and the mean projected range (see fig. 3). The quantity $S_{\text{total}}^{\text{eff}}$ as a function of ϵ can be obtained easily from fig. 5 by graphical differentiation. For practical calculational purposes the following relationships between $\bar{\rho}$ and ϵ were obtained from the data in fig. 5:

$$\bar{\rho}_{^3\text{He} \text{ and } ^4\text{He}} \approx 0.07\epsilon^{0.5} \quad \text{for} \quad \epsilon < 0.02; \quad (10a)$$

$$\bar{\rho}_{^3\text{He}} \approx 0.12\epsilon^{0.7} \quad \text{for} \quad \epsilon \geq 0.02; \quad (10b)$$

$$\text{and} \quad \bar{\rho}_{^4\text{He}} \approx 0.4\epsilon \quad \text{for} \quad \epsilon \geq 0.02. \quad (10c)$$

The expressions for $S_{\text{total}}^{\text{eff}}$ followed in a straightforward fashion from eqns. (9) and (10) and they are:

$$S_{\text{total}}^{\text{eff}} (^3\text{He} \text{ and } ^4\text{He}) \approx 2.9\epsilon^{0.5} \quad \text{for} \quad \epsilon < 0.02, \quad (11a)$$

$$S_{\text{total}}^{\text{eff}} (^3\text{He}) \approx 1.2\epsilon^{0.3} \quad \text{for} \quad \epsilon \geq 0.02, \quad (11b)$$

$$\text{and} \quad S_{\text{total}}^{\text{eff}} (^4\text{He}) \approx 2.5 \quad \text{for} \quad \epsilon \geq 0.02. \quad (11c)$$

In addition, in the régime $\epsilon \geq 0.02$ the $\bar{\rho}$ versus ϵ range data for ^3He and ^4He were best approximated by the single expression:[†]

[†] Recently van Gorkum and Kornelsen (1980) measured, employing thermal desorption spectrometry, the E_1 dependence of the mean range of ^4He in tungsten for random incidence. They found that above 250 eV the expression is given by $0.12 E_1^{0.9} \text{ \AA}$, with E_1 in eV, and that for normal incidence along the [100] direction it is a factor of three greater.

$$\bar{\rho}_{\text{eff}} \approx 0.203\epsilon^{0.8} \quad \text{for} \quad \epsilon \geq 0.02, \quad (12)$$

so that the effective total stopping power is

$$S_{\text{total}}^{\text{eff}} (^3\text{He or } ^4\text{He}) \approx 6\epsilon^{0.2} \quad \text{for} \quad \epsilon \geq 0.02. \quad (13)$$

For $\epsilon \leq 0.02$ the TRIM calculations predicted that both ^3He and ^4He should obey a $\bar{\rho} \propto \epsilon^{0.5}$ relationship; eqn. (10a) for the experimental data was in agreement with this prediction. In this low ϵ régime the calculated $\epsilon^{0.5}$ behavior was the result of a combination of nuclear and electronic stopping processes and it cannot be taken as evidence for channeling--for a discussion of channeling see, e.g., Whitton 1973.

Figure 6 is a plot of $\Delta\rho$ versus ϵ . For all values of ϵ the experimental values for $\Delta\rho$ for ^4He were greater than those of ^3He in tungsten. The only exception to this general trend occurred at the smallest measured value of ϵ where the curves for ^3He and ^4He intersected one another. At all values of ϵ --for ^3He and ^4He -- the experimental values of $\Delta\rho$ were almost a factor of 2 greater than the TRIM values. Since $\Delta\rho$ was a measure of the width of the range profile it was concluded that the experimental range profiles were broader than the calculated ones based on the TRIM program.

The experimental values of the relative variance $[(\Delta\rho)^2/(\bar{\rho})^2]$ versus ϵ were constant and equal to ~0.5 and 0.6 for ^3He and ^4He , respectively; see fig. 12 in Amano, Wagner and Seidman (1980). The TRIM value of the relative variance was equal to ~0.3 in this same range of ϵ for both ^3He and ^4He . This discrepancy was consistent with the result that the experimental values of $\Delta\rho$ were significantly greater than the TRIM values.

The last figure (fig. 7) is a plot of $\rho_{0.95}$ versus ϵ . The quantity $\rho_{0.95}$ was denoted the maximum range and its value was obtained by locating the experimental value of the depth which corresponded to 95±5% of the total helium events measured. The experimental data exhibited in fig. 7 demonstrated that ^4He penetrated more deeply in the lattice than did ^3He . The behavior of the experimental data was qualitatively similar to the curves obtained from the TRIM calculations. Although, the absolute values of the experimental $\rho_{0.95}$ s were about 30 to 100% greater than the calculated ones.

(b) Discussion of the comparisons

From all of the above detailed comparisons of our experimental data with the results of the TRIM program it can be seen that quantitative deviations exist between the experimental results and this model. The major sources of this discrepancy were most likely connected with following aspects of the TRIM program: (1) the interatomic potential employed; (2) the expression for S_e used in the calculation; (3) the use of an amorphous model to describe a crystalline lattice. We now consider each of these sources in turn.

The interatomic potential employed determined the elastic (nuclear) stopping power and hence it affected the mean projected range of the projectile. Wilson, Haggmark and Biersack (1977) showed that the Molière potential was not as well screened as their best average potential (see fig. 1 of their paper). The effect of using the Molière potential, as opposed to the best average Wilson-Haggmark-Biersack potential, was to increase nuclear scattering at large impact parameters and hence to decrease the range of the projectile. Therefore the use of the exact Wilson-Haggmark-Biersack potential should have the effect of increasing the range of the ^3He and ^4He projectiles in this ϵ régime.

As pointed out in §3.1 the functional dependence of S_e in this low ϵ régime is not well known. Fortunately the range profiles of low-energy implanted ^3He or ^4He atoms did not appear to be very sensitive to the value of the K employed (Oen and Robinson 1976a): also see our earlier comments in this section. Thus the source of the discrepancy didn't seem to be strongly related to the choice of S_e .

The employment of an amorphous solid in the TRIM program was a problem for us as all our implantation experiments were performed using a crystalline target with the ion beam parallel, within $\pm 5^\circ$, to the $[110]$ direction. The $[110]$ channel, in tungsten, is less open than either the $[100]$ or $[111]$ channels. However, the critical half-angles for axial channeling at low energies are large (Linhard 1965, Andreen and Hines 1967, Kornelsen and van Gorkum 1980).[†] The strongest experimental evidence

[†] For example, at 250 eV Kornelsen and van Gorkum (1980) measured a critical half-angle of 10° for ^4He on tungsten, for the $[100]$ channel.

for channeling along the [110] direction of tungsten, at low energies, comes from the pioneering work of Kornelsen et al. (1964). They implanted radioactive ^{133}Xe in tungsten at E_1 values of 500 and 1000 eV; the anodic oxidation/chemical dissolution technique (McCargo, Davies and Brown 1963) was employed for determining integral penetration profiles. Kornelsen et al. found that the depth of penetration of 1% of the ions along the [110] direction exceeded the amorphous values (Domeij et al. 1964) by a factor of ~ 1.4 and ~ 2.0 at 500 and 1000 eV, respectively. Recently Maderlenchner (1976) employed the MARLOWE simulation program and calculated the range profiles of 0.5 to 8 keV helium ions in a single crystal of niobium. He found clear evidence for the channeling of 500 eV helium ions along the [100] direction. Thus the use of an amorphous model in the TRIM program could be another source of the discrepancies observed between experiment and theory. In conclusion, we can not rule out the possibility that a component of the helium beam had penetrated the tungsten lattice along the [110] channels.

§4. SUMMARY

This paper consisted of two main sections. In Section 2 we discussed, in detail, the identifiable sources of possible systematic errors in the measurement of the mean range ($\bar{x}$) and the straggling (Δx) values reported in Part I; the detailed arguments pertinent to §2 were presented in Appendices A to C. Then in Section 3 we first reviewed briefly the general theoretical situation for the problem of calculating the range properties of low-energy light ions implanted in heavy targets. Next we compared our experimental results with the predictions of Biersack's and Haggmark's (1979) TRIM simulation program for the low-energy range properties of ^3He and ^4He implanted in tungsten. We employed this Monte Carlo program with the full knowledge that it doesn't represent an absolute standard for our measurements but rather it is a reasonable model with which to compare our experimental data.

The following conclusions were reached:

- (1) The hemispherical geometry of the FIM specimen caused the measured values of $\bar{x}$ to exceed the actual mean range ($\bar{x}_a$) by 5% at most (see Tables 1 and 2).
- (2) The actual straggling or standard deviation (Δx_a) of each range profile

was essentially equal to the measured value of Δx because of the small difference between $\bar{x}$ and $\bar{x}_a$ (see Tables 1 and 2).

- (3) The random arrival of helium gas atoms at the surface of the specimen from the background--during the profiling procedure--produced essentially no difference between $\bar{x}$ and $\bar{x}_a$ and, therefore, no systematic error was produced by this effect.
- (4) The effect of helium projectiles on the helium that had already been implanted was considered. A first-order expression for the total probability of a helium projectile atom never hitting an implanted helium atom was derived (see Appendix C). On the basis of this calculation it was concluded that there was a possibility of radiation-induced (or stimulated) diffusion or the simple displacement of helium atoms at the lowest value of E_1 employed (100 eV) and the highest dose ($4 \times 10^{15} \text{ cm}^{-2}$). However, the magnitude of this effect was probably not large enough to have had a major effect on the detailed shape of the profiles.
- (5) The effect of the sample size on the detailed shape of the range profiles was considered employing a simple Monte Carlo simulation approach. Approximately 500 helium atoms were required for the simulated profile to exactly reflect the detailed shape of a theoretical integral profile. However, we believe that the integral profiles were characterized with a reasonable degree of statistical significance for the sample sizes we employed. In particular, values of the range parameters $\bar{x}$ and Δx were determined with rather small values of the standard deviation in the mean (Δx_m) and the universe standard deviation in the sample standard deviation (Δx_s), respectively--also see Part I.
- (6) The experimental data were compared with the results of Biersack's and Haggmark's Monte Carlo TRIM simulation program employing the

- dimensionless energy (ϵ) and range (ρ) parameters--see figs. 5 to 7.
- (7) The experimental values of $\bar{\rho}$, $\Delta\rho$ and $\rho_{0.95}$ as a function of ϵ were always greater than the corresponding values of these same quantities calculated from the TRIM program--see figs. 5 to 7.
- (8) It was suggested that the origins of the differences in figs. 5 to 7 can be possibly explained on the basis of: (a) the use of the Molière interatomic potential in the TRIM program; and (b) the employment of an amorphous solid model, as all the implantations were performed using a crystalline target with the ion beam parallel, within $\pm 5^\circ$, to the [110] direction.

ACKNOWLEDGEMENTS

We wish to thank Drs. J.P. Biersack and L.G. Haggmark for kindly providing us with a copy of the TRIM program, Dr. J.P. Biersack for carefully and patiently explaining its use to us, Dr. A.T. Macrander for writing the BASIC version of the TRIM program and Professor M.S. Taqqu for discussions concerning statistics.

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APPENDIX A

EFFECT OF THE GEOMETRY OF THE FIM SPECIMEN ON $\bar{x}$ AND Δx

In this appendix we present the detailed mathematical arguments of the discussion given in §2.1. The calculations were based on the following physical assumptions:

- (1) The helium atoms were implanted parallel to the central axis (the [110] direction for our experiments) of the FIM specimen;
- (2) The FIM specimen had a hemispherical end form;
- (3) The probe hole was located at the center of the central axial plane--the (110) plane for our experiments--and it had a radius r_a (see fig. 1);
- (4) The transverse range profiles in the y and z-directions obeyed the normal distribution law (see fig. 1) and the transverse standard deviations (Δy and Δz) were equal to one another; and
- (5) The transverse range profile was approximated by a uniform distribution with a maximum transverse range of Δy (the crosshatched rectangular area in fig. 1).

Assumptions (1) to (3) were the standard experimental conditions employed. Assumption (4) was based on the computer simulation (Monte Carlo calculations) work of Oen and Robinson (1976a) and Biersack and Haggmark (1979) which showed that the transverse range profiles were approximately normal. Other calculations by the same two pairs of authors showed that the mean transverse range--for a light projectile ion in a heavy target--was approximately equal to $\bar{x}$ and that $\Delta x \leq (\Delta y = \Delta z)$.

The value of the normal probability distribution function $[\Phi(y)]$ between y and ∞ was given by the value of the integral:

$$\Phi(y) = \frac{1}{\Delta y \sqrt{2\pi}} \int_y^{\infty} \exp\left[-\frac{1}{2} \left(\frac{y-\bar{y}}{\Delta y}\right)^2\right] dy; \quad (A1)$$

for $y = -\Delta y$ the value of $\Phi(y = -\Delta y)$ is 0.84 and $1 - \Phi(y = -\Delta y) = 0.16$. Therefore, the probability for depositing an incident helium ion at a transverse distance greater than Δy from the point of entry in the specimen was small. This result was the physical basis of assumption (4). The following additional quantities were used in the calculation:

r_n = radius of the outer ledge of the nth terrace;

A_n = area of the nth terrace; and

$A_{110} = A_0$ = area of the topmost (110) plane.

Helium ions incident on a terrace with $r_n \leq (\Delta y + r_a)$ were included in the number of helium atoms detected while helium ions incident on terraces with $r_n > (\Delta y + r_a)$ were excluded from the number of helium atoms deposited within the analyzed volume; see assumptions (4) and (5) above. Since the dose of helium ions was a constant on each (110) terrace the total number of helium ions entering the nth terrace was directly proportional to A_n . All ions incident on the nth terrace--where $r_n \leq (\Delta y + r_a)$ --were assumed to have been deposited uniformly in the directions perpendicular to the incident beam within the volume bounded by the outer ledge of the nth terrace (see fig. 1). For example, the ions incident on the topmost (110) plane were assumed to have been distributed uniformly in the transverse directions bounded by radius $r_n \leq (\Delta y + r_a)$. Thus the measured range profile consisted of the superposition of n true range profiles (one for each of the n contributing terraces) and the profile due to the ions which entered the topmost (110) plane. Each of the n profiles ($n \geq 1$) was displaced from the measured profile--due to the ions which entered the topmost (110) plane--by a distance equal to nd_{110} . Thus the quantity $\bar{x}$ was given by:

$$\bar{x} = [A_0 \bar{x}_a + A_1 (\bar{x}_a + d_{110}) + \dots + A_n (\bar{x}_a + nd_{110})] / \sum_{j=0}^n A_j \quad (A2)$$

The error introduced into the measurement of the mean range was equal to $(\bar{x} - x_a)$ and was given by:

$$(\bar{x} - \bar{x}_a) = d_{110} \sum_{j=1}^n j A_j / \sum_{j=0}^n A_j \quad (A3)$$

Based on the geometry of the specimen (see fig. 1) the following expressions were derived:

$$r_n^2 = [2R_t(n+1)d_{110} - (n+1)^2 d_{110}^2] \quad ; \quad (A4)$$

$$r_{n-1}^2 = [2R_t n d_{110} - n^2 d_{110}^2] \quad ; \quad (A5)$$

$$A_n = \pi(r_n^2 - r_{n-1}^2) = \pi[2R_t d_{110} - d_{110}^2(2n+1)] \quad (A6)$$

where $n = 0, 1, 2, 3, \dots$; and

$$\sum_{j=0}^n A_j = \pi d_{110}^2 (n+1) [2R_t - (n+1)d_{110}] \quad \text{where} \quad (A7)$$

$$j=0, 1, 2, 3, \dots, n.$$

Employing eqn. (A7) to evaluate eqn. (A3) yielded:

$$(\bar{x} - \bar{x}_a) = \frac{n d_{110}}{2} \frac{[2R_t - (\frac{4n+5}{3})d_{110}]}{[2R_t - (n+1)d_{110}]} \quad (A8)$$

In general R_t was always very much greater than d_{110} ; the smallest value of R_t employed was $410 \text{ \AA}$ and d_{110} is $2.24 \text{ \AA}$. Therefore for small n eqn. (A8) reduced to

$$(\bar{x} - \bar{x}_a) \cong \frac{n}{2} d_{110} \quad (A9)$$

Employing the boundary condition that $r_n \leq (\Delta y + r_a)$ and eqn. (A4), yielded the following condition on n ;

$$[2R_t(n+1)d_{110} - (n+1)^2 d_{110}^2] \leq (\Delta y + r_a)^2 \quad (A10)$$

Since the second term on the left hand side of eqn. (A10) was generally small with respect to the first term (for small n) we neglected it and eqn. (A9) became

$$n \leq \left[\frac{(\Delta y + r_a)^2}{2R_t d_{110}} - 1 \right] \quad (A11)$$

To determine the maximum values of n ($n_{\max}$) we took Δy to be equal to the measured values of Δx and then used the values r_a and R_t (Tables 1 and 2) to calculate $n_{\max}$. The values of $n_{\max}$, in turn, were used to calculate $(\bar{x} - \bar{x}_a)$ eqn. (A9). The last column of both Tables 1 and 2 lists the calculated values of $(\bar{x} - \bar{x}_a)$.

The values of r_a listed in Tables 1 and 2 were calculated from the expression

$$r_a = [N_c / \pi \rho_{(110)}]^{1/2} \quad (A12)$$

where N_c is the corrected average number of tungsten atoms per plane and $\rho_{(110)}$ is the atomic density of the (110) plane ($0.14 \text{ atom \AA}^{-2}$). The quantity N_c was given by:

$$N_c = N_m / \eta \quad (A13)$$

where η was the detection efficiency of the Chevron detector and N_m the average number

of tungsten atoms. The value of η was taken to be 0.65 (Panitz 1978).

The local tip radius was calculated from the standard equation (Drechsler and Wolff 1960)

$$R_t = nd_{hkl} / (1 - \cos\theta) \quad , \quad (A14)$$

where n was the number of steps from the edge of the central (110) plane to the center of the chosen plane [(231) or (121) plane in our work], d_{hkl} is the interplanar spacing (d_{110} in our case) and θ is the angle between the normal to the central (110) plane and the chosen plane.

APPENDIX B

EFFECT OF THE RANDOM ARRIVAL OF HELIUM GAS ATOM FROM THE BACKGROUND GAS

The measured mean range ($\bar{x}$) was taken to be equal to the weighted average of $\bar{x}_a$ and $\bar{x}_c$ and it was given by the following equation,

$$\bar{x} = [(N-C)\bar{x}_a + C\bar{x}_c] / N \quad (B1)$$

where all quantities were defined in §2.2. Therefore $\bar{x}_a$ of the injected helium atoms was given by

$$\bar{x}_a = [\bar{x} / (1 - \xi) - \xi \bar{x}_c / (1 - \xi)] \quad (B2)$$

It follows that the error in $\bar{x}$ was given by

$$|\bar{x} - \bar{x}_a| = [\xi / (1 - \xi)] |\bar{x}_c - \bar{x}| \quad (B3)$$

APPENDIX C

A SIMPLE STATISTICAL MODEL TO EVALUATE THE PROBABILITY OF DIRECT ENERGY TRANSFERS

In §2.3 we stated that direct energy transfers as a result of helium-helium scattering events may have changed the shape of the range profile either as a result of direct displacements or radiation-induced diffusion of the previously implanted helium atoms. For the case where the projectile and target atoms have the same mass the scattering angle--in the laboratory frame-of-reference--of the projectile atom can range between zero and 90° . This is distinctively different from case of a light projectile atom impinging on a heavy target where this same angle can range between zero and 180° (see §3.2). Thus the implanted helium atoms

that received elastic energy transfers from the helium projectile atoms could not have been backscattered. In this section we present a simple statistical model which is used to evaluate the probability that an injected helium atom does not hit the helium atoms that had already been implanted. We emphasize the fact that this model is a worst case one, as it tends to overestimate the magnitude of the effect.

Assume, for the purposes of this model, that the profile of implanted helium atoms can be described by a normal distribution law of the form

$$c(x) = c_{\max} \exp \left[-\frac{1}{2} \left(\frac{x-\bar{x}}{\Delta x} \right)^2 \right], \quad (C1)$$

where $c(x)$ is the concentration of helium--in atoms cm^{-3} --measured from the surface $x=0$, and $c_{\max}$ is the concentration of helium at $x=\bar{x}$. It can be shown by integration that $c_{\max}$ is given by

$$c_{\max} = c_s / (\sqrt{2\pi} \Delta x), \quad (C2)$$

where c_s is the dose (cm^{-2}) for the total implantation. The mean value of $c(x)$ is approximately given by the expression[†]

$$\bar{c} = c_s / (2\bar{x}). \quad (C3)$$

Thus, the mean atomic fraction of helium is given by

$$\bar{p} = c_s \alpha_o^3 / (4\bar{x}), \quad (C4)$$

where α_o is the lattice parameter of tungsten.

Each helium projectile was assumed to undergo random collisions with the already implanted helium atoms with a constant probability ($\bar{p}$). Thus the probability of a projectile not hitting a helium atom at the l th collision was $(1-\bar{p})$. The total probability of never hitting an implanted helium atom (Γ) is given by

$$\Gamma = \prod_{l=1}^{\zeta} (1-\bar{p}) = (1-\bar{p})^{\zeta}, \quad (C5)$$

[†] The use of this expression implies that $\bar{p}$ [eqn. (C4)] is a constant which is independent of depth. The effect of this assumption was to overestimate the probability of an injected helium atom hitting a helium atom that had already been implanted.

where ζ is the total number of collisions made by the helium projectiles[†] in losing its initial energy. Employing eqn. (C4) the expression for Γ is given by

$$\Gamma = [1 - c_s \alpha_o^3 / (4\bar{x})] \zeta. \quad (C6)$$

To evaluate Γ it was necessary to estimate ζ . This evaluation presented some difficulties since we did not know what fraction of the total number of collisions was due to helium-helium encounters. The perfect matching of masses between the projectiles and implanted atoms implied that a larger amount of energy could be transferred--per collision--as a result of helium-helium collisions than as a result of helium-tungsten collisions, where the mass difference is large. A lower bound to ζ is given by $E_1 / \bar{T}$, where $\bar{T}$ is $T_{\max} / 2$ and $T_{\max} = E_1$ for elastic helium-helium collisions; this implied that the value of the lower bound is two. An upper bound to ζ was calculated on the basis that all the collisions were elastic helium-tungsten events--this yielded $\zeta = 2/\gamma$, where γ is given by eqn. (9). By further assuming that only a fraction (f) of the collisions were elastic then a value of ζ is given by

$$\zeta = 2f/\gamma. \quad (C7)$$

With this approximation eqn. (C5) became

$$\Gamma = [1 - c_s \alpha_o^3 / (4\bar{x})]^{2f/\gamma} \quad (C8)$$

Equation (C7) represents a lower bounds to the value of Γ since the expression used for ζ is an upper bound. The dependence of Γ on E_1 enters through $\bar{x}$ and f ; note that as E_1 increases--at a fixed value of c_s --the value of Γ increases, since $\bar{x}$ increases and f decreases as E_1 is increased. Also note that Γ decreases at constant E_1 as c_s is increased.

[†] It is an approximation to take ζ to be a constant since ζ is subject to statistical fluctuations (Bohr 1948).

Table 1: Geometric parameters which affected the values of $\bar{x}$ and Δx for the ^3He implantations plus the quantity $(\bar{x}-\bar{x}_a)$.

Incident Ion Energy (E_1) (eV)	Measured Standard or Straggling deviation (Δx) ($\text{\AA}$)	Calculated radius of probed area (r_a) ($\text{\AA}$)	Measured local tip radius (R_t) ($\text{\AA}$)	n_{max}	$\bar{x}-\bar{x}_a$ ($\text{\AA}$)
100	22.6	25.5	440	0	0
100	25.0	23.0	440	0	0
200	29.7	25.9	480	1	1.12
200	27.8	24.4	400	1	1.12
300	42.5	26.3	560	1	1.12
300	45.2	25.6	520	1	1.12
500	47.5	29.1	600	2	2.24
1000	75.2	30.7	690	3	3.36
1500	97.3	32.1	780	4	4.48

Table 2: Geometric parameters which affected the values of $\bar{x}$ and Δx for the ^4He implantations plus the quantity $(\bar{x}-\bar{x}_a)$.

Incident Ion Energy (E_1) (eV)	Measured Standard or Straggling deviation (Δx) ($\text{\AA}$)	Calculated radius of probed area (r_a) ($\text{\AA}$)	Measured local tip radius (R_t) ($\text{\AA}$)	n_{max}	$\bar{x}-\bar{x}_a$ ($\text{\AA}$)
100	16.0	15.6	410	0	0
150	24.0	32.6	815	0	0
200	32.2	29.9	730	0	0
300	36.4	15.5	400	1	1.12
300	37.3	15.8	400	1	1.12
500	54.4	16.6	400	2	2.24
700	83.2	22.1	690	3	3.36
700	66.4	15.1	400	3	3.36
1000	107.7	24.7	730	5	5.6
1000	98.9	19.3	440	6	6.72
1500	124.0	20.2	520	8	8.96

Table 3: Values of important parameters for the behavior of ^3He and ^4He in tungsten.

Projectile	Firsov screening length [†] (a_s) Å	Dimensionless energy for $E=1$ keV	Dimensionless length for $x=5.22$ Å ^{††}
^3He	0.1008	4.6532×10^{-2}	6.606×10^{-4}
^4He	0.1008	4.62845×10^{-2}	8.703×10^{-4}

[†] The Thomas-Fermi screening length (a_{TF}), from the Linhard et al. (1963) theory, is given by $0.8853 a_0 (Z_1^{2/3} + Z_2^{2/3})^{-1/2}$. For helium in tungsten the ratio a_{TF}/a_s is 1.06.

^{††} This value of x corresponded to $1 \mu\text{g}/\text{cm}^{-2}$.

FIGURE CAPTIONS

- Figure 1: A schematic diagram of a hemispherical FIM specimen. One set of closepacked planes with an interplanar spacing d_{hkl} is indicated for a specimen with a local tip radius R_t . The quantities r_a and r_n are the radii of the probed area and the n th terrace, respectively. The helium ion beam was normal to the set of closepacked planes, as shown, during the course of each irradiation. The actual transverse range profile, in the y -direction, obeyed the normal distribution law as exhibited (see the bell-shaped curve). For the purposes of the calculations presented in Appendix A the cross-hatched rectangular area was used as an approximation to the normal distribution law.
- Figure 2: Integral profiles for 300 eV He^+ ions, as simulated by a computer program for 25, 50 and 100 heliums--see (a), (b) and (c), respectively. The dotted curve is the theoretical integral profile obtained using the TRIM simulation program.
- Figure 3: The dimensionless depth as a function of dimensionless energy (ϵ) for the energy range 100 to 1500 eV. The calculations were made for ^3He and ^4He in tungsten and the quantities exhibited are the total path length and the mean penetration depth.
- Figure 4: Twenty trajectories of 300 eV ^4He ions implanted in tungsten as calculated employing the TRIM simulation program. The actual trajectories were in three dimensions, whereas the exhibited trajectories are a result of a projection into the plane of the paper.
- Figure 5: The dimensionless mean range ($\bar{\rho}$) as a function of dimensionless energy (ϵ) for both the experimental data and the TRIM results.
- Figure 6: The dimensionless straggling or standard deviation ($\Delta\rho$) as a function of dimensionless energy (ϵ) for both the experimental data and the TRIM results.

Figure 7: The dimensionless depth ($\rho_{0.95}$) as a function of dimensionless energy (ϵ) for both the experimental data and the TRIM results. The quantity $\rho_{0.95}$ corresponds to the value of ρ , for a range profile, at which $95 \pm 5\%$ of the helium events had been detected.

FIGURE 1

FIGURE 2

FIGURE 3

TRIM SIMULATION OF 300 eV ^4He
IMPLANTED IN TUNGSTEN
20 ION TRAJECTORIES
AVERAGE PROJECTED RANGE: 46 Å
AVERAGE TOTAL PATHLENGTH: 348 Å

WIDTH IN ANGSTROMS (Å)

POINT OF ENTRY
↓

↓
 $\bar{x}$

DEPTH IN ANGSTROMS

FIGURE 4

FIGURE 5

FIGURE 6

FIGURE 7