

Backscattering of He⁺ and H⁺ particles from ultra-thin films in the energy range 50–100 keV

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Elastic collision cross sections of He⁺ and H⁺ ions incident on Au, Ag, Cu, Bi, Ni, and In, of density equivalent to less than a monolayer of target material, have been measured in the energy range 50–100 keV by the measurement of particles backscattered through a laboratory angle of 150°. The results point to a Thomas-Fermi potential description of the collision process.

Measurements of the elastic scattering cross section in the 100-keV range in solid targets have been scant. A need exists, however, to test experimentally the Thomas-Fermi screened potential description of Lindhard, Nielson, and Scharff¹ (LNS) for solid targets in this energy region. Such measurements are also needed in studies of sputtering,^{2–5} radiation damage,^{6,7} and energy loss.^{8–10} In the Lindhard description, when a projectile with velocity v , mass M_1 , and nuclear charge Z_1e elastically scatters through a center-of-mass angle Θ from a target atom with mass M_2 and nuclear charge Z_2e , the differential elastic scattering cross section can be expressed as

$$d\sigma = \frac{\pi a^2 f(t^{1/2}) dt}{2t^{3/2}}, \quad (1)$$

where t represents a scaling parameter,

$$t = \epsilon^2 \sin^2(\theta/2), \quad (2)$$

with

$$\epsilon = \frac{M_1 M_2 v^2 a}{2(M_1 + M_2) Z_1 Z_2 e^2}, \quad (3)$$

and a denotes a screening radius,

$$a = \frac{0.8853 a_0}{(Z_1^{3/2} + Z_2^{3/2})^{1/2}}, \quad (4)$$

with a_0 signifying the Bohr radius. The universal elastic scattering function $f(t^{1/2})$ is calculated from a Thomas-Fermi potential. For values of $t^{1/2} > 10$, the collision process is described by pure Rutherford scattering, in which case $f(t^{1/2}) = 1/2t^{1/2}$. As $t^{1/2}$ becomes less than 10, the influence of screening arises and the collision cross section falls below that predicted by the Rutherford model.

Andersen, Bøttinger, and Knudsen¹¹ have tested this description for $t^{1/2}$ values down to 0.4 by using 300–2000-keV H⁺, He⁺, and Li⁺ projectiles scattered through small angles from self-supporting vacuum-evaporated Au films. The thickness of the films ranged from 166 to 1193 Å. After corrections were applied for the effects of multiple scattering and extrapolating to “zero thickness,”

their data followed the LNS dependence, but implied a somewhat weaker screening than is implied by LNS. Van Wijngaarden, Brimmer, and Baylis¹² measured cross sections for $t^{1/2}$ values down to about unity by using 50–110-keV H⁺, He⁺, Li⁺, and B⁺ projectiles backscattered from Au films ranging in thickness from 75 to 350 Å, vacuum evaporated onto Be substrates. Because they were primarily interested in the multiple-scattering corrections, and because they used the shell-shielded Coulomb cross section, their results do not lend themselves to a direct test of the LNS description. Their work did, however, indicate that the multiple scattering corrections to the cross section for Au films of 75 Å thickness were at most 2% for H⁺ and 3% for He⁺. Andersen, Bøttinger, and Knudsen converted their results into the formulation of Ref. 12 and found that the two sets of data agreed reasonably well. Both papers assume the feasibility of extrapolating to “zero thickness” to correct for multiple-scattering effects.

The work reported here avoids the effects of multiple scattering by the use of ultra-thin vacuum-evaporated targets. The targets were very thin vacuum-evaporated films of high-purity Cu, Ni, Ag, In, Au, and Bi. Average film thicknesses were of the order of 10% of a monolayer as determined from H⁺ backscattering measurements. The films were deposited onto commercial glass-mounted 40- $\mu\text{g}/\text{cm}^2$ carbon foils at room temperature. The system pressure during evaporation was approximately 10^{-7} Torr, and the evaporation time was typically a few seconds. The source was a straight tungsten filament wrapped with a quantity of target material calculated to produce a deposit 2 Å thick on a substrate 0.3 m below, assuming 4π geometry. This calculation overestimated the deposit because the minute amount of evaporating material formed a bead near the top of the filament, thus leaving the substrate partially in the shadow of the filament.

A question arises as to whether clustering of atoms during the evaporation process might have

led to films that were locally rather thick even though less than a monolayer deposition. Although the literature on this problem generally does not discuss all of the specific-target material-substrate pairs employed in this work, it does indicate that our targets have clusters of sufficiently small height to lead to a negligible multiple-scattering correction. Feber, Allen, and Grummer¹³ for instance use a computer to simulate the formation of clusters. Their results indicate that, for 10% of the surface covered at a temperature of 145 °K, slightly over half of the target atoms would be in clusters of one or two atoms, and that the average size of the larger clusters would be slightly less than three atoms. Even with 20% of the surface covered, roughly half of the atoms are in the smaller clusters and the average size of the larger clusters is less than four atoms.

Sacedin and Martin¹⁴ indicate that for a quarter of a monolayer of Ag deposited on graphite at room temperature cluster thickness turned out to be about 10 Å and the largest were slightly over 20 Å, assuming hemispherical cluster formations. Phillips, Deslage, and Akofronick¹⁵ deposited Au on carbon substrates at 500 °K in average thicknesses down to 16 Å. Their data, when extrapolated linearly to our thicknesses, lead to a maximum cluster thickness of 10 Å. As part of the present work, an Au deposit vacuum evaporated onto a 5 $\mu\text{g}/\text{cm}^2$ carbon substrate was enlarged 44 000 times in an electron microscope. This film was nearly one monolayer thick as measured by H^+ scattering and thus was five to ten times the thickness of the films used in the scattering measurements. It was found to have cluster heights up to 10 Å, assuming hemispherical caps. All of the references cited, as well as our confirming test, indicate that the films used in this experiment had cluster thicknesses of considerably less than 10 Å, so that the multiple-scattering corrections are negligible.

Backscattered projectile energies were measured with a 25-mm² Si surface barrier detector. The detector was maintained at a temperature of (0 ± 4) °C. The noise bandwidth was typically 9.6 keV full width at half-maximum (FWHM) for 200 keV full scale. The detector intercepted particles backscattered at 150°, with an acceptance angle of 0.009 sr.

During film deposition, a part of the carbon foil was shielded. Each target was cut to include portions from both coated and uncoated regions. These could be introduced into the beam so that the spectra of both the carbon substrate and the substrate-plus-metal deposit could be observed. The backscattered yield per irradiation dose Y/N was obtained from an integration over the spec-

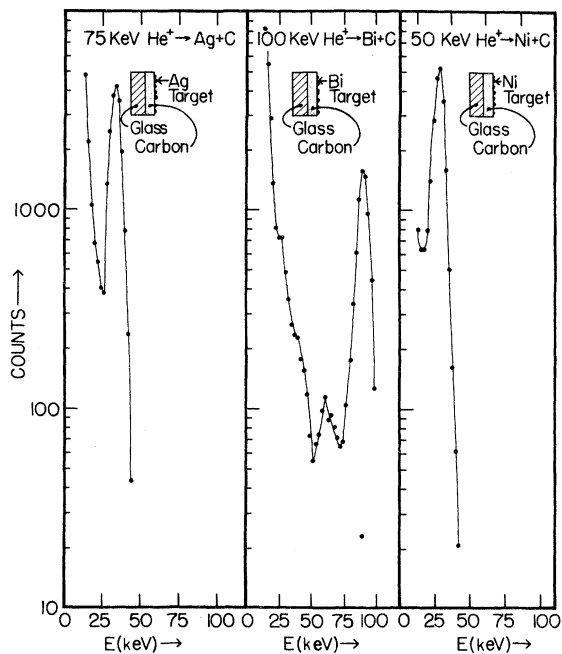


FIG. 1. Typical energy spectrum followed by examples of the best and worst energy separation cases.

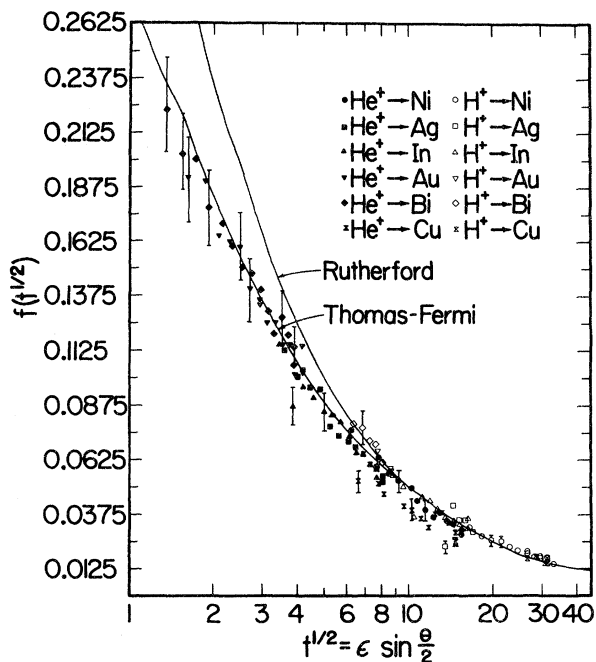


FIG. 2. $f(t^{1/2})$ vs $t^{1/2}$ for He^+ and H^+ ions incident on Ni, Ag, In, Au, Bi, and Cu with incident particle energy of 100–40 keV. Theoretical curves of $f(t^{1/2})$ assuming pure Rutherford scattering and assuming a Thomas-Fermi interaction according to Lindhard, Nielson, and Scharff (Ref. 1) are shown.

trum of the metal-plus-substrate and an integration over the substrate alone. The result of each integration was divided by the corresponding irradiation dose, corrected for leakage currents. The difference between these two numbers was taken as Y/N . The spectrum of the metal was always reasonably separated from that of the carbon. Figure 1 shows typical spectra illustrating the range of separation.

The corrected yield per unit irradiation dose is given by

$$Y/N = D_s \sigma(\Omega) d\Omega, \quad (5)$$

where D_s denotes the surface density of target atoms and $d\Omega$ is the detector acceptance solid angle. Since $dt = \frac{1}{2}(\epsilon^2 \sin\theta d\theta)$, one obtains from Eq. (1)

$$f(t^{1/2}) = (4t^{3/2} / \pi a^2 \epsilon^2 D_s d\Omega)(Y/N). \quad (6)$$

Using the 100-keV H^+ datum for each metal as a

reference then provides a measure of D_s through Eq. (6), with $f_r(t_r^{1/2}) = (1/2t_r^{1/2})$.

The 100-keV H^+ datum was also used as a reference point for the normalization of the rest of the data for each metal. Thus,

$$f(t^{1/2}) = \left(\frac{a_r \epsilon_r}{a \epsilon} \right)^2 \frac{t^{3/2}}{t_r^2} \frac{(Y/N)}{(Y/N)_r}, \quad (7)$$

where the subscript r refers to the 100-keV H^+ values. Figure 2 displays the $f(t^{1/2})$ vs $t^{1/2}$ points, with some typical error bars, obtained from these measurements.

This work points to two conclusions. First, the universal scaling model of LNS describes the cross section for swift-light positive ions with incident energies of 40 keV and above, elastically scattered by a variety of targets. Second, the agreement between this data and that of other workers for similar measurements lends credence to the "zero-depth" extrapolation technique as a reasonable procedure.

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