Differential cross sections for scattering of 300–500-keV H^+, He^+, and Li^+ on selenium in the region of weak screening

H. H. Andersen and H. Knudsen
Institute of Physics, University of Aarhus, DK-8000 Aarhus C, Denmark
(Received 14 March 1974)

Differential cross sections for scattering of 300–500-keV H^+, He^+, and Li^+ through 3–15° have been measured. The targets were 300–9000-Å-thick vacuum-deposited, self-supporting selenium foils. An empirical extrapolation procedure was used to correct for the influence of multiple scattering. The cross sections obtained agree well with the Thomas-Fermi theory, both with regard to scaling and to absolute magnitude.

INTRODUCTION

The differential cross sections for scattering of light ions on atoms have been the subject of study for some years. It was recently shown that the application of an empirical correction for multiple scattering allowed the use of solid target foils in measurements of such cross sections for impact parameters corresponding to a weak screening of the Coulomb interaction.[1] The method was applied to the study of scattering of 300–2000-keV H^+ and 300–500-keV He^+ and Li^+ ions on gold. As argued below, it is of interest to perform measurements also on a lighter material, and selenium was chosen mainly because vacuum-deposited target foils of this material with a wide range of thicknesses are rather easy to obtain.

Differential atomic-collision cross sections based on a Thomas-Fermi (TF) calculation were obtained by Lindhard *et al.*[2] They showed that the cross section to a good approximation could be written as

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

where

$$a = 0.885 a_0 [Z_1^{2/3} + Z_2^{2/3}]^{-1/2}, \tag{2}$$

$$t = \epsilon^2 \sin^2(\vartheta/2), \tag{3}$$

$$\epsilon = E[M_2 a/(M_1 + M_2) Z_1 Z_2 e^2]. \tag{4}$$

Equations (1)–(4) define the TF screening radius a, the reduced cross section f, and the dimensionless, reduced energy ϵ; here a_0 is the Bohr radius of the hydrogen atom; E, M_1, M_2, Z_1, and Z_2 are projectile energy, mass, and atomic number of projectile and target material, respectively; ϑ is the c.m. scattering angle.

The function $f(t^{1/2})$ is determined via the choice of the screening function $\varphi(r/a)$ in the interaction potential

$$V(r) = (Z_1 Z_2 e^2/r)\varphi(r/a). \tag{5}$$

In Ref. 2, for example, the results of a numerical calculation of $f(t^{1/2})$ for φ equal to the TF screening function for a neutral atom were presented. Equation (1) implies that cross sections for all energies, projectiles, targets, and scattering angles may be scaled together into a universal reduced cross section $f(t^{1/2})$.

The experimental results of Ref. 1 showed the TF scaling to work very well for gold as the target material for the $t^{1/2}$ region investigated there ($t^{1/2} > 0.5$). The absolute value of f was slightly larger than calculated from the TF screening function for $0.5 < t^{1/2} < 1.5$, whereas the TF theory and experiment agreed within the experimental uncertainty for $t^{1/2} > 1.5$.

As mentioned above, all results reported in Ref. 1 were obtained on gold targets. As Eq. (1) also implies a scaling with respect to variation of Z_2, we also found it desirable to perform measurements on a lighter target material. Results obtained on selenium targets with 300–500-keV H^+, He^+, and Li^+ scattered through 3–15° will be presented here.

RESULTS AND DISCUSSION

The experimental technique is identical to the one described in Ref. 1 and will only be briefly mentioned here. The intensity of the scattered beam is measured by means of a surface-barrier detector with a small aperture. This detector may be continuously moved through the unscattered beam out to a scattering angle of 15°. Thus the position of the multiple-scattering distribution is known and the scattering angle may be accurately determined (0.05°) from the geometry of the setup. Beam normalization is obtained with another detector fixed at approximately 45° scattering angle.

If it is possible to measure the yield for one projectile, one energy, and one scattering angle, where the cross section may be assumed to be known and where multiple scattering (see below) is assumed to have no appreciable influence, then this

yield may be used to evaluate the target thickness. Such a measurement is performed with 500-keV protons scattered through 15°. With selenium as the target, this particular scattering corresponds to $t^{1/2}=18$. Here, the theoretical cross section is only 2% below the Rutherford cross section and may be assumed to be known accurately enough for normalization purposes. As may be easily seen from the data presented below, the influence of multiple scattering is negligible. Strictly speaking, all cross sections are thus measured relative to the cross section for scattering of 500-keV protons through 15°.

The selenium foils are made by vacuum deposition. Homogeneous, self-supporting foils of thicknesses 300–9000 Å are easily obtained by this method. Because of the high vapor pressure at rather low temperatures, the foils will tolerate only a very weak beam, but we never needed to work with currents exceeding 10^{-10} A.

The target-crystal structure is not expected to influence the scattering yield. The foils were investigated by transmission-electron microscopy and electron diffraction. Only a few grain boundaries could be discerned in the electron microscope, although rather sharp diffraction rings were seen. It was concluded that the foils were nearly amorphous, although their red color implied the monoclinic crystal structure with 32 atoms in the unit cell. Even such a structure is not expected to give rise to a large amount of correlated scattering. The fact that the targets behaved as though they consisted of randomly distributed Se atoms with respect to ion scattering is strongly supported by recent measurements of multiple-scattering distributions. Such distributions are very sensitive to correlated scattering in a simple crystal structure,[3] but in selenium the shape and the width of the distributions agreed with the theory applying to a random target.[4]

The main problem with the type of cross-section measurements used here is corrections for multiple scattering. The measurements do not directly yield $f(t^{1/2})$ but yield rather a thickness-dependent reduced scattering yield $\tilde{f}(t^{1/2})$. If $\tilde{f}$ is depicted as a function of thickness for a fixed value of $t^{1/2}$, extrapolation to zero-thickness yields $f(t^{1/2})$. This extrapolation procedure was discussed in some detail in Ref. 1. Quantitative theoretical support for the method has been obtained in the meantime; hence the method will be further discussed here.

Examples of the raw data (corrected for energy loss of the projectiles while passing through the target) are shown in Figs. 1 and 2. These figures show $\tilde{f}(t^{1/2})$ with the target thickness as a parameter for 500-keV H^+ and Li^+ as projectiles. The thickness dependence of $\tilde{f}$ is clearly seen. For a given thickness, smooth curves are drawn through the measured points, and values of $\tilde{f}$ are read from these curves for a number of different $t^{1/2}$. The $\tilde{f}$ values obtained from the data of Figs. 1 and 2 are shown in Figs. 3 and 4 as a function of thickness with $t^{1/2}$ as a parameter. The curves in Fig. 3 are

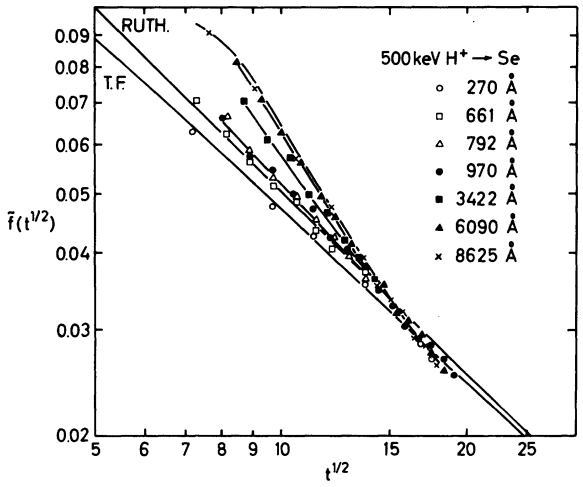

FIG. 1. Reduced scattering yields $\tilde{f}(t^{1/2})$ for the scattering of 500-keV H^+ on self-supporting selenium foils. The measured scattering yields are influenced by multiple scattering. The reduced scattering cross sections $f(t^{1/2})$ may be obtained from the above data by extrapolating to zero thickness. In conversion from atoms/cm^2 to Å, a density of 4.8 g/cm^3 was used for all experimental as well as for the theoretical data.

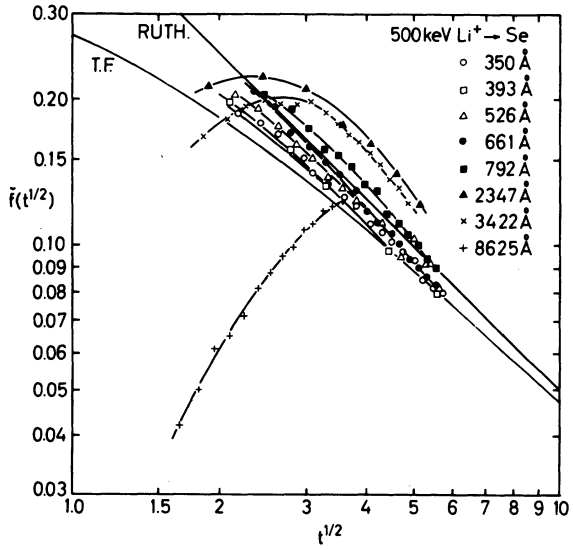

FIG. 2. Reduced scattering yields $\tilde{f}(t^{1/2})$ for the scattering of 500-keV Li^+ on selenium. As in the data of Fig. 1, the reduced yields are strongly influenced by multiple scattering, and the foil thicknesses are given as parameters.

rather well defined, while those in Fig. 4 may look somewhat more dubious. It should, however, still be possible to perform the extrapolations with a fair accuracy.

To support the extrapolation procedure, we have compared our results with theoretical curves. The raw data in Figs. 1 and 2 may, of course, be regarded as representing the tails of multiple-scattering distributions. Thus, the data may also be compared to theoretical predictions of such multiple-scattering distributions. The basis of this comparison is the classical theory of multiple scattering in a TF potential as developed by Meyer[4] and recently by Sigmund and Winterbon[5] (the latter presented extensive tabulations of the distributions applying also to the tails). To use these tabulations, a screening parameter a must be chosen. As measurements of multiple-scattering distributions of light ions in Se films[3] agree very well with theory when the screening parameter (2) is used, we chose the same value. From the tabulations, we have obtained theoretical extrapolation curves, which are shown as dashed lines in Figs. 3 and 4.

It is seen that the theoretical curves extrapolate to zero thickness with the same slope as the experimental ones. This slope to a first approximation determines the size of the multiple-scattering correction for any given $t^{1/2}$ and for small thicknesses. The disparities in curvature and magnitude between theoretical and experimental $\tilde{f}(t^{1/2})$ curves are probably caused by the approximations

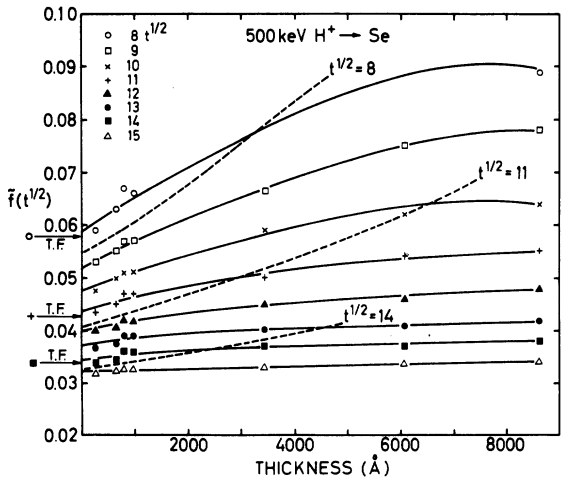

FIG. 3. Empirical correction for multiple scattering of the data of Fig. 1. For fixed values of $t^{1/2}$, $\tilde{f}(t^{1/2})$ is shown as a function of target thickness. The dashed curves are obtained from theoretical distributions (Ref. 5) based on an analytical approximation to the Thomas-Fermi $f(t^{1/2})$ (Ref. 6). Some $f(t^{1/2})$ values calculated by the method of Lindhard *et al.* (Ref. 2) are indicated on the axis.

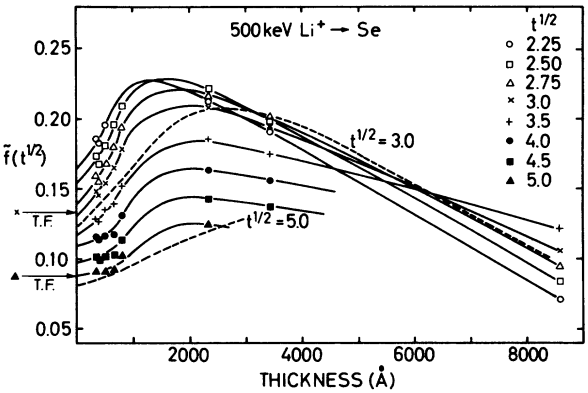

FIG. 4. Empirical correction for multiple scattering performed on the data of Fig. 2. The extrapolation to zero thickness is somewhat uncertain, but good support is gained from the theoretical extrapolation curves based on the computations of Sigmund and Winterbon (Ref. 5). As in Fig. 3, the TF values of $f(t^{1/2})$ belonging to selected values of $t^{1/2}$ are shown.

and corrections involved. The calculated values of Sigmund and Winterbon are seen to extrapolate to $f(t^{1/2})$ values slightly below those predicted by the TF theory. This is owing to the fact that they used an analytical approximation to the Thomas-Fermi $f(t^{1/2})$ curve[6] which, for the values of $t^{1/2}$ used here, yields a slightly too low $f(t^{1/2})$. The rather large deviations between theoretical and experimental $\tilde{f}(t^{1/2})$ curves observed at large thicknesses might be due to the fact that here the energy losses of the ions are not negligible. To calculate the $t^{1/2}$ values, we corrected for energy loss, using the mean energy of the ion as it penetrates the target.

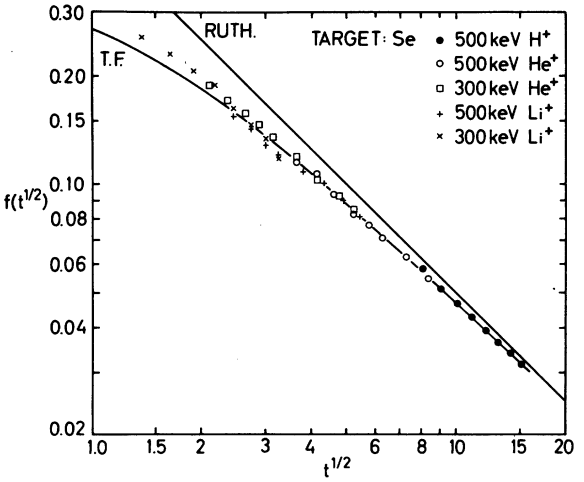

FIG. 5. Reduced differential cross section $f(t^{1/2})$ for scattering of 300–500 keV H^+, He^+, and Li^+ on selenium. All data are corrected for the influence of multiple scattering. Curves belonging to Rutherford (RUTH) and Thomas-Fermi (TF) cross sections are also indicated.

The stopping powers were taken from the work of Northcliffe and Schilling.[7] In extreme cases, the total energy loss is as high as 50% of the incident energy. As the energy losses are assumed to be negligible within the multiple-scattering theory, this theory is not directly comparable to experimental measurements where very thick foils are used. A possible inaccuracy of the stopping power has very little influence on the results for small target thicknesses. Furthermore, the multiple-scattering calculations demand that the absolute scattering angles be small. In the tails of the distributions considered here, the angle is ~15°. However, this was seen to give no deviations between theoretical and experimental multiple-scattering distributions of heavier ions, as presented in Ref. 3.

The $f(t^{1/2})$ values extrapolated according to the above procedure are shown in Fig. 5 together with curves belonging to the unscreened Coulomb and TF potentials. Firstly, the scaling rules are seen to be extremely well obeyed. Different energies as well as projectiles scale together. Secondly, the absolute value fits the TF theory rather well, but below $t^{1/2} \sim 2$, the experimental points are slightly above the theoretical curve. All of this is in good agreement with the results of Ref. 1.

Our measurements are also in agreement with the large-angle scattering work of van Wijngaarden *et al.*[8] on gold, as discussed in Ref. 1. Furthermore, agreement is found with the very limited amount of data published on noble-gas targets.[9,10] Recently, van Wijngaarden and Baylis[11] published results on scattering in mercury vapor. Although this work to some extent overlaps ours in the choice of $t^{1/2}$ values, it is not possible to draw any conclusions with regard to a Z_2 scaling because they normalized to TF theory at $t^{1/2} = 2$.

It may be concluded that the TF scaling in the form of a universal $f(t^{1/2})$ curve is seen to work very well for light projectiles and $t^{1/2} > 1$. This holds for both intermediate and heavy targets. No extensive test has so far been carried out with heavy projectiles in the above range of $t^{1/2}$.

ACKNOWLEDGMENT

We are happy here to thank Dr. Bruce Winterbon, AECL, Chalk River, for placing his extensive computations of multiple-scattering distributions at our disposal prior to publication.

[1] H. H. Andersen, J. Bøttiger, and H. Knudsen, Phys. Rev. A 7, 154 (1973).
[2] J. Lindhard, V. Nielsen, and M. Scharff, Kgl. Danske Videnskab. Selskab, Mat.-Fys. Medd. 36, No. 10 (1968).
[3] H. H. Andersen, J. Bøttiger, H. Knudsen, P. Møller Petersen, and T. Wohlenberg (unpublished).
[4] L. Meyer, Phys. Stat. Sol. B 44, 253 (1971).
[5] P. Sigmund and K. B. Winterbon, Nucl. Instrum. Methods (to be published).
[6] K. B. Winterbon, P. Sigmund, and J. B. Sanders, Kgl. Danske Videnskab. Selskab, Mat.-Fys. Medd. 37, No. 14 (1970).
[7] L. C. Northcliffe and R. F. Schilling, Nucl. Data Tables A 7, 233 (1970).
[8] A. van Winjgaarden, E. J. Brimmer, and W. E. Baylis, Can. J. Phys. 48, 1835 (1970).
[9] P. Loftager and O. Claussen, *Second International Conference on the Physics and Electronics of Atomic Collisions* (MIT Press, Boston, 1969), p. 518.
[10] V. V. Afrosimov, Yu. S. Gordeev, V. K. Nikulin, A. M. Polyanski, and A. P. Shergin, Zh. Exp. Teor. Fiz. 62, 848 (1972) [Sov. Phys.—JETP 35, 449 (1972)].
[11] A. van Wijngaarden and W. E. Baylis, Phys. Rev. A 7, 932 (1973).