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Electronic stopping cross sections of 50–300-keV He and Li ions

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For 50–300-keV He^+ and $^7Li^+$ in C, Al, Cu, Ag, and Au, the applicability of the simplified stopping function is investigated. Using the same targets for He^+ and Li^+ the electronic stopping power S_e in 400–800-Å foils is measured by means of a magnetic spectrometer. The resulting stopping fractions S_e (Li)/S_e(He) can be evaluated to an error of 2%. At energies above 20 keV/amu they are found to be independent of the target material. Applied to our experimental data, the simplified stopping function is shown to be a good approximation in connection with the fits of Andersen-Ziegler for S_e (H) and the stopping ratios.

I. INTRODUCTION

Recent applications of ion implantation and calculations of radiation damage in nuclear reactors have created a special need for stopping-cross-section data. For hydrogen and helium projectiles many electronic stopping cross sections have been measured using the backscattering technique. In the region of heavy ions, however, relatively few experimental data are available. Therefore several attempts have been made to establish a simple physical relation between the stopping cross sections for different ions and targets by scaling laws.[1-4] The present measurements analyze to what extent the target-independent stopping ratios implied in the scaling law can be experimentally verified.

Scaling laws have been shown to be useful tools for systematizing and extrapolating electronic stopping cross sections.[1-4] Making use of the simplified stopping function, (1), unknown stopping cross sections can be derived from data measured for a different ion or target at the same ion velocity[4]:

$$S_e(Z_1,Z_2,V)=P(Z_1^*,V)T(Z_2,V), \qquad (1)$$

$S_e(Z_1,Z_2,V)$ is the cross section, $P(Z^*,V)$ is the projectile function, $T(Z,V)$ is the target function, where Z_1^* is the effective ion charge, Z_2 is the nuclear charge of the target, and V is the ion velocity. One consequence of relation (1) is that the ratios of the cross sections for two different ions at equal velocity are independent of the target material:

$$\frac{S_e(^AZ_1,Z_2,V)}{S_e(^BZ_1,Z_2,V)}=\frac{P(^AZ_1^*,V)}{P(^BZ_1^*,V)}\equiv R(^AZ_1,{}^BZ_1,V). \qquad (2)$$

(Here the indices A and B denote two different ions.) Therefore the stopping ratio R of ions A and B in any target material and the stopping cross section of ion B in the target with nuclear charge Z_2 at the velocity V are sufficient to evaluate the stopping cross section of ion A for the Z_2 target:

$$S_e(^AZ_1,Z_2,V)=R(^AZ_1,{}^BZ_1,V)S_e(^BZ_1,Z_2,V) \qquad (3)$$

In Refs. 3 and 4 S_e is scaled to protons for any ion A. Protons have been chosen because numerous experimental data are available and because the effective charge of hydrogen is independent of energy above 200 keV ($Z_1^*=1$). Hence the ratio

$$P(^AZ_1^*,V)/P(^BZ_1^*,V)$$

only depends on $^AZ_1$ and V for these energies, as shown by Ziegler.[4]

The accuracy of an approximation for S_e is restricted by the limited validity of Eq. (1) and by the errors in the experimental values for R and proton S_e. It is the main objective of the present measurements to investigate to what extent the target-independent stopping ratios presumed in (1) are realistic for helium and lithium ions. For this purpose all experiments were performed using the same set of targets for both ions in order to exclude specific target errors as far as possible.

II. EXPERIMENTAL

The experiment was installed at a 350-keV Danfysik accelerator. For the present foil measurements the same magnetic spectrometer was used as described in.[5] All energy losses were measured for singly charged ions. The ion current did not exceed 15 nA in order to keep faults caused by sputtering as small as possible. A run for determining one energy loss took about 30 sec. The target foils were produced by vacuum deposition on soap-covered glass disks. They floated off in distilled water and were caught on small rings, as used in electron microscopy. The foil thickness was calibrated by means of a microbalance. This calibration imposed the most significant error on the experiments (≈ 5%). All measurements were performed for at least four different sets of targets with different target thicknesses. The stopping ratios are not influenced by this error in thickness calibration, as only the fraction of the energy losses is relevant when using the same foil. The error implied in the energy losses amounted to about 2%. For this experiment the spectrometer was tilted by 6° to the incident beam to eliminate a contribution of particles channeled in the small crystallites forming the foil.[5,6]

III. DATA EVALUATION

The data were collected in a multichannel analyzer (MCA) operated in a multiscaling mode. After completion of a scan, spectra were transferred via CAMAC to a PDP 11/40 computer and stored on a magnetic disk. Off line the MCA spectra were converted into energy-loss spectra. This was accomplished by means of a gauge curve, which related the magnetic field strength to the current in the coil of the bending magnet. For each energy the spectra were recorded with and without the target foil. The energy loss of the ions was calculated by subtracting the mean energy measured for a certain foil from the energy of the beam without a foil. For the energy range investigated here no significant difference between the mean and the most probable energy loss was noted. The resulting energy losses were attributed to a mean ion energy $E = E_0 - \frac{1}{2}\Delta E$. Although the nuclear stopping cross section S_n amounts to $0.1 S_e$ for the lowest ion energies and the highest target masses, no correction for nuclear stopping has been applied. As has been demonstrated by Hvelplund and Fastrup[7] the nuclear contribution to the stopping process is drastically reduced for particles that are transmitted in a forward direction through a thin foil or a gas cell. (See also Ref. 5). The remaining nuclear correction would not have been greater than 1% and hence has been omitted here. The stopping cross sections are derived from the energy losses as $S_e = \Delta E/d$. For d, the results of the weight calibration are used. In all cases at least two different foil thicknesses were used. To exclude an influence of oxide layers on the foils, for ΔE and d the differences $\Delta E = E_2 - E_1$ and $d = d_2 - d_1$ of measurements for two different foil thicknesses d_1 and d_2 were employed.

IV. RESULTS AND DISCUSSION

A compilation of the measurements for helium and lithium ions in carbon, aluminium, copper, silver, and gold foils is given in Figs. 1 and 2.

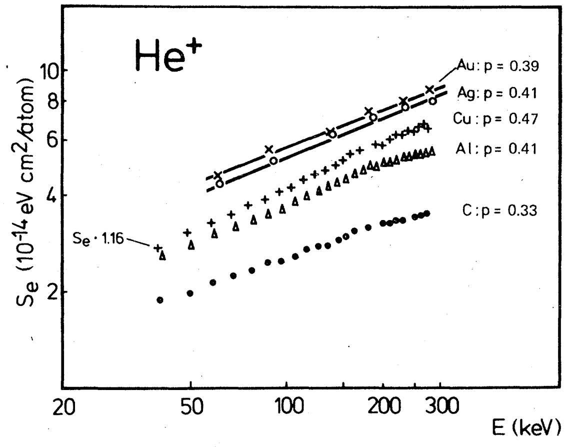

FIG. 1. Energy dependence of the electronic stopping cross section S_e for He$^+$. The p values are the result of a least-squares fit $S_e = \text{const}E^p$ ($\Delta p = 0.005$–0.02). To improve visibility the symbols for Cu are plotted as S_e 1.16.

For three targets the experiment was carried out in steps of 10 keV to check if there was a substructure like an oscillation in the cross sections as a function of energy. Such a substructure would have restricted the applicability of a linear interpolation or a least-squares fit $S_e = \text{const}E^D$. This interpolation is used to derive the ratios of the stopping cross sections. It is obvious from the plots that the points only slightly deviate from a straight line. No substructure can be perceived. Hence the linear fit used for the interpolation in the cases of Au and Ag targets does not produce a systemat-

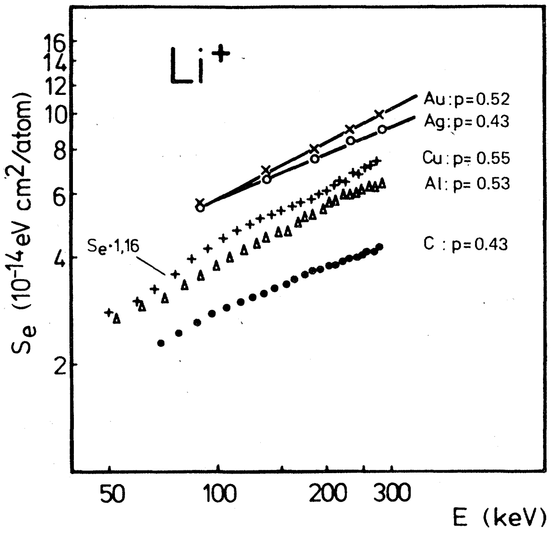

FIG. 2. Energy dependence of S_e for ^{7}Li$^+$.

TABLE I. Stopping cross sections for 50–250-keV helium ions (this experiment and Ziegler's fits in units of 10^{-14} eV cm^2/atom).

	C		Al		Cu		Ag		Au	
E[keV]	exp.	table	exp.	table	exp.	table	exp.	table	exp.	table
250	3.4	3.3	5.4	5.4	5.6	5.4	7.8	8.1	8.1	8.3
200	3.3	3.2	5.0	5.1	5.2	4.8	7.1	7.3	7.4	7.1
150	3.0	2.8	4.5	4.6	4.5	4.2	6.3	6.4	6.6	6.0
100	2.5	2.5	3.7	4.0	3.6	3.4	5.4	5.3	5.7	4.8
50	2.0	1.9	2.8	2.8	2.7	2.4				

ic error.

In Table I the results of the present measurement are compared with the data compiled in Ref. 4. Since the theoretical curves there represent a good interpolation of the experimental data for a very large energy range, the stopping cross sections derived from this curve for helium are accumulated in our table. No systematic deviation among the measured and interpolated values is apparent; the overall agreement is quite satisfactory. Hence it can be stated that the thickness calibration of the thin foils by weight supplied the correct values. For Au and Ag targets the slope of our data is somewhat smaller than that of Ziegler's curve. An influence of nuclear stopping can be ruled out here, as for 50 keV in Au there is $S_n \approx .05 S_e$[8] when all deflection angles are taken into account. On the other hand, the data interpolated for Ag and Au by Ziegler differ measurably from each other. It therefore cannot be decided if this slightly different slope is generally characteristic for foil experiments in the case of heavy elements.

In Table II, our stopping cross sections for Li are compared to data obtained by other authors.[9-12] Our measurements were not run at exactly $E = E_0 - \frac{1}{2}\Delta E = 70$ or 175 keV; the data in the table result from an interpolation or a linear fit. It is apparent that for higher target masses calculated cross sections of Neuwirth *et al.*[10] are significantly smaller than ours.

TABLE II. Comparison of $^7\mathrm{Li}^+$ cross sections.

	C	Al	Cu	Ag	Au	rel. error
175 keV						
this experiment	3.6	5.2	5.0	7.4	7.8	±5%
Neuwirth(calc.)	3.28	5.19	3.84	4.79	4.88	
Neuwirth (exp.)		5.63	4.15			±1%
70 keV						
this experiment	2.3	3.05				±5%
Bernhard et al.	2.2	3.2				±15%
Ormrod et al.	1.86	3.0				±5%

This fact is rather confusing, since our experiments used the same target foils that were taken for the helium runs. For helium, the cross sections obtained agree with the data from other authors. On the other hand, Neuwirth's Doppler-shift attenuation method belongs to the most accurate methods for determining stopping powers,[13] and his calculations agree well with his measurements for tantalum.

Bernhard *et al.*[9] and Ormrod[11,12] carried out a foil experiment similar to ours. The only important difference was that they registered particles that were transmitted exactly in the forward direction ($\phi = 0°$) while we operated at $\phi = 6°$ to avoid an influence of channeling on the energy-loss spectra. For aluminium, all three foil experiments result in almost the same stopping cross section. Ormrod's cross section for carbon is about 17% smaller than the other's experiments. Considering the problems in calibrating thin carbon films, the overall agreement among the foil experiments is satisfying. No indication of a systematic error responsible for the deviation compared with Neuwirth's data can be found.

In Figs. 1 and 2 the exponents resulting from a least-squares fit $S_e = \mathrm{const}E^p$ are indicated. Although it is obvious in the log-log plots that the points are not perfectly described by a straight line, the fit has been extended over all points plotted for the sake of a simpler applicability. For all targets the coefficients p are higher for lithium than for helium. This is due to the fact that the energy range investigated here is already near the maximum of the electronic stopping cross section, which is located in the region of 600–1000 keV for helium. For lithium the p values are oscillating around a mean value of about $p = 0.5$. As the error in p ranges from 0.005–0.02 it can be stated that the linear velocity dependence of S_e around $E = 175$ keV could not be verified. Compared with gas targets investigated by Andersen *et al.*[14] in about the same energy range, the exponent p for foils is about 20% lower.

V. STOPPING RATIOS

The electronic stopping cross sections for helium and lithium ions resulting from the present experiments are found to agree with the data published by other authors. The advantage of this experiment in evaluating stopping ratios is connected with the fact that the measurements with both ions are performed with the same method, using identical target foils. Therefore the precision of the fractions obtained is not restricted by errors in calibrating the foil thickness, energy, etc. The

TABLE III. Ratio of experimental stopping cross sections for He^+ and $^7Li^+$. The measurements are performed with the same set of targets for both ions.

E[keV]/amu	35.7	28.5	21.4	14.2	10
C	1.41	1.39	1.32	1.33	1.21
Al	1.39	1.38	1.34	1.27	1.17
Cu	1.42	1.38	1.38	1.33	1.26
Ag	1.39	1.37	1.38	1.38	
Au	1.42	1.40	1.36	1.29	

limiting experimental error is given by the determination of the energy loss in the foils (≈ 2%). Thus this experiment can detect whether the simplified stopping function (1), applied to the scaling procedure, deviates more than 2% from the physical cross sections.

The fractions of the stopping cross sections for helium and lithium at equal ion velocities, i.e., equal energy per atomic mass unit, are compiled in Table III. The numbers in the Table correspond to 70, 100, 150, 200, and 250 keV for ^7Li. All data were extracted from the measurements plotted in Figs. 1 and 2 by linear interpolation, or using the linear fits (Ag, Au). It turns out that the target-independent stopping ratios implied in Eq. 1 are extremely well verified. Above 20 keV/amu the ratios $S_e(Li)/S_e(He)$ are the same within the experimental error for all the targets investigated. For smaller energies, larger differences in the materials become apparent. Obviously, the ion-target interaction becomes more complicated for this energy region than assumed in Eq. (1).

VI. VALIDITY OF ZIEGLER'S MASTER STOPPING RATIOS

In Ref. 4, Ziegler plotted the ratios $S_e(He)/S_e(H)$ at equal ion velocity (Fig. 3) for a variety of target materials. All these experimental stopping ratios are fitted by a "master curve." This procedure again implies that the stopping ratio is independent of the target material. At energies beyond 100 keV/amu the ratios deviate much more significantly from each other than those observed for lithium and helium in this experiment. It should be noted, however, that the deviations in Ziegler's plot are not necessarily due to a different ion-target interaction at lower velocities; moreover the experimental errors become more dominant in this energy region.

To check the validity of Ziegler's S_e (He)/S_e(H) and $S_e(Li)/S_e(H)$ (Fig. 4) master curve,[15] the stopping cross sections derived are compared with the results of this experiment. For this purpose the following quantities are depicted in Fig. 5: (a) The fit of experimental cross sections for protons in the corresponding material as given in Ref. 16. (b) The fit of experimental cross sections for helium ions in the same material.[4] (c) The product of the H^+ fit for $S_e(a)$ times the stopping ratio $S_e(He)/S_e(H)$ as derived from Ziegler's master curve for helium (Fig. 3). (d) The product of the H^+ fit for $S_e(a)$ times the stopping ratio $S_e(Li)/S_e(H)$

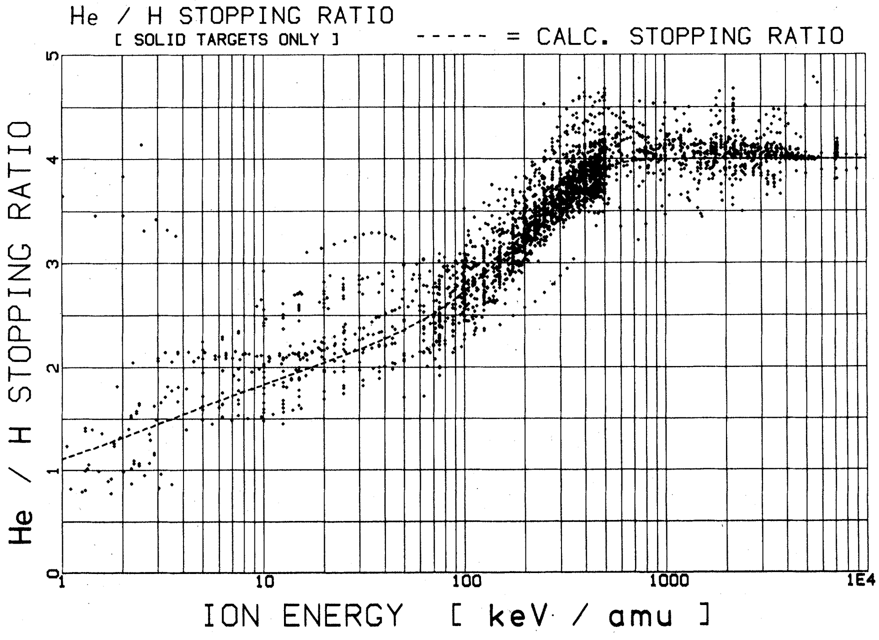

FIG. 3. He/H stopping ratio in solids (Fig. 3(a) in Ref. 4).

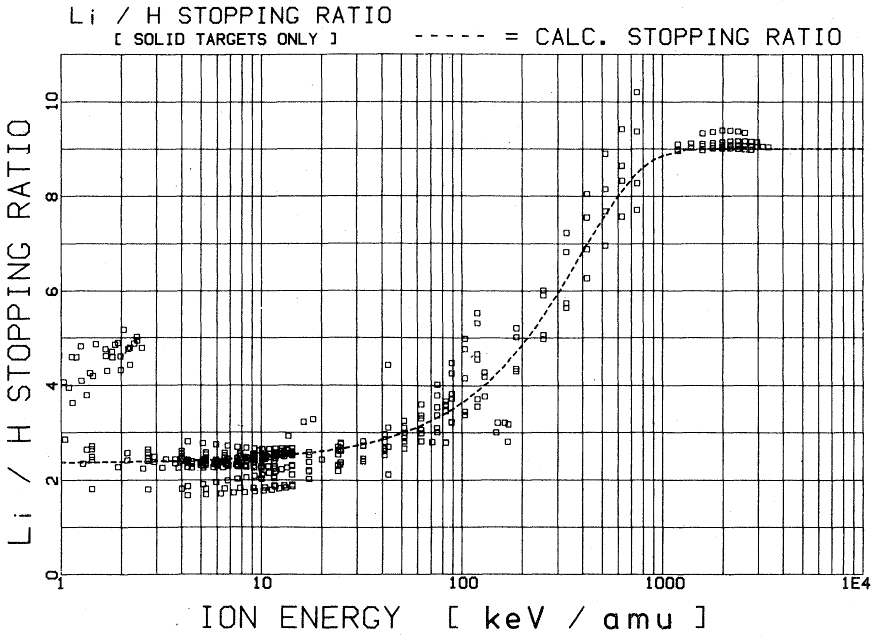

FIG. 4. Li/H stopping ratio in solids (courtesy of Ziegler).

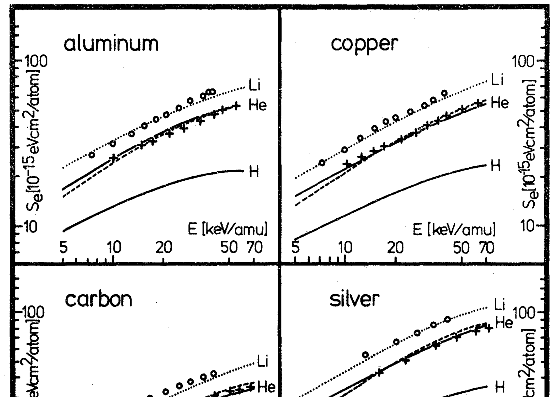

FIG. 5. Validity of Ziegler's scaling factors for helium and lithium ions (7–70 keV/amu).

as derived from Ziegler's master curve for lithium (Fig. 4). (e) S_e—values for helium ions (this experiment). (f) S_e—values for lithium ions (this experiment).

As stated before,[4] the fit for the helium stopping cross sections agrees very well with this experiment. But even the use of the scaling factors for He(*c*) results in about the same values for S_e. Also for Li(*d*) the experimental data can be very well reproduced by using the stopping ratios. The slight deviations for the gold targets are probably due to the fact that the H fit for this material had to be based on relatively few measurements with quite different results.

Finally, it can be concluded that the simplified stopping function (1) is a realistic approach for the electronic stopping cross sections in the energy range investigated here for helium and lithium ions. Above 20 keV/amu the stopping ratios measured for C, Al, Cu, and Ag are identical within the experimental error of 2%. Using Ziegler's master stopping ratios our experimental results can be well reproduced.

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