STOPPING CROSS-SECTIONS AND ATOMIC POTENTIALS

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A strong correlation is shown to exist throughout the periodic table between the dependence of the electronic stopping cross-sections for $^4\text{He}$ ions of a given velocity and the $Z$ dependence of the atomic potentials at a certain radius. An empirical formula is presented which allows the extrapolation of stopping cross-section data for any ion at a given velocity in some elements, to elements for which experimental data are not available. This study covers the energy interval $100 < E/m < 1000$ keV/amu.

In the last few years, several authors have presented measurements and theories about the oscillating behaviour of the stopping cross-section $S$ either as a function of target atomic number $Z_2$ for a given projectile or as a function of projectile atomic number $Z_1$ for a fixed target.$^{1-20}$

Ziegler and Chu$^9$ have presented semiempirical values of $S(Z_2)$ for 400-4000 keV $^4\text{He}$ ions on 92 target materials. These values were derived from experimental data and from the Lindhard-Winther theory for electronic stopping.

Chu and Powers$^4$ have proposed that a Hartree-Fock-Slater (HFS) potential could be used to account for the structure of $S(Z_2)$ they observed for $^4\text{He}$ ions in the region $22 < Z_2 < 29$. We have found that it is possible to fit the semiempirical values of Ziegler and Chu$^9$ at each energy by the expression $S = CVr$, where $V$ is the HFS potential of the target at a certain radius $r$ from the nucleus and $C$ is a constant scale factor. For a given $^4\text{He}$ energy, a fit is obtained using constant values for $r$ and $C$, the oscillatory dependence with $Z_2$ being accounted for only by the variation of $V$ with $Z_2$.

For each data set corresponding to a given $^4\text{He}$ energy $C$ and $r$ were computed to obtain a best fit of the semiempirical $S(Z_2)$ of Ziegler and Chu and the HFS potentials as calculated by Lu et al.$^{21}$ This was done using values for $Z > 20$. The data for elements with $Z_2 < 20$ were not included since the accuracy of the fits is less at these low $Z_2$ values. After establishing $C$ and $r$, $S(Z_2)$ was also calculated for these elements.

Table I shows the values of $C$ and $r$ for different projectile energies. Figure 1 shows $S = CVr$ curves at three different energies together with the semiempirical values of Ziegler and Chu.$^9$ Also shown for 400 keV/amu are the theoretical results of the same authors. It is seen that our curve has the same shape as the theoretical curve but it agrees better with the semiempirical data.

Since the $Z_2$ dependence of $S$ is similar for ions other than $^4\text{He}$,$^{3,5,6,22}$ there is a possibility to obtain values of $S(Z_2)$ for other projectiles for which $S$ is known for some elements. We propose that

$$S(Z_1, Z_2, v) = C(Z_1, v) r(v) V(r, Z_2)$$

where $r$ is given by Table I as a function of the velocity of the projectile $v$ and $C(Z_1, v)$ is a quantity which depends only on $Z_1$ and on $v$.

<table>
<thead>
<tr>
<th>$E/m$ keV/amu</th>
<th>$v$ au</th>
<th>$r$ $a_0$</th>
<th>$C$</th>
</tr>
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<tbody>
<tr>
<td>100</td>
<td>2.00</td>
<td>1.549</td>
<td>35.9</td>
</tr>
<tr>
<td>150</td>
<td>2.45</td>
<td>1.367</td>
<td>32.8</td>
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<td>3.46</td>
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<td>1.064</td>
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<tr>
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<tr>
<td>900</td>
<td>6.00</td>
<td>0.687</td>
<td>8.9</td>
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<tr>
<td>1000</td>
<td>6.32</td>
<td>0.687</td>
<td>8.5</td>
</tr>
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</table>
FIGURE 1 Stopping cross-sections for $^4$He ions as a function of $Z_2$. Full drawn line: semiempirical data of Ziegler and Chu; dotted line: $C \cdot r \cdot V$; and dashed line: theoretical values from Ref. 9.

- a) $E/m = 100$ keV/amu
  - $r = 1.549 a_0$
  - $C = 35.9 \cdot 6.9445 \cdot 10^{-9}$ cm/at.
- b) $E/m = 400$ keV/amu
  - $r = 1.000 a_0$
  - $C = 19.5 \cdot 6.9445 \cdot 10^{-9}$ cm/at.
- c) $E/m = 1000$ keV/amu
  - $r = 0.687 a_0$
  - $C = 8.5 \cdot 6.9445 \cdot 10^{-9}$ cm/at.

This formula was tested by calculating $C(Z_1, v)$ for $^{35}$Cl projectiles of different velocities in the targets Ni, Ge, Y, Ag and Au, using experimental $S$ values of Ward et al. and the values of $r(v)$ given in Table I.

At each velocity, we obtain the same factor $C$ for all the measured elements within 5%, the quoted errors in the experimental data being 4%. This, together with the fact that the elements used cover a wide $Z_2$ range, some of them lying at maxima and minima of the oscillatory $S(Z_2)$ curve, gives a good proof that $C$ is independent of $Z_2$.

The calculated $C$ values, listed in Table II, were then used to extrapolate the data of Ward et al. to other elements. Figure 2 shows the values so derived for $^{35}$Cl ions in Uranium as a function of $E/m$, together with values tabulated by Northcliffe and Schilling. It is interesting to note that the discrepancy between both curves is of the same magnitude as the discrepancy of the semiempirical values of Ziegler and Chu and the tabulations of Northcliffe and Schilling for $^4$He on U.

FIGURE 2 Stopping cross-sections for $^{35}$Cl ions in U as a function of energy per atomic mass unit. Full drawn line: extrapolated from experimental data of Ward et al.; dashed line: from Northcliffe and Schilling.

The same calculations were made for $^{16}$O ions as projectiles, using experimental data of Porat and Ramavataram and Ward et al. for fixed values of the ion velocities. It was again found that $C$ did not depend on $Z_2$.

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