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Single-Electron Capture and Loss Cross Sections vs. Target Z for 1 MeV/u Oxygen Ions Incident on Gases

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SINGLE-ELECTRON CAPTURE AND LOSS CROSS SECTIONS VS.
TARGET Z FOR 1 MeV/u OXYGEN IONS INCIDENT ON GASES

by

Scott Avery Boman

A Thesis
Submitted to the
Faculty of The Graduate College
in partial fulfillment of the
requirements for the
Degree of Master of Arts
Department of Physics

Western Michigan University
Kalamazoo, Michigan
June 1988
Cross sections for 1 MeV/u oxygen projectile ions which have gained or lost an electron after passing through a gas target were measured as a function of target Z for several incident projectile charge states. The targets used were D$_2$, He, Ne, Ar and Kr, and the projectiles had charges of 5+, 6+, 7+ and 8+.

The electron capture measurements are generally in reasonable agreement with existing theoretical and empirical scaling rules. The electron loss cross sections differ appreciably from predictions of the PWBA, particularly for the heaviest targets studied. Empirical scaling relationships are derived for the present capture and loss cross sections which essentially fit all of the data.
ACKNOWLEDGEMENTS

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The following research was partly supported by the United States Department of Energy. This support is appreciated.

In conclusion, I wish to express my gratitude to my family which has supported me during each step of my academic progress.

Scott Avery Boman
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Single-electron capture and loss cross sections vs. target Z for 1 MeV/u oxygen ions incident on gases

Boman, Scott Avery, M.A.
Western Michigan University, 1988
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CHAPTER I

INTRODUCTION

Cross sections for electron capture by, and loss from, few-electron heavy projectiles can be a useful tool for analyzing ion-atom collisions. Electron capture occurs when a positively ionized atom is in close proximity to a neutral atom, and the Coulomb force exerted by the ion exceeds the force that binds the electron to the neutral atom, resulting in a reduction of the initial ionic charge. Electron loss occurs when electrons are excited into the continuum, thereby increasing the charge of the ion or atom.

An understanding of electron capture and loss processes is important for the development of thermonuclear-fusion devices (Drawin, 1978), and for research in astrophysics (Steigman, 1975). Drawin found such elementary reactions to be important when he investigated the dynamics of hydrogen, helium and oxygen Tokamak reactions and the products of their interactions. Steigman used information derived from the study of ion-atom charge transfer to show that certain observed absorption features in spectra could not originate in interstellar gas. Research in these areas can be hampered if cross sections
for the desired projectile species, charge state, energy, and target are not available. Hence, empirical scaling rules can provide a convenient means by which to estimate electron capture and loss cross sections without referring directly to experimental data.

An early attempt to derive a scaling rule for single-electron capture was made by Knudsen, Haugen, and Hvelplund (1981). These authors derived simple estimates of single-electron capture cross sections by using the classical theory of Bohr and Lindhard. Comparisons with existing data showed the estimates to be reasonable approximations.

Schlachter, Stearns, Graham, Berkner, Pyle and Tanis (1983) used electron capture cross section measurements from a number of different experiments to derive a scaling rule for single electron capture as a function of projectile energy, projectile charge state, and target Z. In a more recent effort, Schlachter, Stearns, Berkner, Stockli, Graham, Bernstein, Clark and Tanis (1987) used newer electron capture cross section data to obtain a better, revised scaling rule specifically for helium targets. Data used to obtain the modification were from Clark, Bernstein, Tanis, Graham, McFarland, Morgan, Johnson, Jones and Meron (1986); Hippler, Datz, Miller, Pemiller and Dittner (1987); Graham, Berkner, Bernstein, Clark, McFarland, Morgan, Schlachter, Stearns, Stockli
and Tanis (1985). Projectile species ranging from B(5+) to V(23+) were used in this work.

The scaling rules derived by Schlachter et al. (1983, 1987) were not derived systematically as a function of projectile energy, projectile charge state, and target Z, however. Since a broad range of data is needed to derive accurate scaling rules, and to test the accuracy of prior ones, it is useful to obtain a systematic set of measurements, under well-defined conditions, by varying one parameter at a time. The purpose of the present work is to study the target Z dependence of single-electron capture (and loss) cross sections over a wide range of Z. Additionally, the projectile charge state was varied over a limited range to determine if the target Z dependence varied with charge state. The beam energy remained fixed at 1 MeV/u throughout the present measurements.

Electron loss cross sections have also been a subject of interest and a number of measurements have been made, such as those of Berkner, Graham, Pyle, Schlachter and Stearns (1977); Dillingham, Macdonald and Richard (1981). An attempt was made by Dmitriev, Zhileikin and Nikolaev (1966) to find a theoretical means by which to calculate electron loss cross sections. Also, Choi, Merzbacher and Khandelwal (1973), and Rice, Basbas and McDaniel (1977) derived tables to simplify plane-wave
Born-approximation (PWBA) calculations. The results of the present experiment (for single-electron loss) are compared to these PWBA predictions.

Just as it is useful to have an empirical scaling rule for single-electron capture cross sections, it is also useful to have empirical formulas from which single-electron loss cross sections may be calculated simply and accurately without referring to specific experimental data. An attempt is made to derive such formulas which make it possible to calculate the loss cross sections as a function of the atomic number of the target atoms.

The thesis that follows describes the results of an experiment in which measurements of single-electron capture and loss cross sections were obtained for 16 MeV (1000 keV/u) oxygen ions with the incident charge states, q = 5+, 6+, 7+, and 8+. Deuterium, helium, neon, argon and krypton gases were used as targets. Cross sections for single-electron capture and loss were obtained and compared with previous measurements, theories, and empirical calculations where possible.
CHAPTER II

EXPERIMENTAL METHOD

The experiment was performed on the atomic physics beam line at the Western Michigan University 6 MV EN tandem Van de Graaff facility. After being accelerated to 16 MeV (1000 keV/u), oxygen ions of the desired charge state \(q = 4^+\) were selected with an analyzing magnet which deflected the beam by 90 degrees. The \(\text{O}^{4+}\) ions were then stripped in a carbon foil, following which oxygen ions with charges of \(5^+\), \(6^+\), \(7^+\) or \(8^+\) were selected by a switching magnet and directed into the atomic physics beam line.

A schematic of the experimental apparatus is shown in Figure 1. Ions of the desired charge passed through two sets of insulated collimating slits. The slits, which provided an opening on the order of 0.01 cm\(^2\), defined the beam both horizontally and vertically. The collimated beam of oxygen ions then passed through a differentially-pumped target gas cell which was bounded by two 0.120" apertures 3.65 cm apart. Two additional apertures located 2.94 cm upstream and downstream from the gas cell apertures provided differential pumping and reduced the scattering of ions from the collimating slits.
Figure 1. Schematic of the Atomic Physics Beam Line at W.M.U. (The recoil-ion and x-ray detectors were not used in this work.)
After passing through the gas cell, the beam of emerging oxygen ions was magnetically analyzed into its various charge-state components. Ions having the same outgoing charge as the incident ions were collected in a Faraday cup, while the ions that gained or lost an electron struck solid-state surface barrier detectors.

The number of charge-changed particles striking each of the surface barrier detectors was counted with a scaler, while the main beam current (typically 20 pA), collected in the Faraday cup, was first measured with a Keithley electrometer, and then digitized with a current integrator so the charge could be recorded as counts.

The weak signals produced when charge-changed particles struck the surface barrier detectors were amplified, first by a preamplifier then by a timing filter amplifier (see Figure 2 for a schematic of the electronics). A constant fraction discriminator converted the pulses from the timing filter amplifier into constant amplitude logic pulses which were then counted. A CAMAC crate was used to transfer the scaler counts into the computer. All the data were recorded on disk by the computer.

The pressure dependence of the charge-changed particle fractions was used to calculate cross sections so that systematic errors from slit scattering and background effects could be minimized. Measurements of the
Figure 2. Schematic of Electronics.
charge-changed particle intensities were made at pressures of 5, 3, 0, 2 and 4 microns (in stated order). The gas pressures were staggered to ensure that no time dependent systematic errors would go undetected. The pressure was measured using a capacitance manometer adjusted with a remotely controlled valve. The slope of the pressure dependence and the effective length of the gas cell were then used to calculate the absolute cross sections. A detailed explanation of this method of determining cross sections is in the following chapter. Such measurements were made for all five gas targets and for all four charge states.
CHAPTER III

DATA ANALYSIS AND RESULTS

Using Pressure Dependence to Determine Cross Sections

Under single-collision conditions, in which the total charge-changing probability remains small, the cross sections (\( \sigma \)) for capture and loss are given by

\[
I_{q+1} = I_o t \sigma
\]  

(1)

where:

\( I_{q+1} \) = The number of atoms that undergo either capture or loss.

\( I_o \) = The total number of incident ions that pass through the gas cell.

\( t \) = Target thickness in atoms/cm\(^2\).

Furthermore, \( t = N_0 pL \)  

(2)

where:

\( N_0 = 3.3E+13 \) atoms/(cm\(^3\) \( \mu \))

\( p \) = The gas cell pressure in \( \mu \).

\( L \) = The effective length of the gas cell in cm.

Hence, \( I_{q+1} = I_o N_0 pL \sigma \), where  

(3)
\[ \begin{align*}
I_o &= I_q + I_{q-1} + I_{q+1}.
\end{align*} \]

\( I_q \) is calculated from the current integration settings and is given by:

\[ I_q = 125000 \times (\text{BCI counts})/q. \]  \hspace{1cm} (4)

Since \( N_0 \) and \( L \) are constants, Equation 3 is the equation of a line, where the fraction of particles that undergo capture or loss (\( F_{q+1} = I_{q+1}/I_o \)) is the dependent variable. Then, as long as single-collision conditions are met, \( N_0 \cdot L \sigma \) is the slope of the line. Hence measurements of the fractions (\( F_{q+1} \)) can be made for different pressures and the slope can be found by using the method of least squares fitting. Once the slope is found, the cross sections are obtained from:

\[ \sigma = \text{slope}/N_0 \cdot L \]  \hspace{1cm} (5)

where:

\[ \begin{align*}
L &= L_o + (A_1 + A_2)/2 \\
L_o &= \text{The physical length of the gas cell (1-7/16 \text{"})} \\
A_1 \text{ and } A_2 &= \text{The diameter of the apertures at each end of the gas cell (0.120 \text{"})}
\end{align*} \]

A sample plot of \( F_{q-1} \) vs. \( p \) is shown in Figure 3 for \( 0(6+) + \text{Ne} \) collisions. The absolute uncertainties of the effective length of the gas cell (7\%), pressure in the barocell (10\%), and the Keithley readings (6\%),
Figure 3. The Pressure Dependence of $F(q - 1)$ for 1 MeV/u O(6+) + Ne collisions.
were combined in quadrature with the relative uncertainty of the slopes (10%) to obtain the absolute uncertainty of the cross sections (20%). Comparisons of measurements of yield for the same energy, charge state, and target species were used to estimate the relative error.

Experimental Results

The single-electron capture and loss cross sections were measured for ionized oxygen (q = 5+, 6+, 7+ and 8+) on D₂, He, Ne, Ar and Kr gas targets. The cross sections obtained are listed in Table 1. All of these data are displayed graphically in Figure 4. Open symbols correspond to loss data and solid symbols are for capture data. Data from Dillingham et al. (1981) are included in the plot (diamond and hexagon symbols). Comparison of the present data with the measurements of Dillingham et al. (1981) shows good agreement, with the latter measurements being about 20% smaller than the values obtained in the present experiment. However, this 20% deviation is small compared to the deviations from existing empirical scaling rules. For example, Schlachter et al. (1983) state that their scaling rule for electron capture may deviate by as much as a factor of two from measured values.
Table 1
Electron Capture and Loss Cross Sections
for 1 MeV/u Oxygen

<table>
<thead>
<tr>
<th>Z</th>
<th>q</th>
<th>$\sigma$ (cm$^2$) $q + 1$</th>
<th>$\sigma$ (cm$^2$) $q - 1$</th>
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<td>7.90E-20</td>
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<td>4.16E-19</td>
<td>1.22E-19</td>
</tr>
<tr>
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<td>6.84E-20</td>
<td>2.09E-19</td>
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<td>8</td>
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<td>3.60E-19</td>
</tr>
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<td>1.21E-18</td>
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<tr>
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<td>1.55E-18</td>
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<tr>
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<td>2.55E-19</td>
<td>3.16E-18</td>
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<tr>
<td>2</td>
<td>8</td>
<td>-------</td>
<td>4.83E-18</td>
</tr>
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<td>1.03E-17</td>
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<td>2.27E-17</td>
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<td>4.39E-17</td>
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<td>6.73E-19</td>
<td>8.20E-17</td>
</tr>
<tr>
<td>36</td>
<td>8</td>
<td>-------</td>
<td>1.09E-16</td>
</tr>
</tbody>
</table>
Figure 4. Electron Capture and Loss Cross Sections for 1 MeV/u O(q+) Projectiles.

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Single Electron Capture Cross Sections

Knudsen et al. (1981) used measured single-electron capture cross section data for various ions incident on He, Ar, and Kr combined with theoretical Bohr-Lindhard capture cross sections and the Lenz-Jensen atomic model to derive a universal scaling relationship. The scaling proposed by Knudsen et al. and the capture data from the present experiment are shown in Figure 5 (Part A). All of the data except deuterium are in excellent agreement with the Knudsen scaling. Schlachter et al. (1983) have derived the following scaling rule for single-electron capture cross sections:

\[
\sigma = (1.1E-8)[1 - \exp(-0.037x\tilde{E}^{2.2})]^{2.6} \frac{x[1 - \exp((-2.44E-5)x\tilde{E})]}{\tilde{E}^{4.8}}
\]

where the reduced coordinates (\(\tilde{\sigma}\) and \(\tilde{E}\)) are given by,

\[
\tilde{\sigma} = \sigma Z^{1.8/0.5} \quad \text{and} \quad \tilde{E} = E/(Z^{1.25/0.7} q).
\]

Here \(q\) represents the incident projectile charge state, and \(Z\) represents the atomic number of the target gas. The units to be used in this scaling rule, and in others to be discussed, are \(E(\text{keV}/\text{amu})\) and \(\sigma (\text{cm}^2)\). All the cross sections are in units of \(\text{cm}^2/\text{atom}\), i.e. the meas-
Figure 5. Comparison of Data to Single-Electron Capture Scaling Rules.
(Part A is Knudsen et al. (1981) scaling, and Part B is Schlachter et al.
ured cross sections for molecular hydrogen targets were divided by two.

Cross sections in reduced coordinates from the present experiment (solid points) are displayed in Figure 5 (Part B), along with the scaling curve (solid line) derived by Schlachter et al. (1983). It is evident that the data deviate somewhat from this scaling rule, with the data for krypton being as much as a factor of three larger than the curve.

By using more recent measurements of capture cross sections for helium targets only, Schlachter et al. (1987) have modified the above scaling rule to obtain an improved version applicable to helium targets, given by

$$\sigma = (3.52E-9)[1 - \exp(-0.083x\bar{E}^{1.33})]^{2.85}x[1 - \exp((-7.5E-6)x\bar{E}^{1.25})]/\bar{E}^{4.8}$$

where the reduced coordinates are:

$$\sigma = \sigma^{-1.8}Z^0.7/\bar{q} \quad \text{and} \quad \bar{E} = E/(Z^{1.25}q^{0.5})$$

The reduced data for deuterium and helium from the present experiment (open points) corresponding to this new Schlachter et al. (1987) scaling are displayed along with this latter curve (dashed line) in Figure 5 (Part B). In this case the curve is in agreement with the data for helium as expected. But it is also clear that deuterium obeys this same scaling. In fact, this
curve for helium targets fits the deuterium data better than the earlier curves derived by Schlachter (1983) and Knudsen (1981).

Alternatively, it was found that all the data for electron capture measured in the present experiment, except deuterium, could be fit to a straight line (see Figure 6), for the reduced coordinates

\[ \bar{E} = \frac{E}{q Z} \quad \text{and} \quad \bar{\sigma} = \frac{\sigma Z}{q} \]

Hence for the inert gas targets investigated, the capture cross section is given empirically by

\[ \sigma = (2.35E-21)(q^{3.4})(Z^{1.1}) \text{ cm}^2. \]

The exponents on q and Z for the reduced coordinates were found by varying them one at a time. Each one was adjusted to bring the scaling in close agreement with a straight line. The exponents for Equation 10 and Equation 11 could be varied by as much as 10% without changing the linear nature of the fit displayed in Figure 6.

It is noteworthy that the data which fall on a straight line are for the noble gases; this may mean that this particular scaling rule is a special case applicable only to rare gases. However, the q dependence of this scaling is reasonably consistent with the q^3 scaling found by Knudsen et al. (1981). Also, by using
Figure 6. Alternate Reduced Coordinates Used to Empirically Fit the Present Capture Data to a Line.
the semiclassical continuum theory of Bohr and Linhard, Crothers and Todd (1930) obtain that $\sigma \propto q^3$. Hence it is clear that an exponent on the order of three is expected for the $q$ dependence. This dependence is close to the one derived for Equation 11 (exponent = 3.4).

Electron Loss Cross Sections

Figure 4 shows that the $0(5^+)$ single-electron loss cross sections, for a given target, are on the order of five times larger than the $0(6^+)$ single-electron loss cross sections. This large decrease is expected because an L-shell electron is removed when the $0(5^+)$ is ionized, while the ionization of the $0(6^+)$ (and $0(7^+)$) requires the removal of a more tightly bound K-shell electron.

The electron loss cross sections were found to have a strong target Z dependence for each of the projectile charge states investigated (see Figure 7). Deuterium, the only target that was not an inert gas, does not quite fit the Z dependence observed for the other gases. This may suggest that molecular targets pose a special problem for analysis. Empirical fits to the data yield:

\[
\begin{align*}
q &= 5^+, \quad \sigma = (3.27E-18)Z^{0.98} \\
q &= 6^+, \quad \sigma = (8.83E-19)Z^{0.78} \\
q &= 7^+, \quad \sigma = (2.22E-19)Z^{0.33}
\end{align*}
\]
Figure 7. Electron Loss Cross Sections for $O(q^+)$ as a Function of Target $Z$. (Dashed lines show the predictions of the PWBA, and solid lines show the empirical fits of equation set 12.)
The exponents for Equation 12 could be varied by about about 15% without changing the linear nature of the fit displayed in Figure 7. So it is seen that the Z-dependence of electron loss from the projectile depends strongly on the initial ionic charge state.

In Figure 7, the loss cross sections are also compared to numerical predictions of the plane-wave-Born-approximation (PWBA) model. The PWBA calculations were done with a program written by M.W. Clark. The program made use of tables derived by Choi et al. (1973) and Rice et al. (1977). The dashed lines in Figure 7 show the PWBA predictions. The loss data for light targets seem to be in better agreement with the PWBA than those for heavy targets.

In general the PWBA predicts that \( \sigma \propto Z^2 \), but this is strictly true only for \( Z(\text{projectile}) \gg Z(\text{target}) \). (In the present case the roles of projectile and target are interchanged from their usual designations.) Since the present data are mostly for heavy targets, in which case the PWBA does not strictly apply, the scaling obtained is not inconsistent with the PWBA calculations. It should be noted that the deuterium measurements are in reasonably good agreement with the PWBA as expected. Even though the measured loss cross sections and corresponding theoretical PWBA values for the lighter targets are of the same order of magnitude, there is a deviation
between the two which exceeds experimental error. Hence, the PWBA model appears to be of limited accuracy even when the criteria for the relative masses of the target and projectile are reasonably well satisfied.

R.K. Janev and P. Hvelplund (1981) have plotted the reduced electron-loss cross sections ($\sigma/q$) vs. reduced energy ($E/q$) for the ionization of $H_2$ and He targets. The plots show that the data points for a given ionized species fall upon a common curve, as is predicted by the classical-trajectory-Monte-Carlo method (CTMC). Loss data from the present experiment are used to plot $\sigma/q$ vs. $E/q$ in Figure 8. For each target (which ionizes the O(q+)) the data fall upon smooth curves.
Figure 8. Reduced Ionization Cross Sections ($\sigma/q$) vs. Reduced Energy ($E/q$).
CHAPTER IV

CONCLUSIONS

The single-electron capture data that were obtained in the present experiment indicate that the scaling rule derived by Schlachter et al. (1983) needs to be reevaluated to better account for the target atomic number dependence. However, the data also show that the later version of this scaling rule, derived expressly for helium targets, is accurate for both deuterium and helium.

These single-electron capture data were also found to be in agreement with the scaling suggested by Knudsen et al. (1981) and the $q^3$ dependence predicted by Crothers and Todd (1980).

An alternative empirical scaling rule obtained in the present work was found to represent all of the capture data well except for deuterium as shown in Figure 6. Therefore, this derived relationship may be a special case which only applies to atomic gas targets.

The single-electron loss cross sections for the deuterium target also do not fit the $Z$ dependence observed for the other targets in this work (Figure 7). Since deuterium is the only molecular target investi-
gated, these relationships may be special cases valid for atomic gas targets only. Also, the $Z$ dependence of single-electron loss cross sections differed substantially from the $Z^2$ dependence predicted by PWBA. This latter result is not unexpected since the criteria for validity of the PWBA are not satisfied in the present work.

Finally, a plot of $\sigma/q$ vs. $E/q$ for the loss cross sections shows that the data for ionization by a given target fall on a common curve.
BIBLIOGRAPHY


