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Single-electron capture and loss cross sections versus target Z for 1 MeV/u oxygen ions incident on gases

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In an ion-atom collision electron capture and loss depend, in general, on the beam energy, projectile charge state, and target Z. While most fundamental theories of capture and loss are formulated in terms of a single electron moving in the fields of the pertinent nuclei, various scaling laws have been developed to account for partially stripped ions and multielectron targets. The purpose of the present work is to systematically examine the dependence of capture and loss cross sections on target Z. Cross sections for single-electron capture and loss for 1 MeV/u oxygen ions passing through gas targets were measured as a function of target Z for incident projectile charge states of $5+$, $6+$, $7+$, and $8+$. The targets used were D_2, He, Ne, Ar, and Kr. 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 plane-wave Born approximation, particularly for the heaviest targets studied.

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. Apart from their fundamental interest, an understanding of electron-capture and -loss processes is important for the development of thermonuclear fusion devices and for research in astrophysics. Drawin[1] 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[2] 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 reliable cross sections for the collision systems of interest are not readily available. In general, electron capture and loss depend on the beam energy, projectile charge state, and target Z. Scaling laws can provide a convenient means by which to estimate electron-capture and -loss cross sections in the absence of actual measurements for the system of interest.

A widely used scaling rule for single-electron capture is that of Knudsen *et al.*,[3] which is based on the classical theory of Bohr and Lindhard. Using a purely empirical approach, Schlachter *et al.*[4] 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, charge state, and target Z. In a more recent effort,[5] newer electron-capture cross section data were used to obtain a revised scaling rule applicable specifically to helium targets. Data used to obtain this more accurate estimate were from Clark *et al.*,[6] Hippler *et al.*,[7] and Graham *et al.*,[8] and included projectile species ranging from B^{5+} to V^{23+}.

Electron-loss cross sections have also been a subject of interest and several measurements have been made.[8–10] Dmitriev *et al.*[11] have formulated a theoretical means by which to calculate electron-loss cross sections, and Choi *et al.*[12] and Rice *et al.*[13] have derived tables of plane-wave Born-approximation (PWBA) calculations which can be applied to electron loss. Just as it is useful to have scaling rules for single-electron capture, it is also useful to have a means by which single-electron loss from a projectile may be estimated simply and accurately for a wide range of energies, incident charge states, and target Z. The results of the present data for single-electron loss are compared with PWBA predictions, and, furthermore, are used to derive empirical formulas which parametrize the electron-loss cross sections as a function of the atomic number of the target atoms.

Since a broad range of data are 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 dependence of single-electron capture and loss cross sections for a wide range of target Z. Additionally, the projectile charge state was varied over a limited range to determine if the target Z dependence varied significantly with charge state. Cross sections for 1 MeV/u oxygen projectile ions which have gained or lost an electron after passing through a gas target were measured for targets of D_2, He, Ne, Ar and Kr, and for incident projectile charge states of $5+$, $6+$, $7+$, and $8+$.

The electron-capture measurements are generally found to be in reasonable agreement with existing scaling rules of Knudsen *et al.*[3] and Schlachter *et al.*[4,5] The electron-loss cross sections differ appreciably from predictions of the PWBA,[12,13] particularly for the heaviest targets studied.

II. EXPERIMENTAL METHOD

The experiment was performed using the Western Michigan University 6 MV EN tandem Van de Graaff facility. After being accelerated to 16 MeV (1 MeV/u), oxygen ions with charge $q=4+$ were selected with an analyzing magnet which deflected the beam by 90°. The O^{4+} ions were 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 target region.

Ions of the desired charge passed through two sets of collimating slits which defined the beam horizontally and vertically to a size of about 1 mm^2. The collimated beam of oxygen ions then passed through a differentially-pumped target gas cell which was bounded by 0.30 cm apertures spaced 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. The gas-cell pressure was measured using a capacitance manometer adjusted with a remotely controlled value.

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 were detected with solid-state detectors. The charge-changed particles striking each of the solid-state detectors were counted with a scaler, while the main beam current (typically <20 pA) was first measured with a Keithley electrometer, and then digitized with a current integrator so that the total number of incident ions could be determined for each measurement.

Charge-changed particle fractions were measured as a function of gas-cell pressure to calculate the cross sections from the relation

$$\sigma_i = \frac{\Delta F_i/\Delta P}{N_0 L} , \qquad (1)$$

where $\Delta F_i/\Delta P$ is the slope of the fractional yield, L is the gas-cell length, and $N_0 = 3.3\times10^{13}$ atoms/cm^3 mTorr. Measurements of the fractional yields were made at pressures of 5, 3, 0, 2 and 4 mTorr. The gas-cell pressures were staggered to ensure that any time-dependent systematic errors would be detected. These procedures were used for all targets and incident charge states investigated. A typical plot of the fractional yield for electron capture as a function of the target pressure is shown in Fig. 1.

Errors in the cross sections obtained are due to uncertainties in the effective length of the gas cell (7%), pressure measurement with the capacitance manometer (10%), and measurement of the incident current (6%). These uncertainties were combined in quadrature along with the relative uncertainty of the slopes (10%) to obtain the absolute uncertainty in the cross sections (20%). Comparisons of several independent measurements for the same energy, charge state, and target species were used to estimate the relative uncertainties in the slopes.

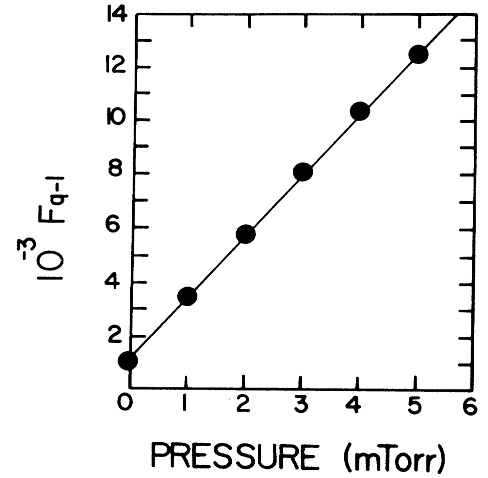

FIG. 1. Pressure dependence of the fractional yield for single-electron capture in 1 MeV/u O^{6+} + Ne collisions.

III. RESULTS AND DISCUSSION

A. Measured cross sections

A list of the cross sections obtained, along with the absolute uncertainties, is given in Table I, and these data are displayed graphically in Fig. 2. Open symbols correspond to loss data and solid symbols are for capture data. Data from Dillingham *et al.*[10] are included in the plot. Comparison of the present data with these earlier mea-

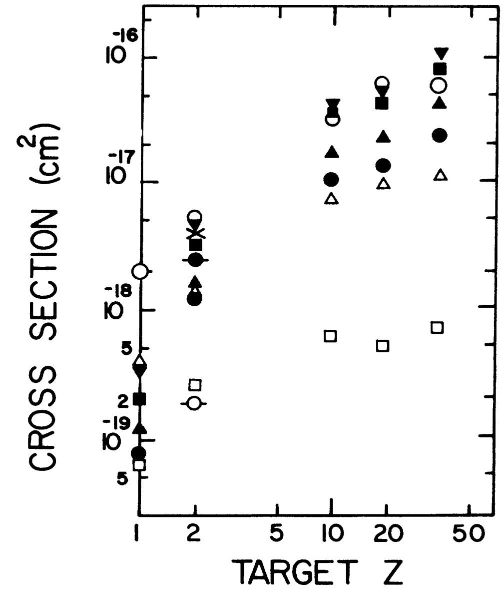

FIG. 2. Single-electron capture and loss cross sections for 1 MeV/u O^{q+} ($q=5,6,7,8$) ions colliding with D_2,He,Ne,Ar,Kr. Symbols represent charge states as follows: circles, 5+; upright triangles, 6+; squares, 7+; inverted triangles, 8+. Solid symbols are for capture and open symbols are for loss. Data from Dillingham *et al.* (Ref. 10) are also shown: ●, 7+ capture; ×, 8+ capture; ○, 7+ loss.

TABLE I. Electron-capture and -loss cross sections for 1 MeV/u oxygen ions incident on D_2, He, Ne, Ar, and Kr. The measured D_2 cross sections have been divided by 2. Uncertainties shown are absolute. $x[y]=x\times10^{y}$.

Target	Z	q	$\sigma_{q,q-1}$ (cm^2)	$\sigma_{q,q+1}$ (cm^2)
D_2	1	5	(7.9±1.6)[−20]	(1.9±0.4)[−18]
	1	6	(1.2±0.2)[−19]	(4.2±0.8)[−19]
	1	7	(2.1±0.4)[−19]	(6.8±1.4)[−20]
	1	8	(3.6±0.7)[−19]	
He	2	5	(1.2±0.2)[−18]	(5.2±1.0)[−18]
	2	6	(1.6±0.3)[−18]	(1.3±0.3)[−18]
	2	7	(3.2±0.6)[−18]	(2.5±0.5)[−19]
	2	8	(4.8±1.0)[−18]	
Ne	10	5	(1.0±0.2)[−17]	(3.3±0.7)[−17]
	10	6	(1.7±0.3)[−17]	(7.3±1.5)[−18]
	10	7	(3.5±0.7)[−17]	(6.1±1.2)[−19]
	10	8	(4.2±0.8)[−17]	
Ar	18	5	(1.3±0.3)[−17]	(6.1±1.2)[−17]
	18	6	(2.3±0.5)[−17]	(9.4±1.9)[−18]
	18	7	(4.4±0.9)[−17]	(5.0±1.0)[−19]
	18	8	(5.2±1.0)[−17]	
Kr	36	5	(2.3±0.5)[−17]	(6.2±1.2)[−17]
	36	6	(4.4±0.9)[−17]	(1.1±0.2)[−17]
	36	7	(8.2±1.6)[−17]	(6.7±1.3)[−19]
	36	8	(1.1±0.2)[−16]	

surements shows good agreement, with the latter values generally being about 20% smaller than the values obtained in the present experiment. The differences are within the experimental uncertainties, however, and are small compared to the observed deviations from existing empirical scaling rules. For example, Schlachter *et al.*[4] state that their scaling rule may deviate by as much as a factor of 2 from measured values.

B. Single-electron capture

Knudsen *et al.*[3] used measured single-electron capture cross sections 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 for capture. The scaling proposed by Knudsen *et al.*[3] and the capture data from the present experiment are shown in Fig. 3(a). All of the data except those for deuterium are in excellent agreement with the predicted scaling. (The measured cross sections for molecular deuterium targets have been divided by 2).

Schlachter *et al.*[4] have derived an empirical scaling rule for single-electron capture cross sections given by

$$\tilde{\sigma}=(1.1\times10^{-8})[1-\exp(-0.037\tilde{E}^{2.2})]\times[1-\exp(-2.44\times10^{-5}\tilde{E}^{2.6})]/\tilde{E}^{4.8}\ , \tag{2}$$

where the reduced coordinates $\tilde{\sigma}$ and $\tilde{E}$ are

$$\tilde{\sigma}=\sigma Z^{1.8}/q^{0.5} \text{ and } \tilde{E}=E/(Z^{1.25}q^{0.7})\ . \tag{3}$$

Here q is the incident projectile charge state and Z represents the atomic number of the target gas. In this scaling rule, and in the others to be discussed here, units of keV/u are used for the energies and units of cm^2/atom for the cross sections.

The data from the present experiment (solid symbols) reduced according to Eq. (3) are displayed in Fig. 3(b) along with the empirical scaling curve (solid line) derived by Schlachter *et al.*[3] It is evident that the data deviate somewhat from this scaling rule, with the results for krypton being as much as a factor of 3 larger than the curve.

By using more recent measurements[6–8] of capture cross sections for helium targets, Schlachter *et al.*[5] have modified the above scaling rule to obtain an improved version applicable only to helium, given by

$$\tilde{\sigma}=(3.52\times10^{-9})[1-\exp(-0.083\tilde{E}^{1.33})]\times[1-\exp(-7.5\times10^{-6}\tilde{E}^{2.85})]/\tilde{E}^{4.18}\ , \tag{4}$$

with the reduced coordinates

$$\tilde{\sigma}=\sigma Z^{1.8}/q^{0.7} \text{ and } \tilde{E}=E/(Z^{1.25}q^{0.5})\ . \tag{5}$$

The reduced data for deuterium and helium from the present experiment (open symbols) corresponding to this new Schlachter *et al.*[5] scaling given by Eqs. (4) and (5) are displayed along with the new empirical curve (dashed line) in Fig. 3(b). In this case the curve is in agreement with the data for helium as expected. The data for deuterium also appear to obey this same scaling. In fact, this new curve for helium targets fits the deuterium data better than either of the earlier scaling rules of Schlachter *et al.*,[4] and Knudsen *et al.*[3]

An examination of the charge-state dependence of the present measurements (not shown) indicate that the data for the noble gases scale approximately as $q^{3.4}$. This q dependence is reasonably consistent with the q^3 scaling found by Knudsen *et al.*[3] Also, by using the semiclassical continuum theory of Bohr and Lindhard, Crothers and Todd[4] show that σ is proportional to q^3.

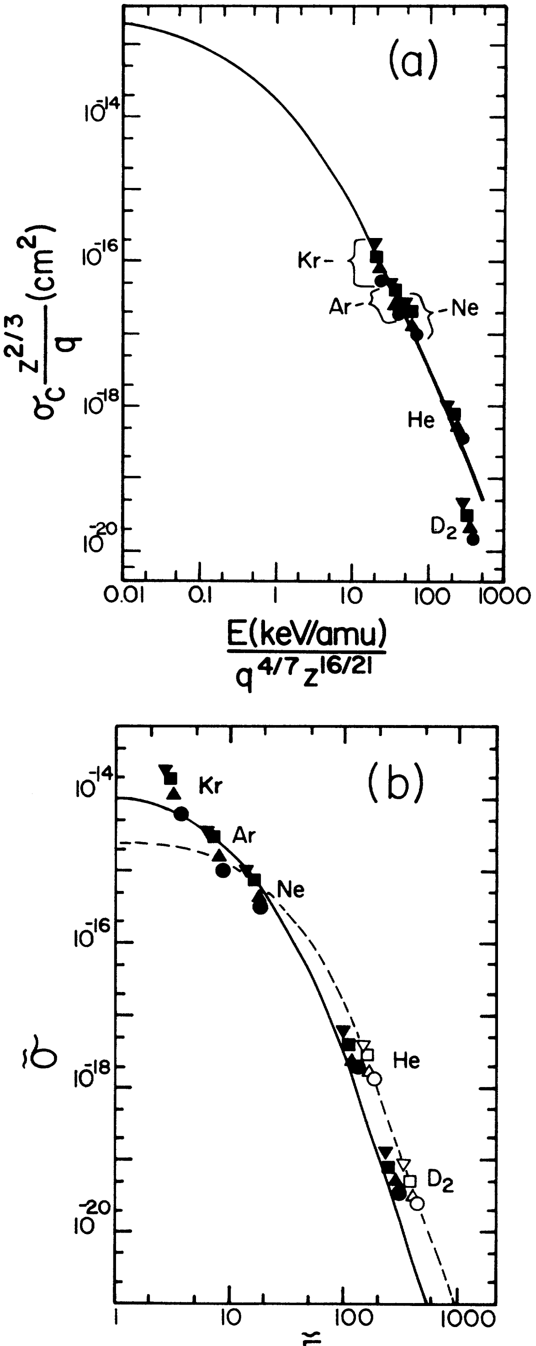

FIG. 3. Comparison of present data to single-electron capture scaling rules. (a) shows a comparison with the Knudsen *et al.* (Ref. 3) scaling, and part (b) is the comparison with the Schlachter *et al.* (Refs. 4 and 5) scaling; solid curve and solid symbols, Ref. 4; dashed curve and open symbols, Ref. 5. Symbols for charge states are the same as in the caption for Fig 2.

C. Single-electron loss

As seen in Fig. 2 the O^{5+} single-electron loss cross sections for a given target are on the order of five times larger than the O^{6+} single-electron loss cross sections, and more than an order of magnitude larger than the O^{7+} cross sections. Such a large decrease with charge state is, of course, expected because an L-shell electron is removed when the O^{5+} is ionized, while the ionization of O^{6+} and O^{7+} requires the removal of a more tightly bound K-shell electron.

The strong target Z dependence of projectile electron loss for each of the projectile charge states investigated is parametrized in Fig. 4 in which σZ^3 is plotted as a function of Z. The solid lines represent empirical fits to the data for each charge state with Z dependences as follows: for $q=5+$,

$$\sigma=(3.27\times10^{-18})Z^{0.98}\ (\text{cm}^2)\ , \tag{6a}$$

for $q=6+$,

$$\sigma=(8.83\times10^{-19})Z^{0.78}\ (\text{cm}^2)\ , \tag{6b}$$

and for $q=7+$,

$$\sigma=(2.22\times10^{-19})Z^{0.33}\ (\text{cm}^2)\ . \tag{6c}$$

In general, the exponents in Eqs. (6) could be varied by about 15% without significantly changing the goodness of the linear fits (solid lines) displayed in Fig. 4. These empirical equations predict the experimental cross sections for electron loss to better than about 25–30 % in all cases expect for deuterium, the only target that is not an inert gas, which does not appear to follow these fits as well as the other gases. This may suggest that molecular targets pose a special problem for analysis, or that simply

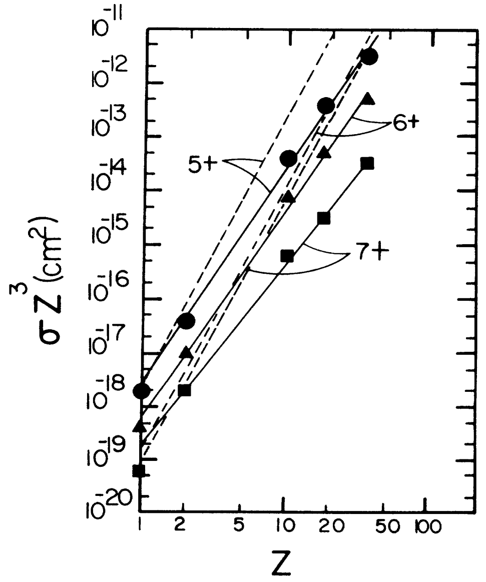

FIG. 4. Parametrized single-electron loss cross sections for 1 MeV/u O^{q+} as a function of target Z. Dashed lines show the predictions of the PWBA, and the solid lines show empirical fits to the data given by Eqs. (6). Symbols for charge states are the same as in the caption for Fig. 2.

dividing the measured molecular cross section by two does not adequately give the atomic cross section.[15]

The loss cross sections are also compared to numerical predictions of the plane-wave Born approximation (PWBA). The PWBA calculations, shown by the dashed lines in Fig. 4, were obtained from the tables of Choi *et al.*,[12] and Rice *et al.*[13] The loss data are seen to be in better agreement with the calculations for light targets than for heavy targets. However, even for the lighter targets the deviation between experiment and theory exceeds the experimental errors in some cases.

In general the PWBA predicts that σ is proportional to Z^2, but this is strictly true only for $Z_{\text{proj}} \ll Z_{\text{targ}}$. (In the present work the roles of projectile and target are reversed.) Since the present data are mostly for heavy targets, in which the case PWBA does not really apply, the observed deviations are not unexpected. It should be noted that the deuterium and helium measurements are in reasonable agreement with the PWBA.

IV. CONCLUSION

Single-electron capture and loss have been investigated systematically as a function of target atomic number for 1 MeV/u oxygen ions incident on D_2, He, Ne, Ar, and Kr. The single-electron capture cross sections were found to be in generally good agreement with the theoretical scaling rule of Knudsen *et al.*,[3] while these same data indicate that the scaling rule derived by Schlachter *et al.*[4] needs to be reevaluated in terms of the target atomic number dependence. The helium data show the more recent scaling rule of Schlachter *et al.*,[5] derived expressly for helium targets, to be quite accurate. Furthermore, this latter scaling was found to accurately predict the present data for deuterium. The q dependence of the measured capture cross sections is generally consistent with the q^3 dependence predicted by the calculations of Crothers and Todd.[14]

The single-electron loss cross sections exhibit a strong target Z dependence, but the results for deuterium do not seem to fit the Z dependence observed for the other targets. Since deuterium is the only molecular target investigated in the present work, this result may indicate that such targets pose a special problem for parametrization. Furthermore, the Z dependence of the single-electron loss cross sections differs substantially from the Z dependence predicted by the PWBA. This latter result is not unexpected since the criterion for validity of the PWBA is not satisfied in the present work.

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