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Contribution of transfer ionization to total electron capture from a helium target

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The contribution of transfer ionization (TI) to total electron capture has been measured for O^{q+} ions ($q=5$, 6, 7, and 8) colliding with helium at energies from 0.5 to 1.5 MeV/u. These measurements, along with other published results, suggest a maximum TI contribution to total capture of $\sim 0.15q^{0.5}$ at E (in keV/u)$/q^{0.5} \simeq 100$. The results demonstrate that the failure to account for transfer ionization in total single-charge-transfer cross sections may lead to large discrepancies between experiment and theory.

Electron capture in collisions between ions and atoms has been studied theoretically and experimentally for several decades. While most of the theories have been formulated in terms of fully stripped ions striking one-electron "atoms," most experimental work has been done on more complex systems. In order to account for electron capture involving multielectron systems, various scaling rules have been proposed based on both theory[1] and on empirical observations.[2] In spite of intensive efforts to understand electron capture and to predict the cross sections, there remain several unanswered questions and discrepancies with experiment, except for perhaps the simple one-electron systems.

In more complex systems, starting with the case of a bare ion striking a two-electron target such as a helium, a complication arises since capture may be accompanied by the loss of additional electrons from the target, a process sometimes referred to as transfer ionization. In general then, the process of electron capture is described by the reaction

$$A^{q+} + B \rightarrow A^{(q-k)+} + B^{i+} + (i-k)e,$$

where $i \geq k$. If $i=k$, then the interaction involves direct capture to a bound state, whereas if $i > k$, then transfer ionization (TI) takes place. In earlier studies[1,2] of electron capture from multielectron targets, no differentiation was made between these two possible single-electron-capture channels. Furthermore, the data did not scale as predicted by theories based on a one-electron target-atom picture.[2] The goal of the present work is to provide information on the branching between these two reaction channels in order to assess the relative contribution to the two-electron transfer-ionization process to single capture.

Several different mechanisms can contribute to the transfer-ionization process. For example, in very slow collisions ($\lesssim 1$ eV/u) Niehaus[3] has shown that TI can result from autoionization of the quasimolecule formed during the collision. At higher velocities (~ 100 eV/u) Cocke *et al.*[4] have attributed TI to double capture by the projectile followed by autoionization. At velocities near 100 keV/u, Andersen *et al.*[5] have obtained evidence that TI is due to the transfer of two electrons to a highly correlated state of the ion followed by the loss of one of the electrons to the continuum. At still higher energies ($\gtrsim 1$ MeV/u), where the electrons can be treated independently, it is expected that TI will be due mainly to single electron capture plus direct impact ionization of the target.

In the measurements reported to date, which have been done primarily for velocities $\lesssim 1$ MeV/u, TI has been found to account for as much as 30% of all the events leading to a reduction of the initial projectile charge state by one unit (i.e., single electron capture). Recently Olson, Wetmore, and McKenzie, *et al.*[6] reported calculations which indicate, for 1 MeV/u projectiles in charge states $q > 10$, that TI may be responsible for up to 80% of all the single-electron-capture events. Likewise, we have presented preliminary measurements and a scaling relationship which show that the TI component can exceed 50% of the total single-electron-capture events.[7]

In this work, we investigate the contribution of TI to total electron transfer as a function of energy and charge state. We limit the discussion to cases involving helium-atom targets. New measurements of TI were obtained for 0.5, 0.75, 1.0, and 1.5 MeV/u O^{q+} + He collisions with incident charge states $q=5$, 6, 7, and 8. The fraction of transfer ionization contributing to the total single-charge transfer is determined and compared with previous measurements at lower energies.

The present measurements were conducted at Western Michigan University using the EN tandem Van de Graaff accelerator. The target consisted of a differentially pumped gas cell 4.0 cm in length. Recoil ions from the

middle 0.8 cm of the interaction region were extracted and then detected with a microchannel plate. Charge-changed ions were magnetically analyzed and detected with solid-state detectors. Coincidences between oxygen ions capturing one electron and singly or doubly charged helium recoil ions were measured with a time-to-amplitude converter using time-of-flight techniques. Coincidence yields were measured as a function of target gas pressure to check for linearity to ensure that single-collision conditions prevailed. Gas pressures were limited to 0.3×10^{-3} Torr which was well within single-collision conditions.

In order to assess the importance of the two-electron TI process relative to total single capture, and to examine the dependence of TI on energy E and charge state q, we define the fraction

$$f=\frac{\sigma^{02}_{q,q-1}}{\sigma^{01}_{q,q-1}+\sigma^{02}_{q,q-1}}\ , \tag{2}$$

where we have adopted the cross-section notation used by previous authors.[5,8] This fraction is just the ratio of the transfer-ionization cross section to all cross sections leading to single electron capture. The fractions f for the present O^{q+} + He measurements are shown in Fig. 1, where it is seen that f decreases with beam energy and increases slightly with charge state. Over this limited energy and charge-state regime f ranges from a high of about 55% to a low of about 30%. The largest value of f we find is 57% for O^{7+} at 8 MeV.

In order to investigate the behavior of TI over wider ranges of E and q, we can compare the present data with previously reported measurements at lower energies. To take into account both the energy and charge-state dependence of f for the various sets of available data, we choose the parameters $f/q^{0.5}$ for the ordinate and $E/q^{0.5}$ for the abscissa. Such a parametrization is close to that used by Schlachter *et al.*[2] for the scaling of the electron-capture cross sections. The resulting scaled data are shown in Fig. 2. In addition to our measured values for O^{q+} ions with

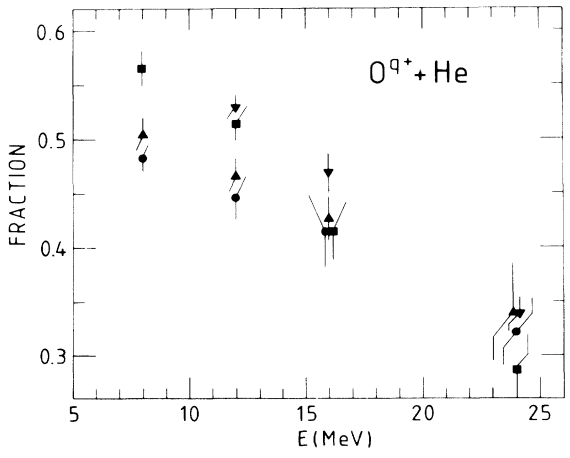

FIG. 1. Fraction of transfer ionization compared to total single-charge transfer, i.e., $f=\sigma^{02}_{q,q-1}/(\sigma^{01}_{q,q-1}+\sigma^{02}_{q,q-1})$. The symbols denote charge states as follows: ●, 5+; ▲, 6+; ■, 7+; ▼, 8+.

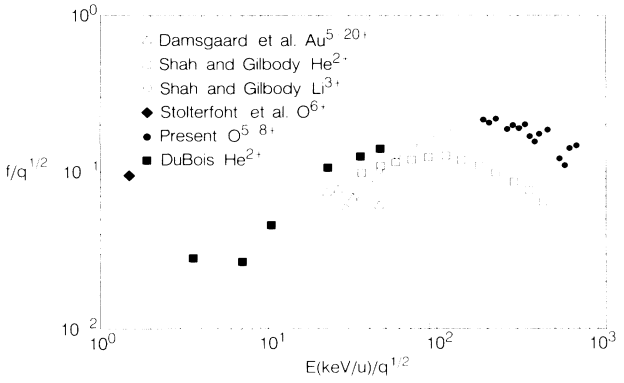

FIG. 2. Scaled TI fraction plotted as a function of $E/q^{0.5}$ with E in units of keV/u. Previously published data are as follows: Shah and Gilbody, Ref. 9; DuBois, Ref. 10; Damsgaard *et al.*, Ref. 12.

$q=5$ to 8 and $E=500$ to 1500 keV/u, the values of Shah and Gilbody[9] for He^{2+} and Li^{3+} ions with energies $E=50$–600 keV/u, are also displayed, as well as the recent measurements by DeBois[10] for He^{2+} at lower energies. Results are also available for Au^{q+} ions with $q=5$–20 at 101.5 keV/u from studies by Damsgaard, Haugen, Hvelplund, and Knudsen.[11] A single point, derived from the recent results of Stolterfoht *et al.*,[12] for 60 keV O^{6+} ions, is also plotted.

Figure 2 suggests that there is a maximum in $f/q^{0.5}$ for $E/q^{0.5}\sim100$ keV/u. The maximum value of f (i.e., the maximum TI fraction) is approximately $0.15q^{0.5}$. Such a maximum may indicate a transition from a region (lower energies) where double capture followed by autoionization is the dominant mechanism for TI to a region (higher energies) where single capture plus impact ionization dominates.

Based on these limited available data, it is difficult to draw definite conclusions regarding the overall energy and charge-state dependence of the TI fraction. In the high-energy regime (≥ 1 MeV/u) of the present $O^{(5-8)+}$ measurements, f is found to vary approximately as

$$f\propto q^{0.25}E^{-0.5}\ . \tag{3}$$

This behavior suggests that at high energies for multiply charged ions, the scaling dependence of the electron-capture cross sections predicted by first-order theories will be questionable due to the lack of incorporating the effect of the TI component in the scattering mechanism.

The reduced energy scaling in Fig. 2 can be justified by using the independent-electron approximation.[13,14] In this model, the numerator of Eq. (2) can be written as

$$\sigma^{02}_{q,q-1}=4\pi\int P_c(b)P_i(b)bdb\ , \tag{4}$$

where $P_c(b)$ and $P_i(b)$ are the electron-capture and ionization transition probabilities calculated within the context of a one-electron model. Since we know from both experiment and theory[1,2] that the denominator of Eq. (2) decreases monotonically for E (in keV/u)$/q^{0.5}\gtrsim1$, we are led to deduce that the TI fraction will be roughly proportional to the product of the electron-capture and ioniza-

tion cross sections. Since the electron-capture cross section is monotonically decreasing, any structure will be due to the ionization mechanism.

The ionization cross section is known experimentally[15] to be at its maximum at E (in keV/u)$/q^{0.65} \approx 100$. The TI fraction shown in Fig. 2 is consistent with this behavior and shows a maximum at E (in keV/u)$/q^{0.5} \approx 100$ as noted above. The magnitude of f at the maximum $\sim 0.15q^{0.5}$ is found to increase with charge state slower than the ionization cross section which varies as $\sim q^{1.3}$ at the maximum.[15] Such a difference probably reflects the additional contribution to f from double electron capture followed by autoionization which is known[4,5] to be important for $E \lesssim 100$ keV/u.

In summary, we have presented new measurements of the transfer-ionization contribution to electron capture for collisions involving helium targets in the velocity range of 0.5 to 1.5 MeV/u for incident charge states $q = 5,6,7$, and 8. This velocity region is higher than that investigated in previously published measurements of TI for helium targets. The present measurements, in conjunction with other measurements at lower energies, tend to show two distinct energy and charge-state regimes, which may correspond to different mechanisms, being responsible for TI in these respective regions. A maximum is found in the TI contribution to total capture for E(in keV/u)$/q^{0.5} \simeq 100$. More work is needed to clearly identify the origins of the TI process and to assess its contribution to the total single-electron-transfer cross section.

Significant in the results presented here is that, for a multielectron target such as He at high projectile energies and charge states, single electron capture is accompanied with high probability by additional target ionization. Such additional ionization mechanisms are not included in first-order theories of single electron capture, and may explain the difference between the predicted and observed scaling of the total single-electron-capture cross sections noted by Schlachter *et al.*[2] The present results clearly demonstrate that the failure to account for the possibility of transfer ionization in measurements of single electron capture may lead to large discrepancies between experiment and theory.

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