Presented at the Conference on the Physics of Multiply Charged Ions,
Groningen, The Netherlands, 17 - 19 September, 1986, and to be published
in Nuclear Instruments and Methods.

CONF-8609252--2

TRANSFER IONIZATION IN 0.5 - 1.5 MeV/u O^{5-8+} + He COLLISIONS

J.A. Tanis
Western Michigan University, Kalamazoo, Michigan 49008 USA
and
Hahn-Meitner-Institut, 1000 Berlin 39, Germany F.R.

M.W. Clark, R. Price, and S.M. Ferguson
Western Michigan University, Kalamazoo, Michigan 49008 USA

R.E. Olson
University of Missouri, Rolla, Missouri 65401 USA

CONF-8609252--2

DE87 005810

ABSTRACT

Transfer ionization (TI), in which electron capture is accompanied by loss of the other electron from the target, been measured for 0.5-1.5 MeV/u O^{q+} ions (q=5-8+) colliding with helium. These new measurements, in conjunction with previous measurements at lower energies, are used to formulate a scaling rule to describe the projectile energy and charge state dependences of TI for collisions involving helium targets.

AC02-83ER13116

Introduction

In the collision between an ion and an atom, transfer ionization (TI) is a term which has been used to describe any process in which electron capture to a projectile bound state is accompanied by the loss of additional electrons from the target, i.e.,

$$A^{q+} + B \rightarrow A^{(q-k)+} + B^{i} + (i-k)e \qquad (1)$$

where i>k. Mechanisms which can contribute to TI include (1) autoionization of the quasimolecule formed during the collision[1], (2) double capture followed by autoionization[2], (3) double capture with associated electron loss to the continuum[3], and (4) single electron capture plus direct impact ionization of the target. The first two mechanisms are expected to dominate at low energies ($\lesssim$ 100 eV/u), the third has been proposed at intermediate energies (~100 keV/u), and the fourth is expected to prevail at high energies ($\gtrsim$ 1 MeV/u). The present study is limited to the case of helium targets for which k=1 and i=2. in Eq. (1).

Recent studies[2-4] have investigated the probability for TI compared to the probability for "pure" charge transfer in which no additional electrons are lost from the target, i.e., i=k in Eq. (1). In the measurements reported to date, which have been done primarily for velocities $\lesssim$ 100 keV/u, TI has been found to account for as much as 50% of all events leading to a reduction in the initial projectile charge state by one unit (i.e. electron capture). Recently, Olson[5] reported calculations which indicate, for 1 MeV/u projectiles in charge states q>5+ incident on helium, that TI may be responsible for up to 80% of all electron capture events.

To test this prediction of Olson, we have investigated the energy and charge-state dependences of transfer ionization over the energy range 0.5 - 1.5 MeV/u for O^{q+} + He collisions with q=5-8+. In addition, a scaling rule describing the ratio of pure charge transfer to transfer ionization as a function of energy and charge state is formulated for helium targets, incorporating these new results and the previously reported measurements at lower energies.

Experimental Procedure

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 interaction region were accelerated and extracted over a 0.8 cm length, and then detected with a microchannel plate. Charge-changed ions were magnetically analyzed and detected with solid-state detectors. Coincidences between oxygen ions capturing an electron and single- 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 of less than 0.3×10^{-3} Torr were typically needed to achieve linearity. Relative cross section values were obtained from the slope of the measured coincidence fractions plotted as a function of gas pressure over the linear region of this dependence.

Results and Discussion

In Figure 1 we show the ratio $\sigma^{01}_{q,q-1}/\sigma^{02}_{q,q-1}$, i.e., the ratio of pure charge transfer to transfer ionization. [Here we have adopted the notation used by previous authors[3,4] in which the subscript refers to the initial and final charge states of the projectile while the superscript refers to the initial and final charge states of the target]. Both $\sigma^{01}_{q,q-1}$ and $\sigma^{02}_{q,q-1}$ decrease with increasing energy (not shown), so the energy dependence of the cross section ratio indicates that $\sigma^{02}_{q,q-1}$ falls off faster with incident projectile energy than does $\sigma^{01}_{q,q-1}$.

These results indicate that low velocities and high charge states are most likely to result in TI in this particular energy and charge state range. The highest fraction of TI events we observe in the present work, compared to all events leading to single capture in the final state, is 57% for 0.5 MeV/u O^{7+}. This fraction is considerably lower than the 80% fraction predicted by Olson[5] for 1 MeV/u ions with $q>5+$ incident on helium targets.

In order to compare our data to those of others and to assess the importance of the two-electron transfer ionization process relative to "pure" single capture, we define the ratio

$$R+1 = \frac{\sigma^{01}_{q,q-1} + \sigma^{02}_{q,q-1}}{\sigma^{02}_{q,q-1}} \qquad (2)$$

From the work of Knudsen et al.[6] and Schlachter et al.[7] it is known that the numerator of Eq. (2) can be parametrized in terms of the inital charge and energy of the projectile. In these earlier works[6,7] no differentiation was made between the two possible electron capture channels, whereas the goal of the present work is to provide information on the branching between the two channels in order to determine the relative importance of the two-electron transfer ionization process as a function of energy and charge state.

To scale our results and those of other investigators, the abscissa was chosen to be $\sqrt{E(\mathrm{keV/u})}/q$, i.e., velocity divided by charge. To encompass the scaling dependences expected over the range of energies for which data are available, the ordinate was taken to be $q^3(R+1)/E(\mathrm{keV/u})$. Fig. 2 shows the results of such a scaling for the present measurements with O^{q+} ions, as well as the scaling for previously reported measurements.[2,8-10] (The data for H^+ + He from Ref. 9 are not included in the plot since the available collision mechanisms for protons preclude double-electron transfer with subsequent Auger or transfer-to-the-continuum events).

All of the measured data closely follow a universal line with a slope of approximately -2.6 which yields the relationship

$$R+1 \approx \frac{40}{E^{0.3}q^{0.4}} \qquad (3)$$

where E is in units of keV/u. This scaling implies that the cross section for the two-electron transfer ionization process will surpass the "pure" single-electron capture cross section at higher energies and charge states. A representative value for ions with q=10+ is that the cross sections will be equal for E ~1.1 MeV/u.

Although the overall features of most of the data in Fig. 2 are reproduced by a single universal curve, a close examination reveals discrepancies. The scaling given by Eq. (3) indicates that R should decrease with increasing projectile energy and charge state. In the case of the present data for O^{q+} + He, the measured charge-state dependence agrees with Eq. (3) while the energy dependence does not (see Fig. 1). The measurements of Shah and Gilbody[9] show a similar deviation at the highest energies investigated.

To account for these deviations, we note that at high energy TI is expected to be mainly due to single-electron capture plus direct impact ionization of the target occurring independently of each other in a single encounter. Hence, the observed breakdown in the scaling given by Eq. (3) is most likely caused by the decreasing target ionization cross section (probability) with increasing projectile energies in the high energy region ($\gtrsim$ 1.0 MeV/u).

The results of the present work, therefore, imply that the energy and charge-state dependences of transfer ionization compared to "pure" single-charge transfer can be scaled to a single universal curve over a large range of energies and charge states. Significant in these results is that, for a multielectron target such as He at high projectile energies and charge states, single-electron capture is accompanied by a high degree of additional target ionization. Such additional ionization mechanisms are not included in first order theories[6,7] of single electron capture, and may explain the difference between the predicted and observed scaling of total single electron capture cross sections.

This work was supported in part by the U.S. Department of Energy under Contract Nos. DE-AC02-83ER13116 and DE-FG02-84ER53175.

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FIGURE CAPTIONS

Figure 1: Measured ratio of cross sections for "pure" single capture, $\sigma^{01}_{q,q-1}$, and transfer ionization, $\sigma^{02}_{q,q-1}$. The symbols represent charge states as follows: ● - 5+; ▲ - 6+; ■ 7+; and ▼ - 8+. Relative uncertainties are estimated to be ± 15%.

Figure 2: Scaled cross section ratio $R = \sigma^{01}_{q,q-1}/\sigma^{02}_{q,q-1}$. The solid line has a slope of -2.6. Previously published data are as follows: Cocke et al., Ref. 2; Damsgaard et al., Ref. 8; Shah and Gilbody, Ref. 9; and Stolterfoht et al., Ref. 10.

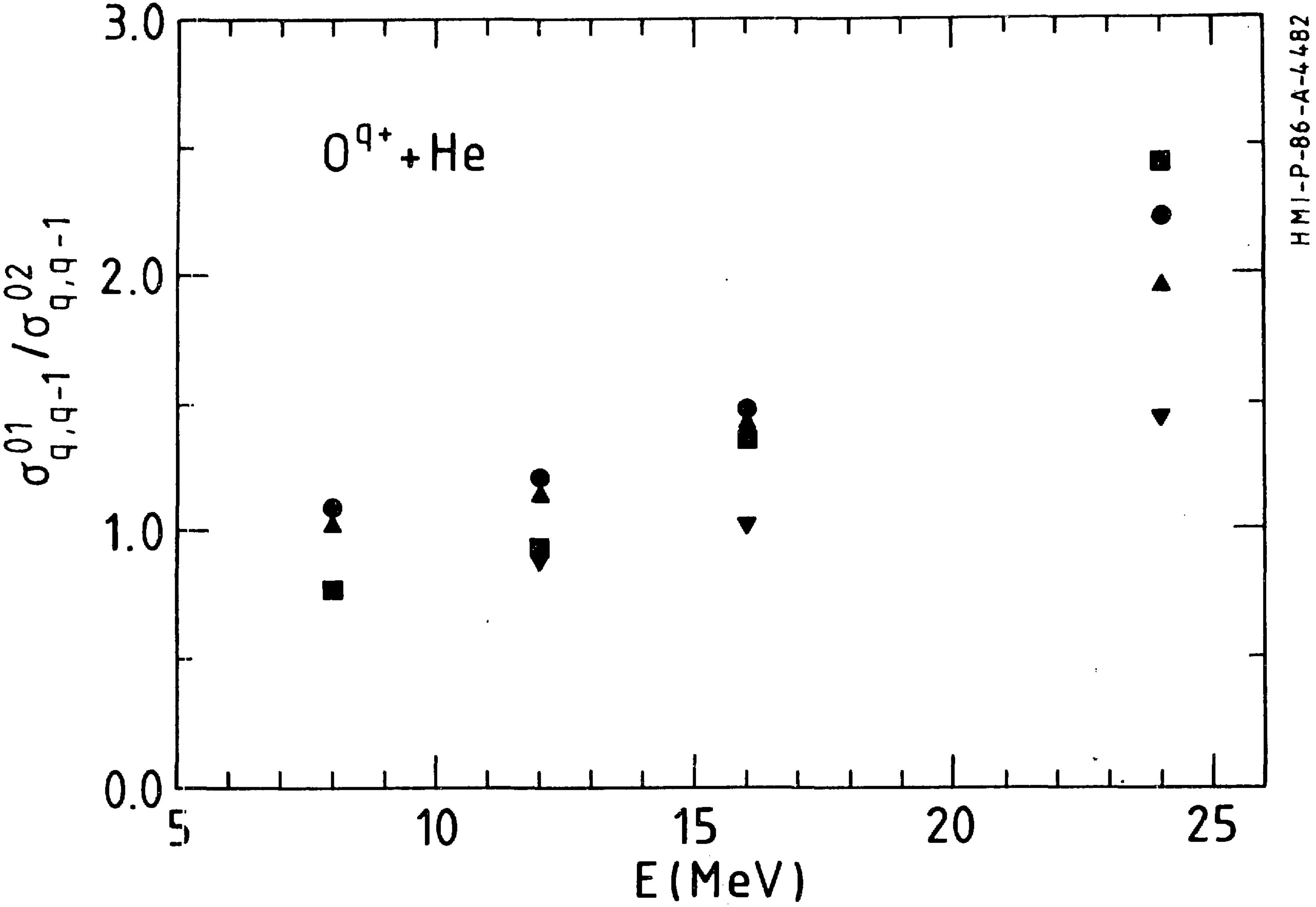
$O^{q+} + He$
$\sigma^{01}_{q,q-1} / \sigma^{02}_{q,q-1}$
E (MeV)
0.0
1.0
2.0
3.0
5
10
15
20
25
HMI-P-86-A-4482

Fig. 1

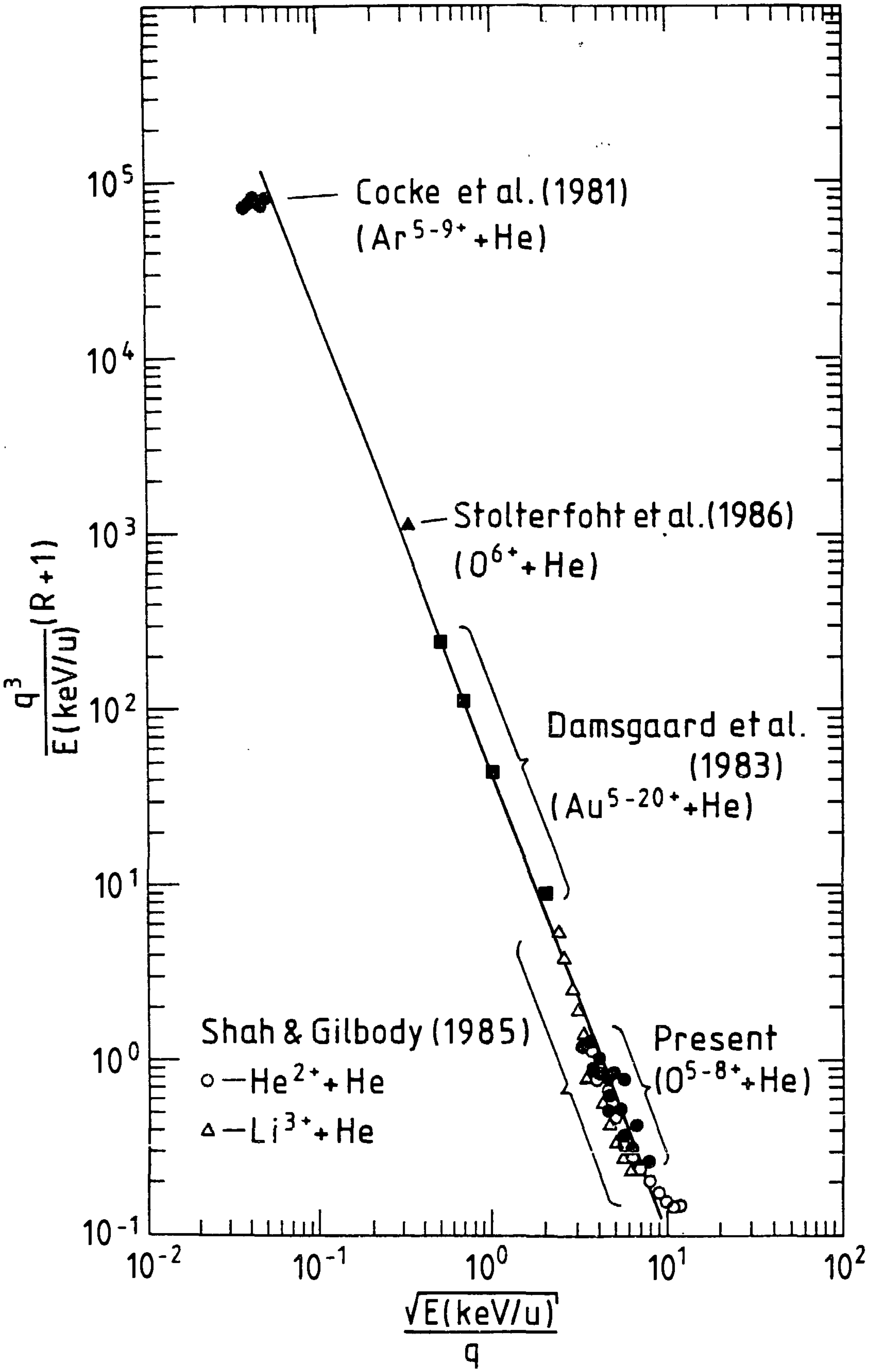
10^5
10^4
10^3
10^2
10^1
10^0
10^-1
10^-2
10^-1
10^0
10^1
10^2
q^3 / E(keV/u) (R+1)
√E(keV/u) / q
Cocke et al. (1981)
(Ar^5-9+ +He)
Stolterfoht et al. (1986)
(O^6+ +He)
Damsgaard et al.
(1983)
(Au^5-20+ +He)
Shah & Gilbody (1985)
○ —He^2+ +He
△ —Li^3+ +He
Present
(O^5-8+ +He)

Fig. 2