Dissociative and non-dissociative charge-changing processes in 1.0-2.0 MeV/u O$^{5+}$ + O$_2$ collisions

D P Cassidy, E Y Kamber, A Kayani and J A Tanis

Department of Physics, Western Michigan University, Kalamazoo, MI 49008 USA

E-mail: john.tanis@wmich.edu

Abstract. In the present work molecular ionization and dissociation correlated with projectile single electron capture and loss is investigated as a function of energy for O$^{5+}$ + O$_2$ collisions. Coincidence recoil-ion spectra as well as total projectile charge-changing yields were measured for projectile energies of 1.0, 1.5, and 2.0 MeV/u. Charge states for dissociative and non-dissociative recoiling products of the target molecular oxygen were identified. Ratios of charged molecular fragment yields to single non-dissociative ionization yields as a function of projectile energy were determined as well as total cross sections for projectile single electron capture and loss.

1. Introduction

Fundamental interactions of molecular oxygen during collisions with charged particles are relevant to numerous fields of study including but not limited to astrophysics, atmospheric physics, biophysics, and plasma physics [1]. These interactions are especially relevant to the life sciences as both atomic and molecular oxygen are abundant in most living matter, as well as being one of the essential components of many organic molecules. The generation of ion-radiation induced reactive oxygen and how it affects surrounding cellular tissue is a primary example [2]. Within the field of atomic physics results for the ionization of molecular oxygen by fast ions are important for analyzing the fragmentation of H$_2$O and other molecules. Similar work has been the subject of recent attention for protons, neutral hydrogen, and carbon projectiles [3] [4] colliding with H$_2$O. In an effort to gain additional understanding of these and other such interactions, dissociative and non-dissociative ionization of O$_2$ associated with single electron capture, single electron loss, and direct ionization have been investigated for 1.0, 1.5 and 2.0 MeV/u O$^{5+}$ + O$_2$ collisions.

2. Experimental setup

The measurements were conducted at Western Michigan University using the 6 MV tandem Van de Graaff accelerator. An O$^{5+}$ beam was collimated to a diameter of about 2 mm before entering the target region. In the target region the O$^{5+}$ projectile beam impacted an O$_2$, Ne, or He gas target contained within a differentially pumped target cell 4.0 cm in length. The pressure in the target cell, monitored by a capacitance monometer system, was varied between 0 - 2 mTorr.

Time-of-flight techniques were used to detect coincidences between recoiling charged molecular and atomic oxygen fragments and individual outgoing projectile charge states. The recoiling

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1 To whom any correspondence should be addressed.
target ions were extracted transverse to the beam direction by an electric field created by a pair of electrodes biased at ±1000 volts respectively. Following extraction the fragments drifted in a field-free region at a velocity determined by their charge-to-mass ratio and then were detected using a set of coupled microchannel plates. Meanwhile the outgoing projectile beam was magnetically analyzed and the individual charge-changed components were detected using silicon surface-barrier detectors to determine the respective coincidence and total charge-changing yields. Simultaneously the unchanged primary beam was collected in a Faraday cup for normalization.

Figure 1. Relative yields for ionization and fragmentation of molecular oxygen associated with projectile single electron capture (left panel) and loss (right panel) for 1.0, 1.5, and 2.0 MeV/u O$^{5+}$ + O$_2$ collisions normalized to the incident beam current. The bottom panel in each case shows the corresponding normalized spectrum for 2.0 MeV/u O$^{5+}$ + Ne.

3. Results and data analysis

Typical coincidence spectra are shown in figure 1. The spectra show recoiling products of the target molecular oxygen with charge states as high as 4+ for capture and 3+ for loss. All of these spectra were collected at a pressure of 2.0 mTorr and are normalized to the total beam current and as such show the changing fragmentation yields of measured coincidences as the beam energy increases.

To ensure the validity of the O$^{5+}$ + O$_2$ data and to determine the recoil-ion products, additional recoil-ion spectra for He and Ne, as well as total projectile charge-changing yields, were measured for projectile energies of 1.0, 1.5, and 2.0 MeV/u. For each of the three target gases at all energies a minimum of three pressures was used, typically with values of 0.5, 1.0, 1.5, and 2.0 mTorr. The pressure dependence was used to determine the fractional yields and to check that the experiment was within single collision conditions. In addition spectra for no target gas were measured for purposes of background correction.

For O$^{5+}$ + He the fractional yields for total projectile capture and loss were determined by normalizing the measured numbers of counts to the total incident beam current and plotting the results as a function of the target gas pressure. Then the He total capture and loss cross sections were determined from
where $F$ is the fractional yield, $P$ is the target gas pressure, $(\Delta F/\Delta P)$ is the slope of the linear regression of $F$ vs. $P$, $K = 3.3 \times 10^{13}$ atoms/mTorr-cm$^3$, $L$ is the target length in cm, and $\epsilon$ is the detection efficiency (assumed to be unity for the surface-barrier detectors). The calculated He cross sections for 1.0 and 1.5 MeV/u O$^{5+}$ were compared to previous results [5] [6] and subsequently used to check for systematic error, which was found to be about 20%. The He electron capture cross sections also provided an overall normalization factor, which was used to determine the total capture and loss cross sections for O$^{5+}$ + O$_2$ as well as the cross sections for recoil-ion production.

The recoiling molecular and atomic oxygen peaks in the coincidence spectra were identified by comparison with the spectra for O$^{5+}$ + Ne (see figure 1) for which the peaks are readily identified [7]. The observed peaks for oxygen were integrated, the background subtracted, and the ratios of the charged molecular fragment yields to the single non-dissociative ionization yields of molecular oxygen associated with projectile single electron capture and loss as a function of projectile energy were calculated as shown in figure 2. The ratios associated with electron capture increase nearly uniformly over the energy range measured, while those associated with electron loss increase non-uniformly. The fragment ratios associated with electron capture are generally larger than those associated with electron loss likely because capture has a higher probability to be accompanied by
excitation or ionization. While the underlying mechanisms for the observed dependences are unknown, more data are clearly needed over a broader range of energies to better define the behaviours with collision energy.

The fractional yields for total electron capture and loss as a function of pressure were also determined for O$_2$, and the corresponding cross sections were obtained using equation 1 and by normalizing to the known He cross sections [5] [6]. These cross sections with their systematic plus statistical uncertainties are listed in table 1.

### Table 1. Total single capture and loss cross sections for 1.0, 1.5, and 2.0 MeV/u O$^{5+}$ incident on molecular oxygen with absolute uncertainties. Scaled estimates from other work are given for comparison.

| Energy (MeV/u) | $\sigma_{q,q-1}$ ($\times 10^{-18}$ cm$^2$) | Ref. [8]$^a$ | $\sigma_{q,q+1}$ ($\times 10^{-17}$ cm$^2$) | Refs. [5] [9]$^b$ |
|---------------|------------------------------------------|-------------|------------------------------------------|-------------------|
| 1.0           | 10±2                                     | 25          | 3.5±0.7                                  | 4.2               |
| 1.5           | 2.9±0.6                                  | 9.3         | 4.4±0.9                                  | 8.0               |
| 2.0           | 0.29±0.06                                | 4.2         | 23±5                                     | 15                |

$^a$ Calculated from Ref. [8] assuming that the cross section for O$_2$ is twice that for O.

$^b$ Estimated by scaling results for Ne targets in Refs. [5] [8]

### 4. Conclusion

Ratios of charged molecular fragment yields associated with projectile charge-changing have been investigated for 1.0-2.0 MeV/u O$^{5+}$ + O$_2$ collisions. Measured yields for the molecular and atomic recoil-ion products were compared to the yields for singly-charged non-dissociative O$^+$s. Additionally, total projectile electron capture and loss cross sections were determined for O$^{5+}$ + O$_2$. This study of molecular oxygen ionization and dissociation correlated with projectile single electron capture and loss for O$^{5+}$ + O$_2$ collisions will be extended to a wider range of incident energies. This will help to better determine the energy dependence of these ratios. Other projectile ion charge states will also be investigated, particularly fully-stripped and hydrogen-like ions. This information combined with data already available can be used to further investigate the more complex system of O$^{9+}$ + H$_2$O.

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