J. Phys. B: At. Mol. Opt. Phys. **29** (1996) 2847–2853. Printed in the UK

Electron capture in collisions of 5–67 keV amu^{-1} He^{2+} ions with oxygen atoms

W R Thompson, M B Shah and H B Gilbody

Department of Pure and Applied Physics, The Queen's University of Belfast, Belfast, UK

Received 26 March 1996

Abstract. A crossed beam technique incorporating time-of-flight analysis and coincidence counting of the collision products has been used to study O^+ and O^{2+} formation in both one- and two-electron capture by 5.3–66.7 keV amu^{-1} He^{2+} ions in collisions with ground-state oxygen atoms. In the case of one-electron capture, cross sections for simple charge transfer, which are known to be dominated by the $He^+(n = 2) + O^+\,{}^4S$ product channel at low energies, are found to attain a large peak value of about 1.8×10^{-15} cm^2 at about 20 keV amu^{-1}. The low-energy trend of these cross sections is in satisfactory accord with the single value measured previously at 2 keV amu^{-1} in this laboratory using a different technique. There have been no other experimental or theoretical studies of the He^{2+}–O collision system. Production of O^{2+} ions, mainly by transfer ionization involving one-electron capture, is surprisingly effective with the O^{2+}/O^+ production ratio increasing from 0.23 to 0.64 over the energy range considered.

1. Introduction

A detailed understanding of the complex way in which energetic ions of extra-terrestrial origin interact with the Earth's upper atmosphere continues to be of considerable interest. In this context, reliable laboratory measurements of collision processes involving atomic oxygen as a primary constituent of the high atmosphere are important. In recent work in this laboratory (Thompson *et al* 1996) we used a crossed beam technique incorporating time-of-flight analysis and coincidence counting of the collision products to study one-electron capture by 6–100 keV protons in collisions with ground-state oxygen atoms derived from an iridium tube furnace source. In this case, one-electron capture at low energies is dominated by the accidentally resonant simple charge transfer process associated with the $H(1s)+O^+\,{}^4S$ product channel. However, we also showed that transfer ionization involving one-electron capture simultaneous with double ionization of oxygen became significant at the higher impact energies, accounting for about 18% of the total one-electron capture cross section at 100 keV. This observation may be significant in the interpretation of O^{2+} production in the upper atmosphere where Geos satellite data (Geiss *et al* 1978) show local O^+/O^{2+} concentration ratios as high as 30%.

In the present work we have used the same experimental approach to study both one- and two-electron capture by He^{2+} ions. Although protons are the primary ionic constituent of the solar wind (including the more energetic products of solar flares), alpha particles are an important minor constituent comprising about 5% of the total (cf Johnson 1990). The simple charge transfer process for collisions with ground-state oxygen atoms

$$He^{2+} + O(2s^2 2p^4)\,{}^3P \rightarrow He^+ + O^+ \qquad (1)$$

0953-4075/96/132847+07$19.50

is of special interest since, like the corresponding He^{2+}–H(1s) process, it is accidentally resonant for capture of a 2p electron into the $n = 2$ states of He^+. However, while He^{2+}–H(1s) electron capture has been the subject of many experimental and theoretical studies (cf review by Gilbody 1994), the only previous study of electron capture in He^{2+}–O collisions has been limited to a single experimental measurement carried out in this laboratory (McCullough *et al* 1992). In that work, translational energy spectroscopy with atomic oxygen contained within an iridium tube furnace was used to confirm that, at the single energy of 2 keV amu^{-1}, the $He^+(n = 2) + O^+ {}^4S$ product channel is dominant, accounting for about 90% of the total cross section. In the present work we have obtained cross sections ${}_{20}\sigma_{11}$ for (1) in the energy range 5.3–66.7 keV amu^{-1}. Within the same energy range, cross sections ${}_{20}\sigma_{12}$ for the transfer ionization process

$$He^{2+} + O(2s^2 2p^4)\,{}^3P \rightarrow He^+ + O^{2+} + e \tag{2}$$

(which could include a He^+ contribution arising from autoionizing two-electron capture collisions) have also been determined. The total cross section for one-electron capture may be expressed as $\sigma_{21} = \sum {}_{20}\sigma_{1n}$ and the extent to which transfer ionization processes (for which $n > 1$) contribute to σ_{21} and lead to multiple ionization of oxygen is of interest.

We have also determined cross sections ${}_{20}\sigma_{02}$ for simple charge transfer in the two-electron capture process

$$He^{2+} + O(2s^2 2p^4)\,{}^3P \rightarrow He + O^{2+}. \tag{3}$$

2. Experimental approach

2.1. General description

The experimental approach was essentially the same as that used in our recent studies of H^+–O collisions (Thompson *et al* 1996). The basic method together with the measuring and calibration procedures are similar to those used in our earlier studies of collisions involving H and H_2 (Shah and Gilbody 1981, 1982). Since full experimental details may be found in these earlier papers, only a brief description of the main features need be repeated here.

A momentum analysed beam of ${}^3He^{2+}$ ions of selected energy within the range 5–67 keV amu^{-1} was arranged to intersect (at right angles) a thermal energy beam of partially dissociated oxygen in a differentially pumped region maintained at a pressure not exceeding 2×10^{-7} Torr. As in our previous work the oxygen beam was derived from an iridium tube furnace source. The tube was directly heated to a temperature of about 2300 K (determined by an optical pyrometer) by passing an alternating current through it. Oxygen gas, introduced at one end of the tube, flowed through it at a constant rate and emerged through a 2 mm diameter aperture at the midpoint of the hot central region. In order to obtain satisfactory signal to background ratios, the oxygen flow rate had to be raised (as in our previous work) to a level where the dissociation fraction was reduced to about 0.5.

Slow ions and electrons formed as collision products in the crossed beam region were swept out by a transverse electric field of up to 75 V cm^{-1} applied between two high transparency grids on either side of the crossed beam region. Particular care was taken to ensure that the small deflection of the primary beam produced by this field caused a negligible change in the collision volume. The slow extracted product ions were further accelerated by passage through a second grid and then recorded by a particle mutiplier. O^{n+} ions of a particular charge state n could be identified and distinguished from O_2^+ and background product ions by their characteristic times of flight to the multiplier in accordance with their charge to mass ratios.

In order to distinguish the O^+ and O_2^+ ions arising from processes (1), (2) and (3) from those arising from the pure ionization process

$$He^{2+} + O(2s^2 2p^4)\,{}^3P \rightarrow He^{2+} + O^{n+} + ne \tag{4}$$

the fast He^+ ions formed by one-electron capture or the fast He atoms formed by two-electron capture were counted in coincidence with the O^+ or O^{2+} ions arising from the same events. Beyond the interaction region the fast He^+ or He product components present in the primary ion beam were selected by electrostatic deflection and recorded by a particle multiplier.

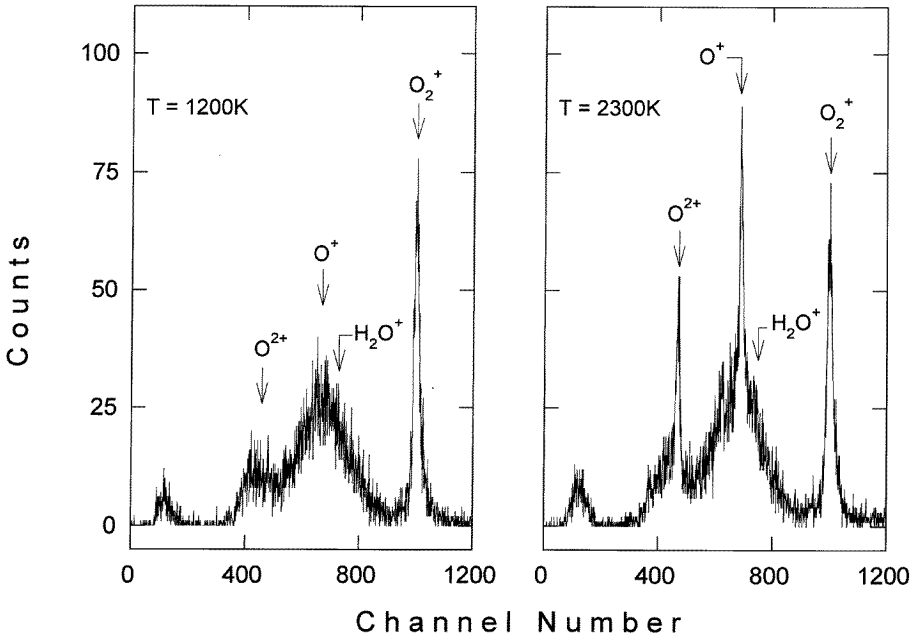

Figure 1. The slow ion–fast He^+ time-of-flight coincidence spectrum for one-electron capture by 67 keV amu^{-1} He^{2+} ions in collisions with oxygen derived from an iridium furnace at temperatures of 1200 K and 2300 K.

A time-to-amplitude converter operated with start pulses from the fast neutral beam and stop pulses from the slow ion product detector, after an appropriate delay, allowed a slow ion–fast ion/atom coincidence spectrum to be obtained. Figure 1 shows a typical coincidence spectrum for the one-electron capture process obtained with the iridium furnace at 2300 K when the oxygen beam was partially dissociated and at 1200 K when the beam was entirely molecular. Production of O^{n+} ions for $n > 2$ through one-electron capture was too small to detect. Similar coincidence spectra were obtained for two-electron capture by He^{2+} ions. In these, a small O^{3+} contribution was detectable but accurate quantitative analysis was precluded by poor signal to background ratios. Relative cross sections for (1), (2) and (3) at different He^{2+} energies were determined by comparing the coincidence count rates from the same oxygen target beams.

2.2. Calibration and normalization procedure

Cross sections ${}_{20}\sigma_{11}$ for the simple one-electron capture process (1) and ${}_{20}\sigma_{12}$ for the transfer ionization process (2) may be expressed as

$$ {}_{20}\sigma_{1n} = S_{\mathrm{T}}(\mathrm{O}^{n+})/k\mu \tag{5} $$

where $S_{\mathrm{T}}(\mathrm{O}^{n+})$ is the O^{n+}–fast He^{+} coincidence signal per unit primary beam intensity with the furnace at temperature T, μ is the effective thickness of the O atom beam and the constant k reflects the overall detection efficiency of the collision products. A similar expression can be used to describe the two-electron capture cross section ${}_{20}\sigma_{02}$. It was essential to make accurate allowance, as detailed in our previous work on H^{+}–H collisions (Shah and Gilbody 1981), for contributions to the observed coincidence signals arising from interactions with the background gas, particularly from the incompletely resolved $\mathrm{H_2O}^{+}$ peak and from dissociative electron capture in He^{2+}–$\mathrm{O_2}$ collisions. A small increase in background pressure also occurs when oxygen gas is admitted to the furnace and this also leads to an increase in the signal from $\mathrm{O_2}$ molecules.

The total O^{n+}–He^{+} coincidence signal S_0^{n+} per unit primary ion beam current obtained with the furnace set at our standard low temperature of $T_0 = 1200$ K, when the oxygen beam is entirely molecular, is given by

$$ S_0^{n+} = S_0^{\mathrm{D}}(\mathrm{O}^{n+}) + S_{\mathrm{B}} \tag{6} $$

where $S_0^{\mathrm{D}}(\mathrm{O}^{n+})$ is the contribution arising from dissociative ionization of $\mathrm{O_2}$ molecules present in the beam and the crossed beam region while S_{B} is the background contribution arising from incompletely resolved products of dissociative ionization of residual gases and vapours.

When the furnace was operated at our usual high temperature of 2300 K, the observed total O^{n+}–He^{+} coincidence signal S_{T}^{n+} per unit ion beam current is given by

$$ S_{\mathrm{T}}^{n+} = S_{\mathrm{T}}(\mathrm{O}^{n+}) + S_{\mathrm{T}}^{\mathrm{D}}(\mathrm{O}^{n+}) + S_{\mathrm{B}} \tag{7} $$

in terms of the respective contributions from the O and $\mathrm{O_2}$ components of the oxygen beam and the background gas. By comparing the $\mathrm{O_2^+}$–He^{+} coincidence signals $S_{\mathrm{T}}(\mathrm{O_2^+})$ and $S_0(\mathrm{O_2^+})$ at respective furnace temperatures T and T_0, the contribution $S_{\mathrm{T}}^{\mathrm{D}}(\mathrm{O}^{n+})$ in equation (7) can be obtained from the relation

$$ S_{\mathrm{T}}^{\mathrm{D}}(\mathrm{O}^{n+}) = S_0^{\mathrm{D}}(\mathrm{O}^{n+}) S_{\mathrm{T}}(\mathrm{O_2^+})/S_0(\mathrm{O_2^+}). \tag{8} $$

The residual gas contribution to both $S_{\mathrm{T}}(\mathrm{O_2^+})$ and $S_0(\mathrm{O_2^+})$ was negligible. In the case of the two-electron capture process, the time-of-flight coincidence spectra required a slightly different method of analysis in that the contributions of the dissociative two-electron capture processes in collisions with $\mathrm{O_2}$ could not be accurately assessed from an expression similar to (8) because the $\mathrm{O_2^{2+}}$ was too small. The required O^{2+} signal was separated from the various dissociative product ion contributions within a much broader peak which could be assessed through a Gaussian-type fitting procedure.

Equations (6) and (7) allow determination of $S_{\mathrm{T}}(\mathrm{O}^{n+})$ which is required in (5) for cross section determination. The product $k\mu$ in (5) was determined by normalizing our relative cross sections for He^{2+} impact to our recently determined cross sections for one-electron capture by proton impact (Thompson *et al* 1996). The latter values were in fact normalized to absolute cross sections for electron impact ionization of O atoms by Brook *et al* (1978) (see also Thompson *et al* 1995) after applying the +2.4% correction advocated by Montague *et al* (1984). The normalization was carried out using beam energies within the range 9–13 keV amu^{-1} by replacing the He^{2+} beam by a proton beam while the oxygen target conditions remained unchanged.

3. Results and discussion

Table 1 shows our measured cross sections $_{20}\sigma_{11}$ for the simple charge transfer process (1), $_{20}\sigma_{12}$ for the transfer ionization process (2) leading to O^{2+} production and $_{20}\sigma_{02}$ for two-electron capture process (3). The uncertainties associated with individual cross sections are assessed at the 67% confidence level and reflect the degree of reproducibility of the values in terms of the various experimental parameters and statistical fluctuations. All the cross sections are subject to an additional estimated uncertainty of ±13% in absolute value as a consequence of our normalization procedure.

Table 1. Cross sections $_{20}\sigma_{11}$ for simple charge transfer, $_{20}\sigma_{12}$ for transfer ionization and $_{20}\sigma_{02}$ for two-electron capture in collisions of He^{2+} ions with oxygen atoms.

Energy (keV amu^{-1})	$_{20}\sigma_{11}$ (10^{-16} cm^2)	$_{20}\sigma_{12}$ (10^{-16} cm^2)	$_{20}\sigma_{02}$ (10^{-16} cm^2)
5.3	5.7 ± 0.9	1.3 ± 0.3	—
6.0	6.7 ± 1.0	1.5 ± 0.3	—
6.7	7.7 ± 1.1	1.6 ± 0.3	—
8.0	11.7 ± 1.8	2.0 ± 0.4	—
9.3	13.6 ± 2.3	2.6 ± 0.5	—
10.7	14.1 ± 2.2	2.9 ± 0.6	1.4 ± 0.4
12.0	14.7 ± 2.2	3.1 ± 0.6	1.7 ± 0.5
14.7	17.3 ± 2.2	3.3 ± 0.6	1.7 ± 0.5
16.0	18.1 ± 2.7	3.5 ± 0.7	1.5 ± 0.5
18.0	16.0 ± 2.5	3.3 ± 0.7	1.5 ± 0.4
20.0	18.4 ± 2.8	3.9 ± 0.8	1.5 ± 0.4
22.7	17.1 ± 2.6	4.7 ± 0.9	1.3 ± 0.4
26.7	17.4 ± 2.6	5.0 ± 1.0	1.1 ± 0.3
30.7	18.2 ± 2.7	6.4 ± 1.3	0.7 ± 0.2
35.7	16.0 ± 2.4	5.8 ± 1.2	0.6 ± 0.2
40.7	14.9 ± 2.2	6.3 ± 1.3	0.7 ± 0.2
46.7	12.5 ± 1.9	5.3 ± 1.0	0.5 ± 0.1
53.3	13.4 ± 2.0	6.4 ± 1.3	0.5 ± 0.1
60.0	10.7 ± 1.6	5.8 ± 1.2	0.31 ± 0.08
66.7	8.9 ± 1.3	5.7 ± 1.1	0.21 ± 0.06

Our values of $_{20}\sigma_{11}$, $_{20}\sigma_{12}$ and $_{20}\sigma_{02}$ are shown in figure 2. Values of $_{20}\sigma_{11}$ for simple charge transfer which, as already noted, are dominated by accidentally resonant 2p electron capture to the $He^+(n = 2)$ states at low energies, can be seen to attain a large peak value of about 1.8×10^{-15} cm^2 at about 20 keV amu^{-1}. This behaviour, unlike the accidentally resonant H^+–O charge transfer process which continues to increase with decreasing energy (Thompson *et al* 1996), reflects the Coulomb repulsion between the collision products. There have been no theoretical studies of He^{2+}–O charge transfer unlike the corresponding He^{2+}–H process which is dominated by $He^+(n = 2)$ formation over a very wide energy range (see a review by Gilbody 1994). In the latter case, charge transfer cross sections $_{20}\sigma_{11}$ attain a lower peak value of about 1.2×10^{-15} cm^2 and at a lower energy of 11.3 keV amu^{-1} than the present values of $_{20}\sigma_{11}$ for He^{2+}–O collisions. In figure 2 the low energy trend of our values of $_{20}\sigma_{11}$ can be seen to be in satisfactory accord with the single cross section at 2 keV amu^{-1} measured previously in this laboratory by McCullough *et al* (1992).

Production of O^{2+} ions by electron capture is surprisingly effective and involves both the transfer ionization process (2) and the two-electron capture process (3). The O^{2+}/O^+ production ratio through these electron capture processes rises from about 0.23 at 5.3 keV amu^{-1} to 0.66 at 66.7 keV amu^{-1}. The transfer ionization process (2) is clearly the

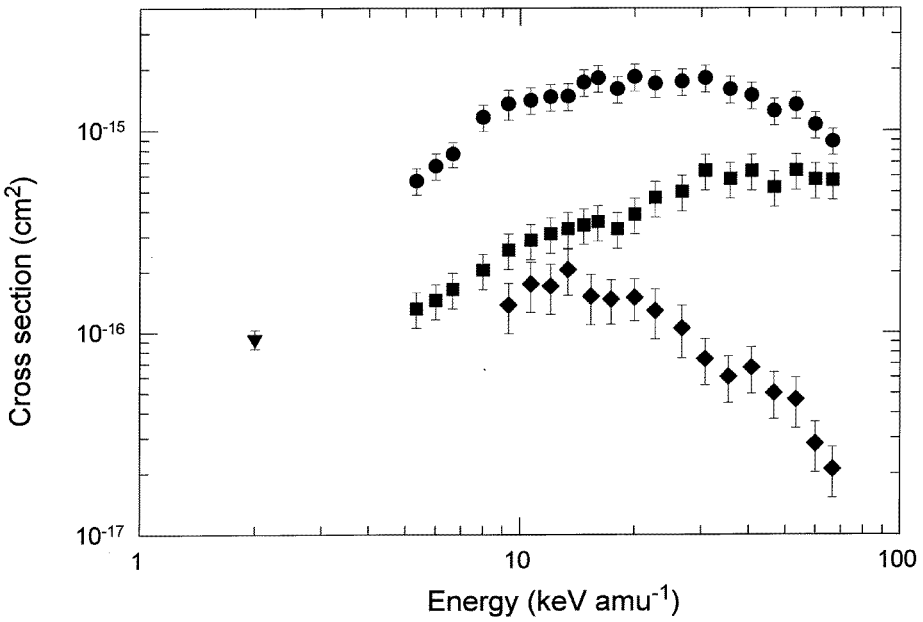

Figure 2. Cross sections for one- and two-electron capture in collisions of He^{2+} ions with oxygen atoms. One-electron capture: ●, $_{20}\sigma_{11}$, simple charge transfer, present data; ▼, $_{20}\sigma_{11}$, simple charge transfer, McCullough *et al* (1992); ■, $_{20}\sigma_{12}$, transfer ionization leading to O^{2+} formation, present data. Two-electron capture: ♦, $_{20}\sigma_{02}$, simple charge transfer, present data.

dominant O^{2+} production mechanism in the present range with evidence of a peak in $_{20}\sigma_{12}$ around 50 keV amu^{-1}. In addition, while a detailed scrutiny is precluded by the experimental uncertainties, there is some evidence of structure in the $_{20}\sigma_{12}$ cross section curve at energies below about 20 keV amu^{-1}. It is possible that this low-energy structure reflects contributions to $_{20}\sigma_{12}$ from two-electron capture into states whch subsequently undergo autoionization. Our measured cross sections $_{20}\sigma_{02}$ for the two-electron capture process can be seen to pass through a peak value at about 15 keV amu^{-1} in the general region where there is evidence of structure in $_{20}\sigma_{12}$.

4. Conclusions

In this work a crossed beam technique incorporating time-of-flight analysis and coincidence counting of the collision products has been used to study both one- and two-electron capture in He^{2+}–O collisions within the energy range 5–67 keV amu^{-1}. In the case of one-electron capture, cross sections $_{20}\sigma_{11}$ for simple charge transfer, which are known to be dominated by accidentally resonant electron capture to the $He^+(n = 2)$ states at low energies, attain a large peak value of about 1.8×10^{-15} cm^2 at about 20 keV amu^{-1}. This peak value is larger and observed at a higher energy than the corresponding He^{2+}–H process which is also dominated by $He^+(n = 2)$ ion formation. O^{2+} formation through electron capture processes is found to be very effective with the O^{2+}/O^+ production ratio rising from 0.23 to 0.64 over the range 5.3–66.7 keV amu^{-1}. While transfer ionization is the main O^{2+} production mechanism, there is some evidence which suggests that cross sections $_{20}\sigma_{12}$ may contain some low-energy contributions arising as a result of two-electron capture into states which

subsequently undergo autoionization.

Acknowledgments

This research is part of a large programme supported by a rolling research grant from the Engineering and Physical Sciences Research Council. One of us (WRT) is indebted to the Department of Education, Northern Ireland for the award of a research studentship.

References

Brook E, Harrison M F A and Smith A C H 1978 *J. Phys. B: At. Mol. Phys.* **11** 3115
Geiss J, Balsiger H, Eberhardt P, Walker H P, Weber L and Young D T 1978 *Space Sci. Rev.* **22** 537
Gilbody H B 1994 *Advances in Atomic, Molecular and Optical Physics* vol 33 (New York: Academic) p 149
Johnson R E 1990 *Energetic Charged Particle Interactions with Atmospheres and Surfaces* (Berlin: Springer)
McCullough R W, McLaughlin T K, Koizumi T and Gilbody H B 1992 *J. Phys. B: At. Mol. Opt. Phys.* **25** L193
Montague R K, Harrison M F A and Smith A C H 1984 *J. Phys. B: At. Mol. Phys.* **17** 3295
Shah M B and Gilbody H B 1981 *J. Phys. B: At. Mol. Phys.* **14** 2361
——1982 *J. Phys. B: At. Mol. Phys.* **15** 413
Thompson W R, Shah M B and Gilbody H B 1995 *J. Phys. B: At. Mol. Opt. Phys.* **28** 1321
——1996 *J. Phys. B: At. Mol. Opt. Phys.* **29** 725