LETTER TO THE EDITOR

Ionization of atomic oxygen by protons

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Abstract. A crossed-beam technique incorporating time-of-flight analysis and coincidence counting of the collision products, recently used in this laboratory to study one-electron capture in collisions of H^+ ions with ground-state oxygen atoms, has been adapted to allow measurements of the corresponding cross sections for ionization for the first time. Cross sections for the single ionization of O atoms have been determined within the range 34–100 keV. These cross sections pass through a peak value at an energy of about 60 keV. At higher energies, the process of ionization rather than electron capture becomes the main source of O^+ production. O^{n+} formation for $n > 2$ was too small to detect in the energy range considered. It is also shown that although production of O^{2+} through transfer ionization is quite significant, the yield of O^{2+} from pure ionization is unimportant.

Protons comprise the bulk of the ions present in the solar wind and the products of solar flares which continually bombard the Earth's upper atmosphere in which atomic oxygen is a primary constituent. A quantitative knowledge of the relevant collision processes is therefore important for accurate modelling of the ionization balance in the high atmosphere.

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 $O(2s^2 2p^4)^3P$ atoms. Cross sections, $_{10}\sigma_{01}$ for the simple charge transfer process

$$H^+ + O(2s^2 2p^4)^3P \rightarrow H + O^+ \tag{1}$$

and $_{10}\sigma_{02}$ for the transfer ionization process

$$H^+ + O(2s^2 2p^4)^3P \rightarrow H + O^{2+} + e^-, \tag{2}$$
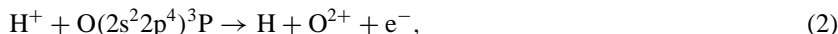
were separately determined for the first time. Cross sections $_{10}\sigma_{01}$, which at low energies are large and dominated by the accidentally resonant channel involving capture of a 2p electron, were found to rise with decreasing energy over the range considered. Our values of $_{10}\sigma_{01}$ were also found to be in good accord with most of the previous lower energy measurements carried out using several different methods and different calibration and normalization procedures. Our measured values of $_{10}\sigma_{02}$ were found to attain a peak value at 34 keV where transfer ionization leading to O^{2+} formation accounts for about 9% of all one-electron captures rising to 17.5% at 100 keV, the limit of our range.

In the present work we have adapted the experimental method used in our previous work (Thompson *et al* 1996) to allow, for the first time, studies of the pure ionization process

$$H^+ + O(2s^2 2p^4)^3P \rightarrow H^+ + O^{n+} + ne^- . \tag{3}$$
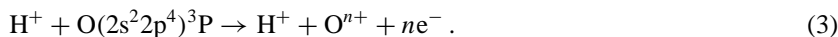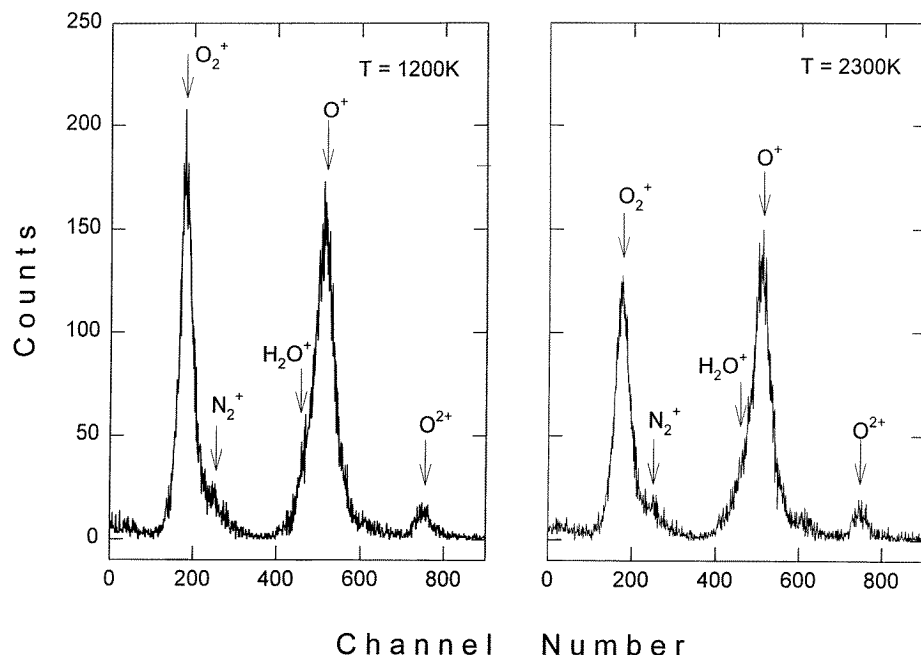
Figure 1. Slow ion–electron time-of-flight coincidence spectrum for 80 keV proton impact ionization of a beam of oxygen produced by an iridium tube furnace at temperatures of 1200 and 2300 K.

Cross sections $_{10}\sigma_{11}$ for single ionization corresponding to $n = 1$ have been determined in the energy range 34–100 keV. Within this range, pure ionization processes leading to $n > 1$ are found to be too small to detect.

The experimental approach and measuring procedure has been described in our previous papers (Thompson *et al* 1996, Shah and Gilbody 1981, 1982) and only an outline of the main features need be given here. A momentum-analysed proton beam of the required energy was arranged to intersect (at right angles) a thermal energy beam of partially dissociated oxygen in a differentially pumped high-vacuum region. The oxygen beam was derived from an iridium tube furnace dissociation source, the temperature of which was determined using an optical pyrometer. As in our previous work, in order to obtain satisfactory signal-to-background ratios, the oxygen flow rate to the furnace had to be raised to levels which resulted in a dissociation fraction of about 0.5. Slow ions and electrons formed in the collision region were swept out with high and uniform efficiency by a transverse electric field applied between two high transparency grids located on either side of the crossed-beam region and, after further acceleration, were recorded by two particle multipliers. O^{n+} ions of 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 the charge-to-mass ratios. By counting the O^{n+} ions in coincidence with the electrons arising from the same collision events, an O^{n+}–electron coincidence time-of-flight spectrum of the type shown in figure 1 could be obtained at each primary beam energy. In the energy range considered O^{n+} formation for $n > 2$ was too small to detect.

The observed O^+–electron and O^{2+}–electron coincidence yields contained the required information on the pure ionization processes (3) leading to O^+ and O^{2+} formation. The O^{2+}–electron coincidence signal contains contributions from both the transfer and pure ionization

processes (2) and (3). However, the transfer ionization contribution (2) has already been separately determined in our previous studies of one-electron capture (Thompson *et al* 1996) in which the product O^{2+} ions were counted in coincidence with the fast H atoms from the same collision events. These results were used in the analysis of the present O^{2+}–electron coincidence measurements to show that the O^{2+} contribution arising from pure ionization is negligible in the energy range considered.

The cross section $_{10}\sigma_{11}$ for single ionization in (1) may be expressed as

$$_{10}\sigma_{11} = S_T(O^+)/k\mu \tag{4}$$

where $S_T(O^+)$ is the O^+–electron coincidence signal per unit primary beam intensity with the iridium furnace set at a high temperature, $T = 2300$ K, when the oxygen was partially dissociated, μ is the effective thickness of the O atoms in the target beam and the constant k reflects the overall detection efficiency of the collision products.

As in our previous work, it was essential to make accurate allowance (in the manner described previously by Shah and Gilbody 1981) for contributions to the observed O^+–electron coincidence signals arising from interactions with the background gas, particularly from the incompletely resolved H_2O^+ peak (figure 1) and $S_T^D(O^+)$ from dissociative ionization of the O_2 molecules present in the target beam. A small increase in background pressure in the crossed-beam region also occurs when oxygen is fed into the furnace, thereby resulting in an increase in the signal from O_2 molecules. When the iridium furnace was operated at a high temperature $T = 2300$ K, the observed O^+–electron coincidence signal can be expressed as

$$S_T = S_T(O^+) + S_T^D(O^+) + S_B \tag{5}$$

in terms of the respective contributions from the O, O_2 and background gas contributions; the background contribution S_B was determined from measurements in the absence of gas flow to the furnace. The corresponding signal when the furnace was operated at our standard low temperature $T_0 = 1200$ K (when the oxygen beam was entirely molecular) can be expressed as

$$S_0 = S_0^D(O^+) + S_B . \tag{6}$$

By comparing the O_2^+–electron coincidence signals $S_T(O_2^+)$ and $S_0(O_2^+)$ obtained at respective furnace temperatures T and T_0, the contribution $S_T^D(O^+)$ in (5) was determined from the expression

$$S_T^D(O^+) = S_0^D(O^+)S_T(O_2^+)/S_0(O_2^+) . \tag{7}$$

The residual gas contributions to both $S_T(O_2^+)$ and $S_0(O_2^+)$ were negligible.

As in our previous studies of one-electron capture (Thompson *et al* 1996), in order to allow cross section determination, the product $k\mu$ in (4) was effectively evaluated by normalizing our relative cross sections $_{10}\sigma_{11}$ to our recently measured cross sections for electron impact ionization (Thompson *et al* 1995); the latter were normalized to the absolute cross sections measured by Brook *et al* (1978) after applying the $+2.4\%$ correction advised by Montague *et al* (1984). The normalization procedure has been previously described in detail (Shah *et al* 1987) and involved the careful substitution of an electron beam for the proton beam while the oxygen target beam conditions remained unchanged.

Table 1 shows our measured values $_{10}\sigma_{11}$ of the cross sections for single ionization of atomic oxygen within the range 34–100 keV. Measurements at lower energies were precluded by the rapidly deteriorating signal-to-background ratios complicated by large O^+ contributions arising from the collisional break-up of O_2 molecules. The uncertainties shown at the 67% confidence level reflect the degree of reproducibility of the individual cross

Table 1. Cross sections $_{10}\sigma_{11}$ for single ionization of O atoms by H^+ ions.

Energy (keV)	$_{10}\sigma_{11}$ (10^{-16} cm^2)
34	1.34 ± 0.32
40	1.58 ± 0.32
46	1.63 ± 0.31
53	1.98 ± 0.39
61	1.76 ± 0.30
70	1.83 ± 0.31
80	1.48 ± 0.25
90	1.70 ± 0.29
100	1.56 ± 0.25
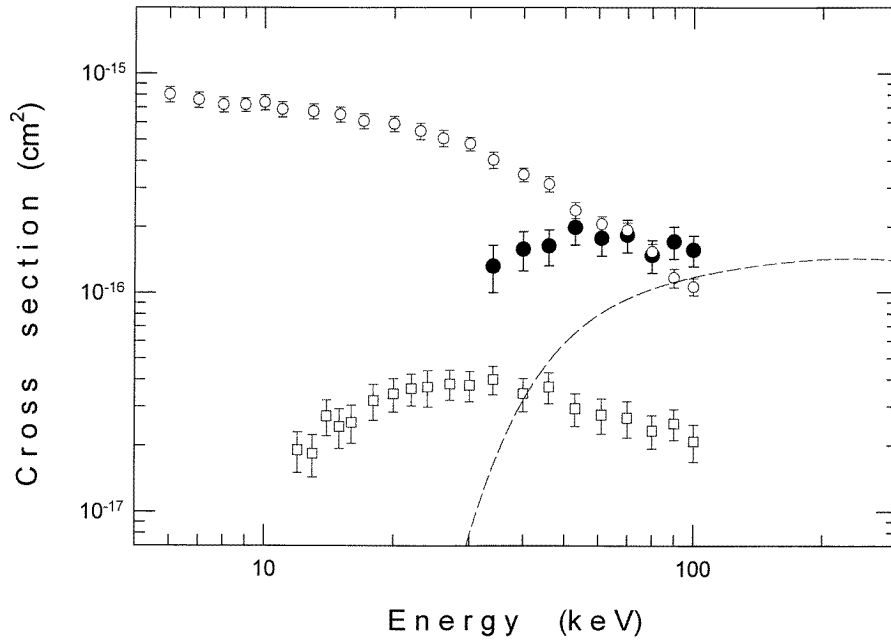
Figure 2. Present cross sections $_{10}\sigma_{11}$ (●) for single ionization of ground-state oxygen atoms by protons compared with equivelocity values of corresponding cross sections for electron impact ionization (– – –) measured by Thompson *et al* (1995). Also included are cross sections $_{10}\sigma_{01}$ for simple charge transfer (○) and $_{10}\sigma_{02}$ for transfer ionization (□) in H^+–O collisions measured by Thompson *et al* (1996).

sections. In addition, all cross sections are subject to an additional estimated uncertainty of $\pm 14\%$ in absolute value as a consequence of our normalization procedure.

In figure 2 the present cross sections $_{10}\sigma_{11}$ for single ionization of ground-state oxygen atoms are shown together with our previously measured cross sections (Thompson *et al* 1996) for one-electron capture. While it is evident that O^+ production at low energies is dominated by the accidentally resonant simple charge transfer process (1), the present results show that the cross section for pure ionization begins to exceed this at energies above about 70 keV. Values of $_{10}\sigma_{11}$ can be seen to attain a peak value within the energy range considered and, beyond this peak, our measured cross sections can be seen to exhibit

the expected high-energy trend to merge with the equivelocity values of cross sections for single ionization by electron impact (Thompson *et al* 1995) also included in figure 2. As already noted, in our previous work O^{2+} production by the transfer ionization process (2) is significant with the O^{2+}/O^+ production ratio due to electron capture rising to 0.17 at 100 keV. However, the present measurements show that O^{2+} production through pure ionization is unimportant in the energy range considered. When account is taken of both ionization and electron capture processes, the total O^{2+}/O^+ ion production ratio changes very little from 0.09 at 34 keV to 0.07 at 100 keV.

References

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