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To cite this version:

HAL Id: jpa-00229333
https://hal.archives-ouvertes.fr/jpa-00229333
Submitted on 1 Jan 1989
SLOW COLLISIONS OF O$^{6+}$ WITH He AND H$_2$ STUDIED IN ULTRA-SOFT X-RAY EMISSION


Department of Physics, Uppsala University, Box 530, S-751 21 Uppsala, Sweden
*Manne Siegbahn Institute of Physics, S-104 05 Stockholm, Sweden
**Agrippa, GIS CEA/CNRS, F-38041 Grenoble, France
***Département de Physique, Université Laval, Québec, G1K 4P4, Canada

Abstract
Photon emission in the 100-200Å region following slow O$^{6+}$ + He, H$_2$ collisions has been analyzed using a new grazing incidence spectrometer. The ions were produced in an ECR type ion source, accelerated to 60 keV, and passed through a target gas cell. Intensity from decay associated with single electron transfer to nl levels is seen, and is used to deduce the relative nl subshell selective capture cross sections. Many lines corresponding to double electron transfer are detected, and discussed in terms of different transfer mechanisms. Several lines are interpreted as due to correlated double capture. We also attribute intensity to the decay of quartet states, formed on metastable 1s2s 3$^1$S oxygen ion states by one-electron capture. About half of the quartet lines give evidence of non-core-conserving electron transfer.

1. Introduction
Information on electron transfer processes in collisions of slow multicharged ions with atoms is of great interest to many areas of research. The large cross sections for population of excited ionic states that have been observed underlie some of the importance of these phenomena in astrophysics, fusion research and plasma physics in general.

Early evidence for population of excited states originating from electron capture during collisions between atoms and highly charged ions was given by soft x-ray emission from a tokamak plasma /1,2/. Emission lines from O$^q+$ (q=4,5,6,7) states, formed in collisions with hydrogen atoms, were identified. At about the same time, UV and VUV photon emission spectra from slow collisions were recorded /3/, using an ion beam extracted from a Penning type ion source. Development of the ECR ion source /4/ opened up the possibility to study slow charge transfer processes involving multicharged ions in more detail, and photon spectroscopic techniques from the UV to the ultra-soft x-ray (USX) region /5,6/ has been applied to the excited projectile states populated in the collisions.

The aim of the present paper is to report on photon emission in the 100-200Å region subsequent to 60 keV O$^{6+}$ + He, H$_2$ collisions. The spectra enable us to derive the relative subshell selective single electron transfer cross sections, which we compare with previous experimental results and calculations. For the first time in the present wavelength region lines corresponding to correlated double electron transfer are identified. We also present observations implying non-core conserving single electron capture.
2. Experiment

The experiment was performed at the MINIMAFIOS type Electron Cyclotron Resonance (ECR) ion source /4,7/ at CEA in Grenoble (Agrippa). Separator magnets were used to select the correct ions, and the beam, with a typical current of a few μA, was focused into a collision chamber. The gas pressures were $1 \times 10^{-4}$ mbar for He and $5 \times 10^{-5}$ mbar for H$_2$, which should yield a small probability for double collisions in the interaction region. The acceleration voltage applied was 10 kV, giving the ion velocity $v=0.39$ au.

The emission was recorded in a newly constructed grazing incidence spectrometer /8/. This
instrument is of novel design which is based on the use of one of several fixed mounted gratings and a big two-dimensional detector which can be moved in a three-axis coordinate system. The spectral range 10-250Å can be covered at high luminosity and resolution. Also, the instrument is designed to be portable and easily adapted to different kinds of sources. For the present long wavelength region a 3 m grating with 300 lines/mm was used, and a 68 µm entrance slit width was chosen. The detector is based on multichannel plates and the resistive anode read-out technique. Detection efficiency is achieved by CsI coating of the detector and an electron capturing electric field applied using a grid mounted over the detector surface. The measured intensities were corrected for the spectral photoefficiency of CsI /9/. The spectrometer sensitivity was not yet fully calibrated, and we estimate the accuracy in the intensity determination to be 20% for the stronger lines and 50% for the weaker lines. The uncertainty is even higher for the lines of intensity below 0.1% of the strongest lines. A calibration procedure to establish the sensitivity based on the use of synchrotron radiation is planned for the near future. The wavelength scale is fixed using energies of well-known emission lines /10/, and the wavelength resolution is about 1Å.

3. Results and discussion

The ultra-soft x-ray emission spectra resulting from slow electron transfer collisions between O5+ and He or H2 are shown in Fig. 1. About 40 lines, within an intensity variation of 10⁴, are seen in the 100-200Å region. The three most prominent lines above 140Å are identified as due to emission from O5+ states populated in single electron capture collisions to n=3, while the three strongest lines below 140Å are associated with population of the n=4 level and subsequent decay to n=2. Lines attributed to emission from correlated double capture processes are spread-out over the spectra. For the first time lines of this type are identified in this wavelength region. Several lines with an intensity of a similar order of magnitude are attributed to capture into quartet states formed on metastable 1s2s3S states, which are expected to constitute a certain fraction of the ion beam. Also some lines are attributed to decay of quartet states, populated as a 2s-2p excitation is accompanying the electron transfer. Finally we discern a few weak lines, the assignment of which we leave as an open question. The measured energies and intensities are summarized in Table 1, together with assignments and comments.

a. Single Capture

The relative intensities of the stronger lines in the spectra, associated with one-electron transfer to n=3 and 4, reflect the probabilities for single electron capture to the various nl levels of the incoming 1s² ions.

Comparing the spectra associated with He and H2 targets we note the striking difference in the relative intensity corresponding to electron transfer to n=4 levels. The observation is in accordance with the general notion of a quasi-resonance between the binding energy in the target and in the final excited ionic state, which also quantitatively follows from the classical barrier model /11/.

In Table 2 we compile the partial single-electron capture cross sections, σnl, derived from the present data, taking cascade population and branching ratios in the O VI system /12/ into account. We compare the values with the results of Dijkkamp et al. /13/, who have derived the σ4| values from observed n=4→n=3 transitions, and with Bouchama et al. /14/ for the hydrogen case. The agreement between the values are reasonable considering that they are based on transitions over a wide wavelength range. Table 2 also comprises the calculated cross sections of Fritsch and Lin /15/, which are found to be essentially confirmed.

In the hydrogen case we find a discrepancy between our values and those reported by Ref. 13 for capture to n=4. The reason for this is not obvious, but we note the uncertainties enforced by the incomplete knowledge of the instrument sensitivity. The very low cross section for capture into 3d reported by Ref. 14 seems to be a misprint.
Wavelength | Intensity | Assignment | Comments
-----------|-----------|------------|--------
1 101.5    | 0.01      | 1s2s2p    | 4p-1s2p4p  4S Q+  
2 105.9    | 0.18      | 1s2s2   | 2S -1s2p5p  2p0 S
3 107.7    | 0.02      | -         | U
4 109.8    | 0.02      | 1s2s2p   | 4p-1s2p4p  4D Q
5 110.6    | 0.07      | -         | U
6 111.9    | -         | 1s2s2p   | 4p-1s2p4s  4S Q
7 114.5    | 0.02      | 1s2p2    | 4p-1s2p4p  4p Q+
8 115.8    | 2.23      | 1s2s2p   | 2S -1s2p4s  2p0 S
9 117.3    | 0.08      | 1s2p2    | 2p-1s2p5s  2S S
10 119.0   | 0.05      | 1s2s2p   | 1S -1s2p5p 1p0 Dl
11 124.6   | 0.12      | 1s2s2p   | 1S -1s2p5p 1p0 Dl
12 129.8   | 9.3       | 1s2p2    | 2p-1s2p4d  2D S
13 132.3   | 1.43      | 1s2p2    | 2p-1s2p4s  2S S
14 135.7   | 0.39      | 1s2s2p   | 1S -1s2s4p 1p0 D*
15 139.1   | 0.12      | 1s2s2p   | 1S -1s2p3d 1p0 D*
16 140.8   | 0.61      | 1s2s2p   | 4p-1s2s3d  4D Q
17 145.3   | 0.01      | 1s2p2    | 4p-1s2p3d  4p Q+
18 146.1   | 0.16      | 1s2s2p   | 1p0-1s2s6d 1p0 DI
19 147.5   | 0.09      | 0.07      | 1s2s2p1p0-1s2p4p 1D D*
20 150.1   | 100.0     | 42.3      | 1s2s2  2S -1s2p3p  2p0 S
21 151.6   | 1.6       | 1.9       | 1s2s2p3p0-1s2s4d 3D D
22 154.0   | 0.37      | 0.05      | 1s2s2p1p0-1s2s5d 1D DI
23 156.2   | -         | 0.66      | 1s2s2p3p0-1s2s4s 3S D
24 159.0   | 0.36      | 0.13      | 1s2p2  4p-1s2p3s  4p0 Q+
25 162.8   | 0.44      | -         | 1s2p2  1D-1s2p4d 1p0 D*
26 164.0   | 0.36      | 0.10      | 1s2p2  1D-1s2s6f 1p0 DI
27 165.0   | 0.36      | 0.10      | - U
28 166.6   | -         | 0.30      | 1s2s2p3p0-1s2p3p 3S D
29 168.2   | 0.41      | 0.49      | 1s2s2p3p0-1s2p3p 3D D
30 170.3   | 2.0       | 0.60      | 1s2p2  4p-1s2p3p  4p0 Q
31 172.0   | 1.7       | -         | 1s2s2p 1S -1s2p3p 1p0 D*
32 173.0   | 70.0      | 100.0     | 1s2p2  2p-1s2sd  2p S
33 178.8   | 0.49      | 0.09      | 1s2p2  1S -1s2p4d 1p0 D*
34 182.1   | 0.42      | 0.15      | 1s2s2p1p0-1s2p3p 1S D*
35 184.0   | 49.6      | 15.3      | 1s2p2  2p-1s2p3s  2S S
36 185.6   | 1.1       | -         | 1s2s2p1p0-1s2p3p 1D D*
37 191.2   | -         | 0.26      | 1s2p2  3p-1s2p4p 3p0 D
38 192.7   | 3.7       | 3.4       | 1s2s2p3p0-1s2s3d 3p D
39 194.3   | 0.62      | -         | 1s2s2p1p0-1s2p3p 1p D*

Table 1. Emission in the 100 - 200 Å wavelength range following O6+ + He, H2 charge transfer collisions. The intensities are given in percent of the most prominent line. The notations in the comment column are as follows:

- **S** = Single capture.
- **D** = Double capture populating triplet states, formed through double collisions.
- **D** = Double capture populating singlet states, possibly formed through double collisions.
- **D** = Double capture asymmetrically populating the n levels, indicating a correlated process.
Q = Single capture on metastable $1s^22s\ 3S$ oxygen cores, forming $1s2snl\ 4^L$ quartet states.
Qt = Single capture on metastable states, with an accompanying $2s-2p$ excitation.
U = Unidentified lines.

Further comments:
The assignments of lines number 1 and 2 are tentative. Calculations /24/ predict the wavelength of line 1 to be larger (102.8Å) and tabulations /10/ give line 2 at a smaller wavelength (104.8Å).
The wavelength of line number 10 has been deduced from a quantum defect analysis /25/.
In some cases a line is seen in capture from only one of the targets. Line number 6 is not seen in capture from He. Bad statistics in this region may imply that some of the intensity attributed to line number 5 can belong to this transition. Lines number 23, 25, 37 and 39 are just seen in one of the spectra, though their intensities are quite large in the other spectrum. The reason why the lines number 31 and 36 are not seen in both spectra is measurement difficulties since their wavelength positions are close to strong lines.
The uncertainty in the intensity determination is large for lines weaker than 0.1% of the main lines. Values in this intensity range should be seen as rough estimates.

b. Double Capture.
The importance of two-electron capture in single collisions was demonstrated early, and lately projectile emission in the 300-500 Å region indicating double electron transfer to $Ti^{13+}$ has been seen /16/. In electron spectrometry two-electron capture to auto-ionizing states has been studied /17/ and recently a distinction has been made between correlated and non-correlated double capture in single collisions /18,19/. In particular Coster-Kronig electrons from decaying O$^4+$2pn states (n values from 6 up to 12-14), populated in slow O$^6+$ + He collisions were detected. The population of states corresponding to such high quantum numbers clearly demonstrates the importance of correlation in the transfer mechanism. As follows immediately from the single capture results presented above, the population of these states would have been negligible in a non-correlated process.

In Table 1 we identify emission from excited O V states, associated with electron configurations 2snl (n=3,4,5,6) and 2pnl (n'=3,4) singlet states.
For n=3,4 and n'=3 some lines belonging to the triplet system are observed. According to Wigner's spin conservation rule these states can only be formed in double collisions/20/, showing that the single-collision condition was not strictly fulfilled for double capture events. This has the implication that the emission from n and n'=3,4 singlet states also may be influenced by double collisions.
The observation of soft x-ray emission from 2snl (n=5,6) confirms the importance of correlated double capture. The deduction of cross sections, however, is difficult since cascade population from levels of higher n may be important. Recently it was found that the correlated capture process populates high angular momentum states /21/, which is corroborated by our registration within the singlet system of O V of emission from excited p, d and f electrons only.
In the case of 2pn states the cascade decay is to some extent overridden by the competing auto-ionization channel, which is the reason why we do not detect any signals from states corresponding to n'≥6. The 2p$^2$-2p5d line, as deduced from a calculation of Serrao /22/ coincides with the strong 2s-3p transition in O VI, and could thus be present.
The double to single electron capture intensities are in general much larger for He than for the H$_2$ target. This is in accordance with the observation of larger Coster-Kronig electron intensity from states of higher n when helium is used as a target for 120 keV ions, as compared to hydrogen /19/.
The ion beam is expected to contain a fraction of \(1s^2s^3\) metastables on which single electron capture can form non-autoionizing quartet states \(1s2s(p)nl\). The quartet term system in O VI has recently been studied by beam-foil spectroscopy \cite{23} and in a theoretical investigation \cite{24}. In analogy with the single capture doublet states populated on ground state projectiles, we would expect to find radiation from quartet states within all configurations \(1s2s(p)nl\) with \(n=3,4\) and \(l=s,p,d\). Out of these 12 configurations we actually observe intensity from all except 4, and from three of these \((1s2p3p,1s2p4s,1s2s3s)\) the lines may be blended by stronger lines. The remaining configuration \((1s2s4p)\) radiates mainly at longer wavelengths and is not present in the wavelength compilations \cite{23,24}. By comparing the intensities of the observed lines to those corresponding to single capture on the ionic ground state, we estimate the beam content of metastables to be 3%.

The excitation of the 2s electron to 2p must take place during the collision. This is an example of a non-core-conserving capture process, which has also been observed in some other collision systems \cite{20}.

Table 2. Relative single electron capture cross sections to \(nl\) levels for 60 keV \(O^{6+}\) ions impinging He and \(H_2\). The data is normalized to the largest partial cross section, 3p for He and 4s for \(H_2\) targets, respectively.

<table>
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<tr>
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<th>He</th>
<th></th>
<th>H</th>
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<tr>
<td></td>
<td>This work</td>
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<td>Fritsch &amp; Lin \cite{15}</td>
<td>Bouchama et al. \cite{14}</td>
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<td>3s</td>
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<td>0.36</td>
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<td>1.00</td>
<td>1.00</td>
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<td>0.52</td>
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<tr>
<td>4p</td>
<td>0.030</td>
<td>0.034</td>
<td>0.026</td>
<td></td>
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<tr>
<td>4d</td>
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<td>0.17</td>
<td>0.066</td>
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<tr>
<td>4f</td>
<td>-</td>
<td>0.15</td>
<td>0.073</td>
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<td>(H_2) target</td>
<td>(d_{\text{He}})</td>
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<td>Bouchama et al. \cite{14}</td>
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<tr>
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<td>5f</td>
<td>-</td>
<td>0.01</td>
<td>-</td>
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The values from Refs. 13 and 15 are based on linear interpolations between the presented results. The * superscripts indicate corrections for the 4,5f\(-\)3d cascade by means of the intensities measured by Dijkkamp et al. \cite{13}.

4. Conclusions

This work presents a preliminary study, providing new data on electron capture by slow \(O^{6+}\) colliding with He and \(H_2\). Selective \(nl\) single-capture cross sections are derived and compared to previous experiments and calculations. A reasonable agreement is found except in the case of capture from \(H_2\) to the subshells of \(n=4\).

Weak lines corresponding to double capture and to capture on metastable ion states are identified for the first time in the 100-200Å region.
In particular information on double capture may eventually lead to a better understanding of correlated and non-correlated transfer mechanisms. This will, however, require more detailed studies.

The results strongly show the importance of a continuation of this type of work, under the conditions of (attainable) higher resolution and accurate intensity determinations. A full sensitivity calibration of the spectrometer will be performed in the near future.

5. Acknowledgement

S. Dousson is gratefully acknowledged for operating the ECR source facility in Grenoble.

References: