TOTAL AND PARTIAL CROSS SECTIONS FOR ELECTRON CAPTURE
FOR C\textsuperscript{6+}(q=6-2) AND O\textsuperscript{8+}(q=8-2) IONS
IN COLLISIONS WITH H, H\textsubscript{2}, AND He ATOMS

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Abstract
Experimental and theoretical total and partial cross sections for single and double electron capture of $C^{q+}$ and $O^{q+}$ ions in colliding with $H$, $H_2$, and $He$ targets are surveyed. Presently available data for these ions are summarized in the following table:

<table>
<thead>
<tr>
<th>Ionic charge $q$</th>
<th>Target</th>
<th>$C^{q+}$</th>
<th>$O^{q+}$</th>
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<tr>
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<td>T</td>
</tr>
</tbody>
</table>

Note: T and P indicate that the investigations or measurements for total and partial cross sections have been made, respectively.
Introduction

This report is concerned with a survey of total and partial cross sections for electron capture for Cq+(q=6–2) and Oq+(q=8–2) ions in collisions with H, H₂ and He atoms. These Cq+ and Oq+ ions are very typical impurity ions in all fusion plasma apparatus, whereas H, H₂ and He are copious there. These collisions are known to play a key role in plasmas. Therefore, data for these processes are requisite for understanding the behavior of plasmas. In most of such electron capture processes, an electron is captured into excited states of ions, resulting in photon emissions when these ions are relaxed. These photons are one of the important parameters in evaluating the energy balance in plasmas and also one of the most useful techniques to diagnose and investigate plasmas.

These data are urgently needed by plasma community. Here we have made a quick survey for these data, in particular those for partial cross sections involving the impurity ions mentioned above and compiled them in graphical forms. As total cross sections for these processes are already available,¹⁻⁴ we plan to make more extended compilations of these data for partial cross sections in the near future. So we strongly hope that anyone who makes new experiments and calculations supply us new and reliable data on these electron capture processes in order to make the revised version of this compilation.

References
2. K.W. Wu, H.A. Huber and K. Wiesemann, At. Data and Nucl. Data Tables (to be published)
In the following are shown some abbreviated notations for theoretical methods:

- **MO**: Molecular orbital expansion calculation
- **AO**: Atomic orbital expansion calculation
- **AO-MO**: Atomic orbital-orbital matching method
- **LZ**: Landau-Zener method
- **MLZRC**: Multichannel Landau-Zener model with rotational coupling
- **PSS**: Perturbed stationary state method
- **CC**: Close coupling calculation
- **SCA**: Semiclassical approximation
- **OBK**: Oppenheimer-Born-Kramer calculation
- **SPB**: Strong potential Born calculation
- **UDWA**: Unitarized distorted-wave approximation
- **EDWA**: Exponential distorted-wave approximation
- **CDWA**: Continuum distorted-wave approximation
- **R**: R-matrix calculation
- **CTMC**: Classical trajectory Monte Carlo calculation

Acknowledgements

The author would like to thank Dr. T. Kato and M. Suga for making a series of the graphs shown here. He is also grateful to Prof. N. Shimakura and Dr. T. Ohyama-Yamaguchi for providing numerical tables for their calculated results. A lot of typing work of the present manuscript by M. Itonaga, M. Udaka and S. Ito is highly appreciated.
List of electron capture processes

I C^q+ + H(1s) collisions
   I-1 C^6+ + H(1s) → C^5+(n^l) + H^+
   I-2 C^5+(1s) + H(1s) → C^4+(1s^l n^l) + H^+
   I-3 C^4+(1s^l) + H(1s) → C^3+(1s^2 n^l) + H^+
   I-4 C^3+(1s^2 s^l) + H(1s) → C^2+(1s^2 2s n^l) + H^+
   I-5 C^2+(1s^2 s^l^2) + H(1s) → C^+ + H^+

II C^q+ + H_2 collisions
   II-1 C^6+ + H_2 → C^5+(n^l) + H_2^+, C^4+(n^l n^l' e') + H_2^2+
   II-2 C^5+(1s) + H_2 → C^4+(1s^l n^l) + H_2^+, C^3+(1s^l n^l n^l' e') + H_2^2+
   II-3 C^4+(1s^l) + H_2 → C^3+(1s^2 n^l) + H_2^+, C^2+(1s^2 2s n^l) + H_2^2+
   II-4 C^3+(1s^2 s^l) + H_2 → C^2+(1s^2 2s n^l) + H_2^+, C^+ + H_2^2+

III C^q+ + He Collisions
   III-1 C^6+ + He → C^5+(n^l) + He^+, C^4+(n^l n^l' e') + He^2+
   III-2 C^5+(1s) + He → C^4+(1s^l n^l) + He^+, C^3+(1s^l n^l n^l' e') + He^2+
   III-3 C^4+(1s^l) + He → C^3+(1s^2 n^l) + He^+, C^2+(1s^2 2s n^l) + He^2+
   III-4 C^3+(1s^2 s^l) + He → C^2+(1s^2 2s n^l) + He^+, C^+ + He^2+
   III-5 C^2+(1s^2 s^l^2) + He → C^+(1s^2 2s^2 2p^2) + He^+, C^0 + He^2+

IV O^q+ + H collisions
   IV-1 O^8+ + H(1s) → O^7+(n^l) + H^+
   IV-2 O^7+(1s) + H(1s) → O^6+(1s^l n^l) + H^+
   IV-3 O^6+(1s^l) + H(1s) → O^5+(1s^2 n^l) + H^+
   IV-4 O^4+(1s^2 s^l) + H(1s) → O^3+(1s^2 2s n^l) + H^+
   IV-5 O^3+(1s^2 s^l^2 p^2) + H(1s) → O^2+(1s^2 2s^2 2p n^l) + H^+
   IV-6 O^2+(1s^2 s^l^2 2p^2) + H(1s) → O^+ + H^+

V O^q+ + H_2 collisions
   V-1 O^8+ + H_2 + O^7+(n^l) + H_2^+, O^6+(n^l n^l' e') + H_2^2+
   V-2 O^7+(1s) + H_2 → O^6+(1s^l n^l) + H_2^+, O^5+(1s^l n^l n^l' e') + H_2^2+
   V-3 O^6+(1s^l) + H_2 → O^5+(1s^2 n^l) + H_2^+, O^4+(1s^2 2s n^l) + H_2^2+
   V-4 O^4+(1s^2 s^l^2) + H_2 → O^3+(1s^2 2s n^l) + H_2^+, O^2+(1s^2 2s^2 2p n^l) + H^+
   V-5 O^3+(1s^2 2s^2 2p^2) + H_2 → O^+ + H_2^+, O^0 + H_2^2+
VI $\text{O}^{3+} + \text{He}$ collisions

VI-1 $\text{O}^{8+} + \text{He} \rightarrow \text{O}^{7+}(n\ell) + \text{He}^+, \text{O}^{6+}(n\ell'n\ell') + \text{He}^{2+}$

VI-2 $\text{O}^{7+}(ls) + \text{He} \rightarrow \text{O}^{6+}(ls\ell\ell) + \text{He}^+, \text{O}^{5+}(ls\ell'n\ell') + \text{He}^{2+}$

VI-3 $\text{O}^{6+}(ls^2) + \text{He} \rightarrow \text{O}^{5+}(ls^2n\ell) + \text{He}^+, \text{O}^{4+}(ls^2n\ell'n\ell') + \text{He}^{2+}$

VI-4 $\text{O}^{5+}(ls^2s) + \text{He} \rightarrow \text{O}^{4+}(ls^2s\ell\ell) + \text{He}^+, \text{O}^{3+}(ls^2s\ell'n\ell') + \text{He}^{2+}$

VI-5 $\text{O}^{4+}(ls^2s^2) + \text{He} \rightarrow \text{O}^{3+}(ls^2s^2n\ell) + \text{He}^+, \text{O}^{2+}(ls^2s^2n\ell'n\ell') + \text{He}^{2+}$

VI-6 $\text{O}^{3+}(ls^2s^2p) + \text{He} \rightarrow \text{O}^{2+}(ls^2s^2p\ell\ell) + \text{He}^+, \text{O}^+(ls^2s^2p\ell'n\ell') + \text{He}^{2+}$

VI-7 $\text{O}^{2+}(ls^2s^2p^2) + \text{He} \rightarrow \text{O}^+ + \text{He}^+, \text{O}^0 + \text{He}^{2+}$
I C\textsuperscript{9+} + H(1s) collisions

I-1 C\textsuperscript{6+} + H(1s) + C\textsuperscript{5+}(n\ell) + H\textsuperscript{+}

Experimental data for total cross sections are summarized.\textsuperscript{1} A number of total cross sections have been calculated using different techniques:

- Salop and Olson\textsuperscript{2} (LZ model, 0.04 - 2.9 keV/amu) 1976
- Olson and Salop\textsuperscript{3} (CTMC, 20 - 25 keV/amu) 1977
- Bottcher\textsuperscript{4} (IP, <225 keV/amu) 1977
- Vaaben and Briggs\textsuperscript{5} (MO basis, 1.06 - 6.25 keV/amu) 1977
- Greenland\textsuperscript{5a} (S-matrix, 0.06 - 25 keV/amu) 1978
- Ryufuku and Watanabe\textsuperscript{6} (UDWA, 0.025 - 2000 keV/amu) 1979
- Crothers and Todd\textsuperscript{7} (exponential model, 0.25 - 25 keV/amu) 1980
- Ryufuku\textsuperscript{8} (UDWA, 0.025 - 2000 keV/amu) 1982
- Green et al.\textsuperscript{9} (LZ, 0.8 - 52 keV/amu) 1982
- Green et al.\textsuperscript{10} (MO, 3 - 1300 eV/amu) 1982
- Fritsch\textsuperscript{11} (AO, 0.1 - 1.0 keV/amu) 1982
- Suzuki et al.\textsuperscript{12} (EDWA, 0.1 - 10 keV/amu) 1984
- Toshima and Watanabe\textsuperscript{13} (DWA, 0.2 - 500 keV/amu) 1986
- Kimura\textsuperscript{14} (travelling MO, 0.15 - 10 keV/amu) 1986
- Kimura and Lane\textsuperscript{15} (travelling MO, 0.15 - 10 keV/amu) 1987.

It should be noted that the electron capture cross sections from hydrogen atoms in the 2s excited states calculated by Salop\textsuperscript{16} are far large and nearly constant over the energy range 0.02 - 2.5 keV/amu (~ 3 x 10\textsuperscript{-14} cm\textsuperscript{2}) and even at the highest energies are larger by one order of magnitude, compared with those for the ground state which increase sharply with increasing the energy:

\[ \text{C}^{6+} + \text{H}(2s) + \text{C}^{5+}(n\ell) + \text{H}^+ . \]  \hspace{1cm} (1)

Janev et al.\textsuperscript{17}, using MLZRC technique, calculated the n-dependence of the cross sections over 0.05 - 64 keV/amu with n=4 dominance.
At the selected energies the cross sections for \((n\ell)\)
distributions have been also calculated:

- Ryufuku and Watanabe\(^{18}\) (UDWA, 25, 75 keV/amu) 1979
- Hardie and Olson\(^{19}\) (CTMC, \(\frac{25}{2}, 50\) keV/amu) 1983
- Presnyakov and Uskov\(^{20}\) (Keldysh model, \(n\ell=4\ell, 25\) keV/amu) 1984
- Grozdanov and Belic\(^{21}\) (LZ, \(n\ell=4\ell, 0.5 - 20\) keV/amu) 1984.

More systematic calculations for \((n\ell)\) distributions have been
reported as follows:

- Salop\(^{22}\) (CTMC, 25 - 72 keV/amu) 1979
- Green et al.\(^{23}\) (MO, 0.01 - 27 keV/amu) 1982
- Kazanski and Komarov\(^{24}\) (MO, \(n\ell=4\ell, 5\ell, 0.25 - 4\) keV/amu) 1982
- Fritsch and Lin\(^{25}\) (AO, 0.1 - 20 keV/amu) 1984
- Salin\(^{26}\) (MO, 1.0 - 16 keV/amu) 1984
- Bedahman et al.\(^{27}\) (MO, 0.25 - 50 keV/amu) 1985
- Kimura and Lin\(^{28}\) (AO-MO, 0.2 - 4 keV/amu) 1985.

Fritsch\(^{29}\) extended his calculation for less dominant \((n\ell)\)
states, namely for \(n=6, 7, 8\) at 4, 10 and 25 keV/amu. At
higher energies, Crothers and McCann\(^{30}\) calculated the \((n\ell m)\)
distributions using CDW and OBK over 5 - 2000 keV/amu.

Recently Belkic et al.\(^{31}\) reported \((n\ell)\) distributions \((n=1-7)\)
at higher energies (200-3500 keV) calculated by the first
Born approximation with correct boundary condition. Similar
calculations were made by Dube and Burgdorfer.\(^{31a}\)

Experimental work is quite limited. Kimura et al.\(^{32}\), using
translational energy spectroscopy, observed the dominant
channel of the electron capture into \(n=4\) states. Using
photon spectroscopy, Dijkkamp et al.\(^{33}\) determined the emissio.
cross sections for \(n=4 \rightarrow n=2 (13.5 \text{ nm}), n=3 \rightarrow n=2 (18.2 \text{ nm})\) and
\(n=4 + n=3 (52.1 \text{ nm})\) transitions. This measurement was
extended by Hoekstra et al.\(^{34}\) who determined the emission
cross sections for \(n=4 + n=2 (13.5 \text{ nm}), n=4 + n=3 (52.1 \text{ nm}), n=3 + n=2 (18.2 \text{ nm}), n=5 + n=3 (35.6 \text{ nm}), n=7 + n=6 (343.5 \text{ nm})\) and
\(n=8 + n=7 (529.5 \text{ nm})\) transitions over 1 - 9 keV/amu.

References
34. R. Hoekstra, D. Ciric, A.N. Zinoviev, Yu.S. Gordeev, F.J. de Heer and R. Morgenstern, to be published
Fig. 1  $C^6^+ + H \rightarrow C^5^+(\text{total}) + H^+$
Fig. 2 \[ \text{C}^6^+ + \text{H} \rightarrow \text{C}^5^+ (3s) + \text{H}^+ \]

Graph showing the cross section in cm² as a function of energy (eV/amu) for the reaction \( \text{C}^6^+ + \text{H} \rightarrow \text{C}^5^+ (3s) + \text{H}^+ \). The data points are from Green, T.A. et al. (1982).
Fig. 3 \[ \text{C}^6^+ + \text{H} \rightarrow \text{C}^5^+(3\text{p}) + \text{H}^+ \]
Fig. 4.  C^6+ + H → C^5+(3d) + H^+
Fig. 5  \( C^6 + H \rightarrow C^{5+}(4s) + H^+ \)


Cross-section (cm²)

Energy (eV/amu)
Fig. 6  \( \text{C}^{6+} + \text{H} \rightarrow \text{C}^{5+}(4p) + \text{H}^+ \)
Fig. 7  C^6+ + H → C^5+ (4d) + H^+
Fig. 9: $\text{C}^6+ + \text{H} \rightarrow \text{C}^5(5s) + \text{H}^+$
Fig. 10 \( \text{C}^{6+} + \text{H} \rightarrow \text{C}^{5+}(5p) + \text{H}^{+} \)
Fig. 11  \( \text{C}^{6+} + \text{H} \rightarrow \text{C}^{5+}(5d) + \text{H}^+ \)

Cross section (cm\(^2\))

Energy (eV/amu)

\( \odot \) Kazanskii, A.K. et al. (1982)
\( \triangle \) Kimura, M. Lin, C.D. (1985)
\( \oplus \) Green, T.A. et al. (1982)
Fig. 12  $C^6^+ + H \rightarrow C^5^+(5f) + H^+$

Cross section (cm$^2$)

Energy (eV/amu)

- Kazanskii, A.K. et al. (1982)
- Green, T.A. et al. (1982)
Fig. 13  \[ \text{C}^{6+} + \text{H} \rightarrow \text{C}^{5+}(5g) + \text{H}^+ \]

Cross section (cm$^2$)

Energy (eV/amu)

- $\bigcirc$ Kazanskii, A.K. et al. (1982)
- $\square$ Green, T.A. et al. (1982)
\[ I-2 \, C^{5+}(ls) + H(ls) + C^{4+}(l\text{sn}) + H^+ \]

The dominant capture occurs into n=4 states of C\(^{4+}\) ions at low energies, as clearly understood from the energy diagram of the system. Total electron capture cross sections have been calculated by Bottcher and Heil\(^1\) using fully quantal PSS method over the energy range 1 - 250 eV/amu and by Shipsey et al.\(^2\) using MO (for low energy) and CTMC (for high energy) over 10\(^{-2}\) - 200 keV/amu. Experimental situation of total cross sections is summarized.\(^3\)

Total cross sections show a minimum at intermediate energy: The cross sections increase with decreasing the collision energy, reaching about 10\(^{-14}\) cm\(^2\) at the energy less than 1 eV/amu, meanwhile, after passing a minimum (2 x 10\(^{-15}\) cm\(^2\)) at 500 eV/amu, the cross sections reach a maximum (5 x 10\(^{-15}\) cm\(^2\)) at 7 - 8 keV/amu and then decrease rapidly with increasing the collision energy. Unfortunately no experimental and theoretical data for the \((nl)\) distributions have been reported up to now. Shipsey et al.\(^2\) estimated the contribution from n states other than n=4 is quite small at intermediate energy range: for example, that from n=3 state increases with increasing the collision energy, however, being only about 5% at 5 keV/amu and that from n=5 state is even smaller. This situation is also confirmed experimentally by Kimura et al.\(^4\)

References
I-3 C$^4$(1s$^2$) + H(1s) + C$^3$(1s$^2$nℓ) + H$^+$

All the theories predict that the dominant electron capturing level is n=3 and the contribution from other neighbouring levels is small, which are confirmed experimentally. Total electron capture cross sections have been calculated using different methods by Olson et al. (0.05 - 5 keV/amu), Hanssen et al. (0.25 - 25 keV/amu: their numerical numbers are cited by Bendahman et al.) and Bottcher and Heil (0.5 eV - 250 eV), meanwhile experimental data have already been compiled.

On the other hand, the partial cross sections have been calculated by Fritsch and Lin using AO expansion method and by Gargaud et al. using MO mode. Only a single experimental measurement of the partial cross sections was made by Dijkkamp et al. using the photon spectroscopy over the energy range 0.25 - 6.25 keV/amu. Some preliminary data are given by Dijkkamp et al., Ciric et al. and Dijkkamp et al.

Generally speaking, the agreement among theories and experiments is quite good for dominant capturing levels but the discrepancies are obvious for less intense capture cross sections.

Baptist et al. determined relative intensities among 3s, 3p and 3d subshell cross sections at the energy 0.6 - 40 keV using VUV spectroscopy and compared them with calculations by Fritsch and Lin and Gargaud et al. The agreement is found to be good among them. Some related topics on determining the absolute cross sections from photon measurements were discussed. The rate coefficients for this process over the temperature 10$^3$-10$^4$ K have been calculated by Butler and Dalgarno using LZ model.

References
Fig. 15 \[ \text{C}^{4+} + \text{H} \rightarrow \text{C}^{3+}(\text{total}) + \text{H}^+ \]
Fig. 17  $C^4^+ + H \rightarrow C^3^+(1s^22p) + H^+$
Fig. 18  \( C^{4+} + H \rightarrow C^{3+}(1s^23s) + H^+ \)

Cross section (cm\(^2\))

Energy (eV/amu)

© Dijkmamp,D. et al. (1985)
△ Gargaud,M. et al. (1987)
Fig. 19  $C^{4+} + H \rightarrow C^{3+}(1s^23p) + H^+$

Energy (eV/amu)

Cross section (cm$^2$)
Fig. 20  $\text{C}^{4+} + \text{H} \rightarrow \text{C}^{3+}(1s^23d) + \text{H}^+$
Fig. 21 $C^4^+ + H \rightarrow C^3^+(1s^24s) + H^+$

- Cross section (cm$^2$)
- Energy (eV/amu)

© Dijkamp, D. et al. (1985)
Fig. 22 \( \text{C}^{4+} + \text{H} \rightarrow \text{C}^3\left(1s^24p\right) + \text{H}^+ \)

Cross section \( \text{cm}^2 \)

Energy \( \text{eV/amu} \)

© Dijkstra, D. et al. (1985)
Fig. 23  \( \text{C}^4+ + \text{H} \rightarrow \text{C}^5\text{y} (1s_2^4d) + \text{H}^+ \)
Fig. 24 \[ C^4+ + H \rightarrow C^3+(1s^24f) + H^+ \]
Experimental data of the measured total cross sections are summarized. Blint et al. have calculated the cross sections for the dominant (1s\(^2\)2s3s \(^3\)S) states over the energy range 0.1 - 1.75 eV/amu using perturbation theory and also for (1s\(^2\)2s3s \(^1\)S) states which are found to be far weak (only 1-2% of those for \(^3\)S states at 1 eV/amu). They also compared their results with Landau-Zener calculation, their agreement being fairly good. Watson et al. also made the full quantal calculation for 1s\(^2\)2s3s \(^3\)S state over 0.001 - 15 eV/amu. Their results show significant deviation from LZ model at lower energies, in particular below 0.01 eV/amu. The rate coefficients were calculated quantally by Butler et al. over 5\times10^3 - 5\times10^4 K. Using molecular treatment, Heil et al. calculated the partial cross sections for 2s3s \(^3\)S, 2s3p \(^3\)P\(^0\), 2p\(^2\) \(^1\)S and 2p\(^2\) \(^1\)D states over 0.27 - 8.1 eV/amu. Furthermore, Bienstock et al. extended their calculations using UDWA over 10 - 5000 eV/amu. Experimental investigations were reported by McCullough et al. using the translational energy spectroscopy over 0.05-1.5 keV/amu, though their results are sometimes mixed from other states because of the limited energy resolution. On the other hand, Ciric et al. determined the absolute partial cross sections for the following processes using photon spectroscopy over 0.7 - 4.6 keV/amu:

\[
\begin{align*}
& C^3+(1s^22s^2S) + H(ls) \rightarrow C^2+(1s^22s3s^3S) + H^+ \\
& \quad (1s^22s3s^1S) \\
& \quad (1s^22s3p^3P^0) \\
& \quad (1s^22s3p^1P^0) \\
& \quad (1s^22s3d^3D) \\
& \quad (1s^22s3d^1D) \\
& \quad (1s^22s4d^3D) \\
& \quad (1s^22p^2^1S) \\
& \quad (1s^22p^2^1D) \\
& \quad (1s^22p^2^3P). 
\end{align*}
\]
References

Fig. 25  \( C^3+ + H \rightarrow C^2+(\text{total}) + H^+ \)
Fig. 26(a) \( C^3 + H \rightarrow C^2(1s^22s3s \ ^3S) + H^+ \)
Fig. 26(b) \( \text{C}^3 + \text{H} \rightarrow \text{C}^2(1s^22s3s \ 3S) + \text{H}^+ \)
Fig. 27  $C^3+ + H \rightarrow C^2+(1s^22s3s \,^1S) + H^+$
Fig. 28  $C^{3+} + H \rightarrow C^2(1s^2 2s 3p \, ^3p^0) + H^+$
Fig. 29 \[ C^{3+} + H \rightarrow C^2(1s^22s3p \, ^1P^0) + H^+ \]

Cross section (cm²)

Energy (eV/amu)

© Ciric, D. et al. (1985)
Fig. 30  \( \text{C}^{3+} + \text{H} \rightarrow \text{C}^{2+}(1s^2 2s 3d \ 3D) + \text{H}^+ \)
Fig. 32  \( C^3_+ + H \rightarrow C^2_1(1s^22s^24d \,^3D) + H^+ \)
Fig. 33  $\text{C}^{3+} + \text{H} \rightarrow \text{C}^{2+}(1s^22p^2 \, ^1S) + \text{H}^+$

- Cross section (cm$^2$)
- Energy (eV/amu)

- Cric, D. et al. (1985)
- Hell, T.G. et al. (1981)
- McCullough, R.W. et al. (1984)
- Bienstock, S. et al. (1982)
Fig. 34 \[ C^{3+} + H \rightarrow C^2(1s^2 2p^2 \, ^3P) + H^+ \]
Fig. 35 $\text{C}^3^+ + \text{H} \rightarrow \text{C}^{2+}(1s^22p^2 \; ^1D) + \text{H}^+$
Total electron capture cross sections for this process are summarized, showing a broad maximum of $8 \times 10^{-16}$ cm$^2$ at around 200 keV and decrease with decreasing the energy. However, no \textit{(n\ell)} distributions have been determined experimentally. Only a single experiment on \textit{(n\ell)} distributions was reported by McCullough et al.\textsuperscript{2} over the energy range 2-8 keV. Unfortunately they could not provide the cross sections for \textit{(n\ell)} distribution because their C$^{2+}$ ion beams contain not only ions in the ground state, 1s$^2$2s$^2$ 1S, but also an unknown but significant fraction of ions in the metastable 1s$^2$2s2p $^3p^0$ state.

On the other hand, some theoretical investigations have been made at low energies from the astrophysical interest\textsuperscript{3-6}. Generally the cross sections are small at thermal to eV energy region and the rate coefficients of the electron capture process are $10^{-11} - 10^{-12}$ cm$^3$/s, which are two - three orders of magnitude smaller than those for C$^{3+} +$ H collisions. In these investigations, the following processes can be expected to occur:

\begin{align*}
\text{C}^{2+}(1s^22s^2 \ 1S) + H(1s) & \rightarrow \text{C}^+ (1s^22s^22p \ ^2p^0) + \text{H}^+ \quad (1) \\
& \rightarrow (1s^22s2p^2 \ ^2D) \quad (2) \\
& \rightarrow (1s^22s2p^2 \ ^2S) \quad (3) \\
& \rightarrow (1s^22s3p^2 \ ^2D). \quad (4)
\end{align*}

Process (1), electron capture into the ground state, is only important at low energies though the cross sections themselves are small ($10^{-18}$ cm$^2$ at 1 eV\textsuperscript{5}) and decrease with increasing the energy. With increasing the energy, the capture into the excited state accompanying simultaneous excitation, in particular process (2), becomes dominant with the cross section of $10^{-18}$ cm$^2$ at 100 eV. The dominance of process (2) at higher energies has been observed experimentally, though only qualitatively, by McCullough et al.\textsuperscript{2} There the electron capture into 1s$^2$2s2p$^2$ 2S states begins to play a role ($10 - 20\%$ of $^2D$ state at 2-8 keV).
As already mentioned above, the measured total electron capture might be affected by the presence of the metastable \( 1s^22s2p^3p^0 \) state ions. McCullough et al. have shown that at 1 keV energy region the following processes involving the metastable ion beams are observed:

\[
\begin{align*}
C^2+(1s^22s2p^3p^0) + H(1s) & \rightarrow C^+(1s^22s2p^2^2D) + H^+ + (1s^22s2p^2^2S) \\
& \rightarrow (1s^22s2p^2^2D) + (1s^22s2p^3p^0) \\
& \rightarrow (1s^22s2p^2^3P^0) \\
& \rightarrow (1s^22s2p^2^3P^0) \\
\end{align*}
\]

and process (7) where one electron is captured into \( 2s \) state, accompanying \( 2p \) state electron excitation into \( 3p \) state, is found to be dominant (~50% of total).

The radiative electron transfer process

\[
C^2+(1s^22s^2^1S) + H(1s) \rightarrow C^+(1s^22s2p^2^2P^0) + H^+ + hv
\]

has the rate coefficients which are five orders of magnitude smaller than those for non-radiative electron capture mentioned above in the energy range of \( 10 - 10^6 \) K.

References

Fig. 36  \( \text{C}^{2+} + \text{H} \rightarrow \text{C}^1(1\text{s}^22\text{s}^22\text{p}^2\text{P}^0) + \text{H}^+ \)
II $C^q^+ + H_2$ collisions

II-1 $C^6^+ + H_2 + C^5^+(n\ell') + H_2^+$

$+ C^4(n\ell'n\ell') + H_2^{2+}$

Experimental data for total cross sections for single electron capture are summarized$^1$. Using the tunneling model, total electron capture cross sections have been also calculated by Grozdanov and Janev$^2$ at the energies 0.12 and 2.76 keV/amu. Only a single experiment has been reported for the VUV photon emission measurement by Dijkkamp et al.$^3$ over the energy range 1.7 - 9.2 keV/amu who determined the absolute emission cross sections for $n=3 + n=2(13.5 \text{ nm})$, $n=4 + n=2(18.2 \text{ nm})$, and $n=4 + n=3(52.0 \text{ nm})$ transitions of $C^5^+$ ions. Their results show that the dominant electron capture occurs into $n=4$ state. Though no theoretical calculation of $(n\ell)$ distributions has been reported, Kimura and Lane$^4$ have described the adiabatic potential energy curves for this system and found that there is clear difference between $C^6^+ + H$ and $C^6^+ + H_2$ collision systems in the positions of the avoided crossings and the widths of the energy difference there, resulting in different behaviour of total cross sections between two systems. Their calculation also indicates the dominance of electron capture into $n=4$ states, agreeing with the experimental observation by Dijkkamp et al.$^3$ and by Kimura et al.$^5$

No total cross section for double electron capture was reported yet.

References
Fig. 38 \[ C^{5+} + H_2 \rightarrow C^{5+}\text{(total)} + H_2^+ \]
II-2 \[ \text{C}^5^+ (1s) + \text{H}_2 \rightarrow \text{C}^4^+ (1s\text{n}e) + \text{H}_2^+ \]
\[ + \text{C}^3^+ (1s\text{n}e' \text{e'}) + \text{H}_2^{2+} \]

Although total cross sections for single electron capture are summarized\(^1\), no measurement of the partial cross sections has been reported except for the determination of the dominant electron capturing levels, that is, \(n=3\) with a slight contribution of \(n=4\) states.\(^2\)

References
Experimental data of total cross sections for single and double electron capture have been compiled. Only a single set of data for the partial \((n\ell)\) distributions have been reported by Dijkstra et al.\(^2\) over the energy range of 0.8 – 6.7 keV/amu, meanwhile a calculation of the partial cross sections has been made by Gargaud and McCarron\(^3\) using MO treatment over the energy range of 0.5 – 250 eV/amu. Both experiment and theory give the dominant capture into \(n=3\) state which agrees with experimental results obtained through translational energy spectroscopy.\(^4\) The \(\ell\)-distribution among the \(n=3\) states is strongly dependent upon the collision energy, with \(3p\) state being dominant over 1 – 100 eV/amu.

Relative variation of \((n\ell m)\) distributions has been determined by Baptist et al.\(^5\) and found to be in agreement with the calculation by Gargaud and McCarron\(^3\). Also Baptist et al.\(^6\) measured the polarization of VUV photons emitted from \((3\ell m)\) states of \(C^{3+}\) ions over 4 – 40 keV/amu with the result of significant polarization for \(3s\rightarrow 2p\) transition and of \(m=0\) and \(m=\pm 1\) being dominant at low and high energies investigated, respectively.

The behaviour of \((n\ell)\) distribution of this system at much high energies (2 – 5 MeV) has been investigated also theoretically and experimentally.\(^7\) It is found that the observed \((n\ell)\) distributions can well be described by the continuum distorted wave calculation.

The electron capture of \(C^{4+}\) ions involving the metastable state \((1s2s \, ^3S)\) has also been investigated at 3.33 keV/amu energy by Druetta et al.\(^8\):

\[
C^{4+}(1s2s \, ^3S) + H_2 \rightarrow C^{3+}(1s2s\ell\ell') + H_2^+. \]

The dominant transition observed is \(1s2s2p \, ^4p^0 + 1s2s3s \, ^4S\), with the cross section of \(1.5\times10^{-15}\) cm\(^2\).
References

Fig. 39  \( \text{C}^{4+} + \text{H}_2 \rightarrow \text{C}^{3+}(\text{total}) + \text{H}_2^+ \)
Fig. 40  \[ C^4^+ + H_2 \rightarrow C^3^+ (1s^23s) + H_2^+ \]
Fig. 41  $C^4^+ + H_2 \rightarrow C^3^+(1s^23p) + H_2^+$

Energy (eV/amu)

Cross section (cm$^2$)

- Dijkmann, D. et al. (1985)
- Gargaud, M. McCarroll, R. (1985)
Fig. 4.3: \( \text{C}^{4+} + \text{H}_2 \rightarrow \text{C}^3(1s^24s) + \text{H}_2^+ \)
Fig. 4.4 $C^4^+ + H_2 \rightarrow C^3^+(1s^24p) + H_2^+$
\[ \text{II-4} \quad \text{C}^3+(1\text{s}^2 2\text{s}^2 \text{S}) + \text{H}_2 \rightarrow \text{C}^2+(1\text{s}^2 2\ell\ell') + \text{H}_2^+ \]
\[ \rightarrow \text{C}^+ + \text{H}_2^2+ \]

Total cross sections for single electron capture process have been summarized.\(^1\) In collisions with molecular targets, not only the simple electron capture but also target excitation or transfer ionization can occur and, therefore, the collision processes are much more complicated, compared with those of atomic target. In fact, Wilkie et al.\(^2\) observed a number of peaks corresponding to the following processes in their energy spectra:

\[
\begin{align*}
\text{C}^3+(1\text{s}^2 2\text{s}^2 \text{S}) + \text{H}_2 &\rightarrow \text{C}^2+(1\text{s}^2 2\text{s}^3 \text{S}) + \text{H}_2^+ \\
&\text{ (1)} \\
(1\text{s}^2 2\text{p}^2 \text{1S}) &\text{ (2)} \\
(1\text{s}^2 2\text{p}^2 \text{1D}) &\text{ (3)} \\
(1\text{s}^2 2\text{p}^2 \text{3P}) &\text{ (4)} \\
(1\text{s}^2 2\ell\text{2p} \text{1p0}) &\text{ (5)} \\
(1\text{s}^2 2\ell\text{2p} \text{3p0}) &\text{ (6)} \\
(1\text{s}^2 2\text{p}^2 \text{3P}) &\text{ (7)} \\
(1\text{s}^2 2\text{s2p} \text{1p0}) &\text{ (8)} \\
(1\text{s}^2 2\text{s2p} \text{3p0}) &\text{ (9)} \\
(1\text{s}^2 2\text{s}^2 \text{1S}). &\text{ (10)} 
\end{align*}
\]

The first six processes correspond to the electron capture into projectile ions resulting in simple ionization of \(\text{H}_2\), whereas the last four do to the dissociative ionization of target molecules. Even though the limited energy resolution of their system prohibited the complete separation of all these processes, their spectrum clearly shows the dominance of process (3), electron capture plus electron excitation, at their energy range (1.5 - 18 keV). However, they could not determine the cross sections for these processes.

On the other hand, Ciric et al.\(^3\), through photon spectroscopy, determined the cross sections for the same processes as those in atomic hydrogen target (see the above), regardless of the target molecular states after collision. Their result indicates the cross sections for \(2\text{p}^2 \text{1D} \) state are dominant at lower energy (8.28 keV), agreeing qualitatively
with those of Wilkie et al.; and decrease with increasing the energy, whereas at higher energies (55.4 keV) those for 3s $^3S$ state become dominant with significant contribution of 3d $^3D$ state as well as 2p$^2$ $^1D$ state, similar to the trend of atomic hydrogen targets. It should be noted that as their absolute values of the total cross sections obtained by summing up those for all the processes investigated and by their independent direct measurements of total cross sections seem to be inconsistent with each other and also in disagreement with other experiments, their data shown here are renormalized to the known cross sections\(^1\) by multiplying their original data by 1.74, assuming their relative values are correct. No total cross section for double electron capture was reported yet.

References
Fig. 4.7  $C^3_+ + H_2 \rightarrow C^2_+(\text{total}) + H_2^+$

---

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Fig. 50  $\text{C}^{3+} + \text{H}_2 \rightarrow \text{C}^{2+}(1s^22s3p\;^3P^0) + \text{H}_2^+$
Fig. 51  \( \text{C}_3^+ + \text{H}_2 \rightarrow \text{C}_2^+(1\text{s}\,2\text{s}\,3\text{p}^1\text{p}^0) + \text{H}_2^+ \)
Fig. 52 $C^{3+} + H_2 \rightarrow C^{2+}(1s^22s3d \, ^3D) + H_2^+$
Fig. 5.3

C³⁺ + H₂ → C⁺(1s²2s²3d² ¹D) + H₂⁺
Fig. 55 \( \text{C}^{3+} + \text{H}_2 \rightarrow \text{C}^{2+}(1s^22p^2 \ ^1\text{S}) + \text{H}_2^+ \)
Fig. 57  $C^3^+ + H_2 \rightarrow C^{2+}(1s^22p^2 \, ^1D) + H_2^+$

Cross section (cm$^2$)

Energy (eV/amu)

© Ciric, D. et al. (1985)
III C⁹⁺ + He collisions

III-1 C⁶⁺ + He(ls²) → C⁵⁺(nℓ) + He⁺(ls)
   → C⁴⁺(nℓ'n'ℓ') + He²⁺

Experimental data for total cross sections of single and double electron capture are summarized. Dijkkamp et al. have determined the emission cross sections corresponding to the n=3 → n=2 (13.5 nm) and n=4 → n=3 (52.0 nm) transitions. On the other hand, Kimura and Olson, using MO approach, calculated the partial cross sections for 3s, 3p and 3d states over the energy range 1 - 200 keV, indicating that the capture into 3d state is dominant at low energies (<10 keV), meanwhile around 20 - 200 keV these three cross sections are nearly equal. Using AO method, Fritsch and Lin calculated the partial cross sections for (3ℓ) and (4ℓ) states over 0.5 - 40 keV/amu, with the result slightly different from those of Kimura and Olson in particular at lower energies. Jain et al. extended, using two-center AO method, the calculation by Fritsch and Lin to get (nℓm) distributions over 10 keV/amu - 2 MeV/amu with the emphasis of those at higher energies. Their results are in general agreement with those of Fritsch and Lin, except for those of 3d subshell. At around 500 keV/amu, the capture into ²P₀ state is dominant, meanwhile that into 1s state becomes dominant at the energy higher than 1.5 MeV/amu.

Total cross sections over 1 - 10³ keV/amu are also given by Suzuki et al. who used UDWA method. Also total double electron capture as well as total single electron capture have been treated by Ohyama-Yamaguchi recently over the energy range 0.1 - 10 keV/amu using CC method.

References
1. W.K. Wu, B.A. Huber and K. Wiesemann, At. Data and Nucl. Data Tables
2. D. Dijkkamp, Yu.S. Gordeev, A. Brazuk, A.G. Drentje and
Fig. 58 $C^{6+} + \text{He} \rightarrow C^{5+} \text{(total)} + \text{He}^+$

Cross section (cm$^2$)

Energy (eV/amu)

Fig. 59  $C^6^+ + He \rightarrow C^5^+(3s) + He^+$
Fig. 62 $C^5_+ + He \rightarrow C^5_+ (4s) + He^+$


Cross Section (cm$^2$)

Energy (eV/amu)
Fig. 65  \( \text{C}^{6+} + \text{He} \rightarrow \text{C}^{5+}(4f) + \text{He}^+ \)
Fig. 66  \( C^6^+ + \text{He} \rightarrow C^4^+ (\text{total}) + \text{He}^2^+ \)
III-2 \( \text{C}^5^+ \text{(ls)} + \text{He} \rightarrow \text{C}^4^+(1s\text{n}_\ell) + \text{He}^+ \\
+ \text{C}^3^+(1sn_{\ell_{n'}\ell'}) + \text{He}^{2+} \)

Total cross sections for single electron capture are summarized\(^1\).

Although there is an indication that the dominant capture occurs into the \(3\ell\) states, the most likely states being \(3p\) and \(3d\) states,\(^2\) no partial cross section has been reported yet. No total cross sections for double electron capture are reported, either.

References
1. W.K. Wu, B.A. Huber and K. Wiesemann, At. Data and Nucl. Data Tables
\[ \text{III-3 } \text{C}^4+ (1s^2) + \text{He} \rightarrow \text{C}^3+ (1s^2n\ell) + \text{He}^+ \\
+ \text{C}^2+ (1s^2n\ell'n\ell') + \text{He}^2+ \]

Experimental data for single and double electron capture cross sections are summarized\(^1\).

It is known that the double electron capture is more probable at lower energies than the single electron capture\(^2\). In fact Crandall determined total cross sections for single and double electron capture and showed the double capture is dominant at the energies lower than 20 keV over the single electron capture. This feature is explained theoretically through the energy potential curves. The double electron capture proceeds to the following dominant channel:

\[ \text{C}^4+ (1s^2) + \text{He} \rightarrow \text{C}^2+ (1s^22s^2) + \text{He}^2+, \]

meanwhile the single electron capture does through the 2p state\(^3,4\) and becomes dominant at higher energies. Recently this was confirmed experimentally\(^5\), indicating that the double electron capture into \(\text{C}^2+ (1s^22s^2 \, ^1S)\) is dominant at 0.3 keV/amu. Also total double electron capture cross sections have been calculated by Grozdanov and Janev over the energy range 0.01 – 7.5 keV/amu\(^6\).

It should be noted that in order to understand the features in both processes the angular distribution of the products must be known correctly\(^7,9\).

The partial cross sections for single electron capture have been determined by Dijkkamp et al\(^10\) over the energy range 0.8 – 6.7 keV/amu. The observed results indicate the dominance of the capture into 2p state in the energy range investigated, as predicted by theories.

Some features of the \(n\ell\) distributions in this system at higher energies (2–5 MeV) have been investigated theoretically and experimentally\(^11\).

The rate coefficients for single electron capture over the temperature \(10^3 \, \text{–} \, 10^4.5 \, \text{K}\) were calculated by Butler and Dalgarno\(^12\) using LZ model.
References

1. K.W. Wu, B.A. Huber and K. Wiesemann, At. Data and Nucl. Data Tables

-93-
Fig. 67  \( C^4^+ + \text{He} \rightarrow C^3^+(\text{total}) + \text{He}^+ \)

Cross section (cm\(^2\))

Energy (eV/amu)

- Dijkstra, D. et al. (1985)
Fig. 68  $C^4^+ + He \rightarrow C^3^+(1s^22p) + He^+$

© Dijkstra, D. et al. (1985)
Fig. 69: \( \text{Cross section (cm}^2\) vs. Energy (eV/amu)} \)
Fig. 70  \( C^{4+} + He \rightarrow C^{3+}(1s^23p) + He^+ \)

Cross section \((cm^2)\)

Energy \((eV/amu)\)

© Dijkkamp, D. et al. (1985)
Fig. 71  $C^4+$ + He $\rightarrow$ $C^3+(1s^23d)$ + He$^+$

© Dijkstra, D. et al. (1985)
Fig. 72  $\text{C}^{4+} + \text{He} \rightarrow \text{C}^2^+(\text{total}) + \text{He}^2^+$
III-4 \[ C^3^+(1s^22s \ ^2S) + He \rightarrow C^2^+(1s^22s^2 \ ^1S) + He^+ \] (1)  
(1s^22s2p \ ^3p^0) (2)  
(1s^22s^2p \ ^1p^0) (3)  
(1s^22p^2 \ ^3p) (4)  
(1s^22p^2 \ ^1D) (5)

Total cross sections for single electron capture are summarized\(^1\).

In single electron capture, the above processes have been investigated using the translational energy spectroscopy technique. Kimura et al.\(^2\) have shown that the most dominant capture goes into 2s2p \(^1P\) states at 500 eV/amu, with a small contribution of 2s2p \(^3P\) and far less contribution from 2s^2 and 2p^2 states. Lennon et al.\(^3\) determined the partial cross sections for the above processes over the energy range 3-18 keV. Their results show that at the lowest energy 2s2p \(^1P\) states are far dominant over other channels but with increasing the collision energy 2s2p \(^3P\) and 2p^2 \(^3P\), \(^1D\) channels become significant. The rate coefficients over the temperature \(10^3-10^4\) K were calculated by Butler and Dalgarno\(^4\) using LZ mode. No cross section for double electron capture was reported yet.

References
1. W.K. Wu, B.A. Huber and K. Wiesemann, At. Data and Nucl. Data Tables
Fig. 73  
$C^3_2 + He \rightarrow C^{2+}(\text{total}) + He^+$ 

© Lennon, M. et al. (1993)
Fig. 75  \( \text{C}^{3+} + \text{He} \rightarrow \text{C}^{2+}(1s^22s2p \, ^3\text{P}_0) + \text{He}^+ \)

Cross section (cm\(^2\))

Energy (eV/amu)

\( \odot \) Lennon, M. et al. (1983)
Fig. 76 C\textsuperscript{3+} + He \rightarrow C\textsuperscript{2+}(1s\textsuperscript{2}2s2p\textsuperscript{1p\textsuperscript{0}}) + He\textsuperscript{+}

Cross section (cm\textsuperscript{2})

Energy (eV/amu)

\textcopyright Lennon, M. et al. (1983)
Fig. 77  $C^3^+ + \text{He} \rightarrow C^2^+ (1s^2 2p^2 \ 3p^1 \ D) + \text{He}^+$
$$\text{III-5 } \text{C}^{2+}(1s^22s^21S) + \text{He} \rightarrow \text{C}^+(1s^22s^22p^2P) + \text{He}^+ \quad (1)$$

Total cross sections for single electron capture are summarized.\textsuperscript{1} On the other hand, Lennon et al.\textsuperscript{2}, using C\textsuperscript{2+} ion beams containing an unknown, but significant fraction of the metastable state, observed the translational energy spectrum over the energy range 1 - 6 keV and found that the peak corresponding to the process (1) is very small at low energies. This can be understood because the process is endothermic. Instead, the peak corresponding to the metastable beams due to the following process

$$\text{C}^{2+}(1s^22s2p\text{ }^3P) + \text{He} \rightarrow \text{C}^+(1s^22s^22p^2P) + \text{He}^+ \quad (2)$$

is found to be significant, because the process(2) is exothermic. However, as the fraction of the metastable beam is not known, they could obtain no cross sections. Thus it should be noted that the observed total cross sections\textsuperscript{1} are also affected by the presence of the metastable beams.

No cross sections for double electron capture was reported yet.

References
1. W.K. Wu, B.A. Huber and K. Wiesemann, At. Data and Nucl. Data Tables
Experimental data for total electron capture cross sections are summarized.\(^1\) Using MO description, Harel and Salin\(^2\) calculated total cross sections with the indication of the predominance of electron capture into \(n = 5\) state at intermediate energies. Similar results have been given by Salop and Olson\(^3\) (MO + CTMC, 0.5 - 500 keV/amu) with the dominant contribution from \(n = 5\) states. Some calculation of total cross sections was also reported by Grozdanov\(^5\) over 2.5 - 100 keV/amu using his classical model. Kazanskii and Komarov\(^6\), using molecular calculation, have given the \((n\ell)\) distributions \((n = 4,5)\) over the energy range 0.25 - 4 keV/amu, with the dominance of \(n=5\) states and relatively weak contribution from \(n=4\) and \(n=6\) states. Janev et al.\(^7\) calculated the \(n\)-distributions using MLZRC method with the result of the dominant \(n=5\) states over 0.5 - 25 keV/amu. Shipsey et al.\(^8\), combining MO and LZ models, calculated the partial cross sections for \(n\ell = 4\ell, 5\ell\) and \(6\ell\) and for \(n=7\) states over 13 eV/amu - 34 keV/amu. The \((n\ell)\) distributions at 25 and 50 keV/amu have been also calculated by Hardie and Olson\(^9\) using CTMC, with an additional result of total cross sections over 25 - 200 keV/amu. Fritsch and Lin\(^10\) have reported the calculated \((n\ell)\) distributions at 0.1 - 30 keV/amu using AO method. Furthermore, Fritsch\(^11\) calculated, using the same technique, similar cross sections for non-dominant capture processes, namely \(7\ell, 8\ell\) and \(9\ell\) states. Presnyakov and Uskov\(^12\) calculated total and \(n=5\) states partial cross sections at 6.25 - 56 keV/amu. The partial cross sections for \((5\ell m)\) states have been calculated by Salin\(^13\) using MO model over 1 - 16 keV/amu. Using the same method, Bendahman et al.\(^14\) gave the cross sections for different \(n\) states over 0.25 - 50 keV/amu, indicating that those for \(n=5\) states are dominant at low energies and those for \(n=6\) become significant at higher energies. Recently
Kimura and Lane\textsuperscript{15}, using the travelling MO method, reported a similar trend over 0.2 - 5 keV/amu.

Experimentally, Kimura et al.\textsuperscript{16} confirmed the predominance of n=5 states, with the contribution of 20% from n=6 states using the translational energy spectroscopy. Most recently, Hoekstra et al.\textsuperscript{17} determined the emission cross sections for n=3 + n=4 (63.3 nm), n=5 + n=3 (20.0 nm) and n=6 + n=3 (17.0 nm) transitions with the agreement with calculations for the dominant processes but with significant discrepancies for less dominant processes.

References
Fig. 78  \( O^{8+} + H \rightarrow O^{7+}(\text{total}) + H^+ \)
Fig. 7.9  $O^8 + H \rightarrow O^7(4s) + H^+$
Fig. 80 \( \text{O}^{8+} + \text{H} \rightarrow \text{O}^{7+}(4p) + \text{H}^+ \)

Cross section (cm²) vs. Energy (eV/amu)

- © Shipsey, E.J. et al. (1983)
Fig. 8.1  \( \text{O}^8r \ + \ H \longrightarrow \text{O}^7(4d) + H^+ \)
Fig. 8.4. $O^8^+ + H \rightarrow O^7^+(5p) + H^+$

Energy (eV/amu)

Cross section (cm$^2$)

Shipsey, E.J. et al. (1982)
Kazanski, A.K. et al. (1982)
Fig. 86  \( \text{O}^{8+} + \text{H} \rightarrow \text{O}^{7+}(5f) + \text{H}^+ \)

Cross section (cm\(^2\))

Energy (eV/amu)
Fig. 87  \( O^{8+} + H \rightarrow O^{7+}(5g) + H^+ \)

Cross section (cm\(^2\))

Energy (eV/amu)

- Shipsey, E.J. et al. (1983)
- Kazanskii, A.K. et al. (1982)
Fig. 89 $O^{8+} + H \rightarrow O^{7+}(6p) + H^+$
Fig. 90  O$^8+$ + H $\rightarrow$ O$^7^+(6d)$ + H$^+$

Cross Section (cm$^2$)

$10^{-14}$ $10^{-15}$ $10^{-16}$ $10^{-18}$ $10^{-19}$

Energy (eV/amu)

$10^0$ $10^1$ $10^2$ $10^3$ $10^4$ $10^5$ $10^6$

Shipee, E., et al. (1983)
Fig. 91 $\text{O}^{8+} + \text{H} \rightarrow \text{O}^{7+}(6f) + \text{H}^+$

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<th>Cross section (cm$^2$)</th>
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© Shipsey, E.J. et al. (1983)
Fig. 93  $\text{O}^{8+} + \text{H} \rightarrow \text{O}^{7+}(6\text{h}) + \text{H}^+$

- Cross section (cm$^2$)
- Energy (eV/amu)

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IV-2 $\text{O}^7+(1s) + \text{H}(1s) \rightarrow \text{O}^6+(1sn') + \text{H}^+$

Total electron capture cross sections are summarized.\textsuperscript{1} However, no work was reported on the final state distribution except for a single experimental work by Kimura et al.\textsuperscript{2} who observed that the dominant electron capture goes into $n=5$ states at around 500 eV/amu energy range using translational energy spectroscopy.

References
Total electron capture cross sections are summarized.\textsuperscript{1} Theoretical calculations of the cross sections have been reported by Shipsey et al.\textsuperscript{2} who give total cross sections over the energy range 10\textsuperscript{-2} – 200 keV/amu using molecular treatment and CTMC, with the indication of the predominance of electron capture into \(n=4\) states at low energies. Similar results have been given by Hanssen et al.\textsuperscript{3} using MO model over 0.25 – 25 keV/amu who also show the dominant capture into \(n=4\) states with a slight contribution from \(n=3\) states. Bendahman et al.\textsuperscript{4} gave the cross sections for \(n=4\) and 5, showing that the capture into \(n=4\) states is dominant at low energies, whereas at higher energies the capture into \(n=4\) and \(n=5\) becomes comparable.

Experimental confirmation of the dominance of the capture into \(n=4\) states is given by Dijkkamp et al.\textsuperscript{5} and Kimura et al.\textsuperscript{6} In particular, Dijkkamp et al. determined the absolute cross sections for \((n\ell)\) states over 0.94 – 7.5 keV/amu using photon spectroscopy. Their observed average \(\ell\)-distributions \(<\ell>\) are found to be well reproduced theoretically based upon the extended classical over-barrier model.\textsuperscript{7}

References

\[ \text{IV-3 } \text{O}^{6+}(ls^2) + \text{H}(ls) \rightarrow \text{O}^{5+}(ls^2n\ell) + \text{H}^+ \]
Fig. 96  $\text{O}^6+ + \text{H} \rightarrow \text{O}^5(1s^24p) + \text{H}^+$
Fig. 97

\[ \text{O}^6+ + \text{H} \rightarrow \text{O}^5+ (1s^24d) + \text{H}^+ \]

Energy (eV/amu)

Cross section (cm²)
Fig. 98  $\text{O}^6+ + \text{H} \rightarrow \text{O}^{5+}(1s^24f) + \text{H}^+$
IV-4. $O^4+(1s^22s^21S) + H(ls) \rightarrow O^3+(1s^22s^2n\ell) + H^+$

Experimental total cross sections are summarized.\textsuperscript{1} Total rate coefficients over the temperature $10^3 - 10^4.5$ K were calculated by Butler and Dalgarno\textsuperscript{2} using LZ model. No partial cross section measurement has been reported.

References
\[ \text{IV-5. } O^{3+}(1s^22s^22p^2 2p^0) + H(1s) + O^{2+}(1s^22s^22pne) + H^+ \]

Total electron capture cross sections are summarized.\(^1\) On the other hand, Butler et al.\(^2\) made their quantal calculation of total rate coefficients over the temperature range \(5 \times 10^3 - 5 \times 10^4 \) K. Then, Heil et al.\(^3\) showed that the most dominant process is \(2s^22p3p^3D\) state capture followed by \(2s^22p3p^3S\) and \(2s^22p3p^1P\) at the energy range 0.27 - 8.1 eV/amu. Further, Bienstock et al.\(^4\) extended their calculation of the \((n\ell)\) distribution for \(2p3s^1P^0\), \(2p3p^1P\), \(3S\) and \(3D\) states, using the distorted-wave approximation, over the energy range 0.1 - 5000 eV/amu, showing that the capture into \(3\ell\) states, in particular \(3p^3D\) state, is dominant over the energy range investigated.

References
Fig.99  $\text{O}^{3+} + \text{H} \rightarrow \text{O}^{2+}\text{(total)} + \text{H}^+$
Fig. 101  $\text{O}^3^+ + \text{H} \rightarrow \text{O}^2^+ (1s^2 2s^2 2p^3 \, ^1P^0) + \text{H}^+$
Fig. 102  O$_3^+$ + H $\rightarrow$ O$_2^+(1s^22s^22p^3\ 3p^0\ 3S) + H^+$
Fig. 103  \( \text{O}^{3+} + \text{H} \rightarrow \text{O}^{2+}(1s^22s^22p^3 \, ^1P) + \text{H}^+ \)

Cross section (cm\(^2\))

Energy (eV/amu)
Fig. 104: \( \text{O}^3^+ + \text{H} \rightarrow \text{O}^2^+ (1s^22s2p^3d) + \text{H}^+ \)
IV-6. \( \text{O}^2+ (1s^2 2s^2 2p^2 \ 3\P) + \text{H}(1s) \rightarrow \text{O}^+ + \text{H}^+ \)

Total electron capture cross sections are summarized.\(^1\) No experimental investigation has been reported on the cross sections for \((n\ell)\) distributions. Butler et al.\(^2\) calculated the rate coefficients at the thermal energy using Landau-Zener approximation and showed the following process is dominant:

\[ \text{O}^+(1s^2 2s 2p^4 \ 4\P) + \text{H}^+, \]

that is, this dominant process is one-electron capture into 2p state accompanied by 2s electron excitation into 2p state. Butler et al.\(^3\), using quantal method, calculated total rate coefficients over the temperature \(5 \times 10^3 - 5 \times 10^4\) K for the capture into \(2s2p^4 \ 4\P\) state. Further, Heil et al.\(^4\), based upon molecular treatment, calculated the cross sections for \(2s2p^4 \ 4\P\) state over the energy range \(0.27 - 8.1\) eV/amu.

References
Fig. 105  \( O^{2+} + H \rightarrow O^+(1s^22s2p^4 \ 4P) + H^+ \)
V O³⁺ + H₂ collisions

V-1. O⁸⁺ + H₂ → C⁷⁺(nē) + H₂⁺

Experimental data for total cross sections for single electron capture are summarized.¹ Total theoretical cross sections have been calculated by Grozdanov and Janev² using the tunneling model at the energies 0.12 and 2.76 keV/amu and by Kimura and Lane³ using the travelling MO method with the indication of the dominant contribution from electron capture into n=5 states. Bliman et al.⁴, by observing Lyman series emission lines, determined relative populations in 5s, 5p, 5d, 5f and 5g states, with the most dominant contribution from 5d states followed by that from 5f states at 4.4 keV/amu. Similar photon spectroscopic data are reported by Politis et al.⁵ Using the translational energy spectroscopy, Kimura et al.⁶ have shown the dominant capture occurs into n=5 states at 0.75 keV/amu. However, no partial cross sections for this system have been reported. No total cross sections for double electron capture was reported yet, either.

References
Fig. 106  O^{6+} + H_2 \rightarrow O^7^+ (total) + H_2^+

Cross section (cm$^2$)

Energy (eV/amu)

© Kimura, M., Lane, N. F. (1987)
\[
V-2. \quad \text{O}^7+(1s) + \text{H}_2 \rightarrow \text{O}^6+(1sn\ell) + \text{H}_2^+
\]

Total cross sections for single electron capture processes, though limited quantities, are available.\(^1\) However, no investigation was reported on the final state distribution of the system except for one work by Kimura et al.\(^2\) who observed that the dominant electron capture occurs into \(n=4\) and \(5\) states with nearly equal probabilities at around 500 eV/amu using the translational energy spectroscopy. No total sections for double electron capture was reported yet.

References
Total cross sections for single and double electron capture processes are summarized.\(^1\) Baptist et al.\(^2\) determined, using photon spectroscopy, relative populations in \(\ell\)-distributions in \(n=4\) states, which are expected and confirmed experimentally\(^3\) to be dominant channels for single electron capture and have shown that the \(\ell\)-distributions are statistical at 60 keV. The detailed \((n\ell)\) distributions over 0.9 - 7.5 keV/amu have been determined, based upon photon spectroscopy, by Dijkkamp et al.\(^4\) who showed that dominant electron capture occurs into 4s states at lower energies, whereas at higher energies 4f states become significant, with the contribution of 10 - 20 \% from \(n=3s\) states. Their observed average \(\ell\)-distributions \(<\ell>\) are well reproduced theoretically using the extended classical over-barrier model over the energy range 1 - 6 keV/amu.\(^5\)

References

Fig. 107  \( \text{O}^{6+} + \text{H}_2 \rightarrow \text{O}^{5+}(\text{total}) + \text{H}_2^+ \)
Fig. 108

$O^6^+ + H_2 \rightarrow O^{5^+}(1s^2 4s) + H_2^+$
Fig. 109  \( \text{O}^{6+} + \text{H}_2 \rightarrow \text{O}^{5+}(1s^24p) + \text{H}_2^+ \)

![Graph showing cross section (cm\(^2\)) vs. energy (eV/amu) for the reaction \( \text{O}^{6+} + \text{H}_2 \rightarrow \text{O}^{5+}(1s^24p) + \text{H}_2^+ \). The graph includes data points from Dijkstra, D. et al. (1985).]
Fig. 111 $\text{O}^{6+} + \text{H}_2 \rightarrow \text{O}^{5+}(1s^24f) + \text{H}_2^+$
V-4. \( O^{2+}(1s^22s^22p^2 \, 3p) + H_2 \rightarrow O^+ + H_2^+ \)
\[ + O^0 + H_2^{2+} \]

Total cross sections for single and double electron capture processes are summarized.\(^1\) Kamber et al.\(^2\), using translational energy spectroscopy, observed a series of peaks of the energy-changed projectiles and found that the most dominant one-electron capture is into the \( 1s^22s2p^4 \, 4p_{5/2} \) state at their energy of 6 keV. This shows that the dominant electron capture into 2p state is accompanied by 2s electron excitation into 2p state. They did not report any cross section for this process.

References
VI $O^9^+ + He$ collisions

VI-1 $O^8^+ + He \rightarrow O^7^+(n\ell) + He^+ + O^6^+(n\ell' n'\ell') + He^{2+}$

Experimental data of total cross sections for single and double electron capture are summarized\(^1\). Total cross sections for single electron capture have been calculated by Suzuki et al.\(^2\), using UDWA method, over the energy range 1 - 200 keV/amu and by Kimura and Olson\(^3\) using MO model over 0.2 - 50 keV/amu. Bliman et al.\(^4\) have given their calculated cross sections for single and double electron capture based upon molecular treatment, indicating that at low energies the single electron capture into $n = 4$ states is dominant with a weak contribution from $n = 5$ states and the double electron capture into $n = 3$, $n' = 4$ and $n = 3$, $n' = 3$ states is dominant with $n = 4$, $n' = 4$ states becoming significant at higher energies. Another important result of their studies is that the double electron capture is not negligible, over the single electron capture at the keV/amu energy range.

Experimental observation by Ohtani et al.\(^5\) using the translational energy spectroscopy shows the electron is indeed selectively captured into $n = 4$ states at 0.4 keV/amu. Another experiment of Laurent et al.\(^6\) pointed out the importance of the angular distribution of the charged-changed products: that for dominant $n = 4$ states is forward-peaked, whereas the contribution to single electron capture from the autoionizing states due to double electron capture becomes important at larger scattering angles. Relative intensities of different $\ell$-states in $n = 4$ states have been measured by Politis et al.\(^7\) at 4.4 keV/amu. However, no absolute measurement of the $(n\ell)$ distributions has been reported. Theoretical calculations for $(n\ell)$ distributions at higher energies (keV - MeV) by Jain et al.\(^8\) using AO expansion method show that the capture into $n = 4$ states is dominant at around 30 keV/amu, that into $n = 3$ until 15 MeV and $n = 2$ at higher energies. At higher energies the reduction of the cross sections for $m \neq 0$ states is significant, compared to that
for \( m = 0 \) states, indicating that at higher energies the
electron capture needs larger momentum component along the
beam direction, which the \( m = 0 \) states have indeed.

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Total cross sections for single and double electron capture processes are summarized. Only a single work has been reported on the \((n\ell)\) distribution of the final states by Tsurubuchi et al.\(^2\) who used translational energy spectroscopy to identify the most dominant electron capture process into \(1s4\ell\) states at 500 eV/amu energy range.

No information is available on the \((n\ell)\) distribution of this system yet.

References
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The theoretical calculations of the cross sections of \((n\ell\ell')\) distributions have been reported by Fritsch and Lin\textsuperscript{4} using \(\text{\it\text{AO}}\) model over 0.5 - 40 keV/amu and by Shimakura et al.\textsuperscript{5} using \(\text{\it\text{MO}}\) model over 0.14 - 7 keV/amu.

References
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Fig. 112  \( \text{O}^{6+} + \text{He} \rightarrow \text{O}^{5+} \text{(total)} + \text{He}^+ \)
Fig. 113  $^5$O$^+$ + He $\rightarrow$ $^5$O$^+$(1s$^2$3s) + He$^+$
Fig. 115  \( \text{O}^{6+} + \text{He} \rightarrow \text{O}^{5+}(1s^23d) + \text{He}^+ \)

- Cross section \( \text{(cm}^2) \)
- Energy \( \text{(eV/amu)} \)

*(Dijkstra, D. et al. (1985))
*(Shimakura, N. et al. (1987))
Fig. 116  \( \text{O}^{6+} + \text{He} \rightarrow \text{O}^{5+}(1\text{s}^24\text{s}) + \text{He}^+ \)
Fig. 117  \( \text{O}^6^+ + \text{He} \rightarrow \text{O}^{5+}(1s^24p) + \text{He}^+ \)
Fig. 118  $O^{6+} + He \rightarrow O^{5+}(1s^24d) + He^+$

Cross section (cm$^2$) vs. Energy (eV/amu)

© Dijekamp, D. et al. (1985)
VI-4 $^5(1s^22s\,^5S) + \text{He} \rightarrow ^4(1s^22s\ell) + \text{He}^+$

\[ + ^3(1s^22s\ell n\ell') + \text{He}^2+ \]

Total cross sections for single and double electron capture are summarized by Wu et al.\(^1\) However, no investigation of the partial cross sections has been reported. Only a single experiment was made on the observation of the dominant electron capture into \( n = 3 \) states at the keV/amu energy range\(^2\), without knowing the \( \ell \)-distribution.

References
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\end{enumerate}
VI-5 $^04^+(ls^2s^2\ 1S) + \text{He} \rightarrow ^03^+(ls^2s^2nl) + \text{He}^+$
  $\rightarrow ^02^+(ls^2s^2n'nl') + \text{He}^{2+}$

Experimental total cross sections for single electron capture are summarized. However, no experimental studies on the partial cross sections have been reported. The rate coefficients over the temperature $10^3 - 10^4.5$ K were calculated by Butler and Dalgarno using LZ model. No total cross sections for double electron capture was reported yet.

References
1. W.K. Wu, B.A. Huber and K. Wiesemann, At. Data and Nucl. Data Tables
Experimental total cross sections for single electron capture are summarized.\(^1\)

Total rate coefficients over the temperature \(10^3 - 10^4.5\) K were calculated by Butler and Dalgarno\(^2\) using LZ model. However, no work has been reported on the partial cross section measurements.

No total cross section for double electron capture was reported yet.

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On the other hand, Kamber et al.\(^5\), using translational energy spectroscopy, determined that the capture into \(2p^3\) \(^2\)\(D_{5/2}\) state is dominant and also determined relative variation of their intensities over the energy range \(1 \) to \(8\) keV.

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Fig. 121  \( \text{O}^{2+} + \text{He} \rightarrow \text{O}^+(1s^22s^22p^3\,2p^0) + \text{He}^+ \)
Fig. 122  \( \text{O}^{2+} + \text{He} \rightarrow \text{O}^+ (1s^22s^22p^3{}^2\text{D}^0) + \text{He}^+ \)
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