Collisions between \( \text{He}^{2+} \) and Various Cometary and Planetary Molecules

Helium is the most abundant solar wind ion besides \( \text{H}^+ \), and its charge exchange emission in the EUV can provide detailed insight into the interaction between solar system plasmas. Using the two complementary experimental techniques of photon emission spectroscopy and translation energy spectroscopy we have studied state selective charge exchange in collisions between fully ionized helium and target gases characteristic for cometary and planetary atmospheres (\( \text{H}_2\text{O}, \text{CO}_2, \text{CO} \) and \( \text{CH}_4 \)). The experiments were performed at velocities typical for the solar wind (200 – 1500 km/s). We produced a data sets that can be used for modeling the interaction of solar wind alpha particles with cometary and planetary atmospheres.

5.1 Experiments

We have used two complementary experimental techniques, Photon Emission Spectroscopy (PES, see Chapter 4) and Translational Energy Spectroscopy (the TES set up at Queen’s University Belfast - see e.g. Hodgkinson et al., 1995; Kearns et al., 2001) to obtain state selective cross sections for single-electron capture reactions. These are given by:

\[
\text{He}^{2+} + \text{B} \rightarrow \text{He}^+ (n\ell) + \text{B}^+
\]

with \( \text{B} \) the neutral target gas and \( n\ell \) the principal and angular momentum quantum numbers. In PES experiments the photon emission subsequent to charge transfer into an excited state is measured while in TES experiments the energy gained or lost by the ion is determined. The energy change corresponds to the difference in electronic binding energy before and after the interaction.

In the PES experiment at the KVI Groningen, an ion beam is crossed with a neutral gas jet (see Chapter 4). The ions are produced in an ECR-Ion Source, which is floated on high
Collisions between He\textsuperscript{2+} and Various Cometary and Planetary Molecules

34

Potential allowing collision energies between 1.5 and 12 keV/amu in the case of He\textsuperscript{2+} ions. An EUV spectrometer (5 – 80 nm) was used to obtain the emission spectra following charge exchange. Absolute wavelength and sensitivity calibration of the EUV system was achieved by cross-reference to previous measurements on systems with well known cross sections (see e.g. Hoekstra et al., 1991). The spectrometer is equipped with a position sensitive detector allowing for the simultaneous detection of a wavelength range of approximately 20 nm. The He\textsuperscript{II} Lyman series was observed in second order, therefore the He\textsuperscript{II} (2p → 1s), He\textsuperscript{II} (3p → 1s) appear at 60.4 and 51.2 nm, respectively, see Fig. 5.1. At the highest collision energies, very weak traces of emission from higher He\textsuperscript{I} (np) states are detected (around 48 nm). The choice of detecting the Lyman lines in second order allows for the simultaneous measurement of the neutral He\textsuperscript{I}(1s2p \textsuperscript{1P} → 1s\textsuperscript{2} \textsuperscript{1S}) transition at 58.4 nm, that results from two-electron capture. As in our previous studies of He\textsuperscript{2+} – H\textsubscript{2} interactions, the spectra are found to be dominated either by the He\textsuperscript{II} (2p → 1s) line or by the He\textsuperscript{I} (1s2p \textsuperscript{1P} → 1s\textsuperscript{2} \textsuperscript{1S}) line depending on collision energy (Lubinski et al., 2001; Bodewits et al., 2004). The line emission is connected to the population of specific n\ell states.

Translational Energy Spectroscopy (TES) experiments were performed at the Queen’s University Belfast (Hodgkinson et al., 1995; Kearns et al., 2001). A beam of He\textsuperscript{2+} ions is produced by an ECR ion source and extracted and transported via a ‘floating beam line system’ in which the beam line is held at a potential of -4 kV. The momentum analyzed He\textsuperscript{2+} beam passes through two hemispherical energy analyzers to reduce its energy spread and is then decelerated to collision energies between 0.2 and 2.0 keV/amu. At these energies the ion beam crosses the neutral gas target. Analysis of kinetic energy changes of the

Figure 5.1: Part of the He\textsuperscript{II} decay scheme, indicated are the wavelengths (in nm) of the relevant transitions. The numbers in brackets refer to the branching ratios. The forbidden He\textsuperscript{II}(2s – 1s) decay is represented by a dashed arrow.
charge changed ions yields the identification and the determination of the relative contributions of all reaction channels. Because of the degeneracy of the different angular momentum states within a principal quantum shell (cf. Fig. 5.1), they cannot be resolved by the TES method. The TES measurements are therefore directly linked to the total population of the $n$-shells. In addition, attenuation measurements using the TES set-up at Belfast have been carried out to determine the total one electron capture cross sections for He$^{2+}$ – CH$_4$ interactions (Seredyuk et al., 2005b).

Together the present TES and PES experiments cover an energy range of 0.2 to 10 keV/amu, which corresponds to velocities from 190 – 1400 km/s, thereby encompassing typical velocities of both slow (200 – 400 km/s) and fast (~1000 km/s) solar winds (Neugebauer et al., 1998).

### 5.2 Analysis

The relative cross sections from the TES and PES experiments are put on an absolute scale by normalization to total single-electron capture cross sections, $\sigma_{\text{sec}}$. For the TES experiments absolute values for the $n$-shell specific cross sections are obtained from the relative cross sections, $\sigma_{\text{rel}}^n$, as follows:

\[
\sigma_n = \frac{\sigma_{\text{rel}}^n}{\sum_n \sigma_{\text{rel}}^n} \sigma_{\text{sec}} \tag{5.2}
\]

This procedure is repeated for each measurement. The uncertainties are determined by statistical errors and errors associated with the normalization cross sections. The relation between the HeII ($np \to 1s$) Lyman line emission $\sigma_{\text{em}}(np \to 1s)$ and the total cross section is somewhat less straightforward:

\[
\sum_n \sigma_{\text{em}}(np \to 1s) = \sigma_{\text{sec}} - \sigma(n = 1) - \sigma^*(2s) \tag{5.3}
\]

where $\sigma^*(2s)$ represents the 2s population cross section, which aside of being populated by direct capture can accumulate population via $np \to 2s$ transitions, see Fig. 5.1. The only unknown is the direct electron capture contribution $\sigma(2s)$ to $\sigma^*(2s)$, because $\sigma(n = 1)$ is

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**Table 5.1:** Resonant binding energies for He$^{2+}$ one-electron capture. Energies are estimated on basis of the Over-the-Barrier model. The binding energies of the $n=1$, 2, and 3 shells in He$^+$ are 54.4, 13.6, and 6.0 eV, respectively

<table>
<thead>
<tr>
<th>Target</th>
<th>$I_b$ (eV)</th>
<th>$I_f$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td>13.7</td>
<td>17.3</td>
</tr>
<tr>
<td>CH$_4$</td>
<td>12.5</td>
<td>15.8</td>
</tr>
<tr>
<td>CO$_2$</td>
<td>13.8</td>
<td>17.4</td>
</tr>
<tr>
<td>H$_2$O</td>
<td>12.6</td>
<td>15.9</td>
</tr>
<tr>
<td>H, O</td>
<td>13.6</td>
<td>17.1</td>
</tr>
</tbody>
</table>
Collisions between He$^{2+}$ and Various Cometary and Planetary Molecules

Figure 5.2: Single-electron capture related cross sections for He$^{2+}$ – CO$_2$ collisions. Present data: $\bullet$ – $\sigma_{em}(2p-1s)$, $\nabla$ – $\sigma_{em}(3p-1s)$, $\bigcirc$ – $\sigma(n=2)$, $\triangle$ – $\sigma(n=3)$, and $\Delta$ – $\sigma(n=1)$. Total single electron capture cross sections: ■ – Rudd et al. (1985a), □ – Greenwood et al. (2000). Curves – cross sections used for calibration and modeling purposes, see text.

known from the TES experiments and the $np\rightarrow 2s$ contributions to $\sigma^*(2s)$ can be calculated from the corresponding $np\rightarrow 1s$ transitions via their respective branching ratios. For example $\sigma_{em}(3p-2s)$ is equal to $(0.12/0.88)\sigma_{em}(3p-1s)$, see Fig. 5.1. For absolute calibration the data at 10 keV/amu was used under the assumption that the ratio between $\sigma(2s)$ and $\sigma(2p)$ is statistical, i.e., 1:3. At such an energy a (near) statistical distribution over the angular momenta is a common feature of one-electron capture by multiply charged ions (Janev and Winter, 1985; Hoekstra et al., 1990; Fritsch and Lin, 1991). The absolute calibration of the PES experiment at 10 keV/amu is applied to all energies. The uncertainties of the PES data are determined by statistical errors and possible target density fluctuations ($\leq 5\%$). There is a systematic uncertainty of about 20–25% due to the calibration procedure.

Together with existing total single-electron capture cross sections, the TES and PES data for He$^{2+}$ ions colliding on CO$_2$, CH$_4$, CO, and H$_2$O are compiled in Figures 5.2, 5.3, 5.4, and 5.5. The following general trends are observed: i) the total one-electron capture cross sections are of similar order of magnitude and they decrease with decreasing collision energy; ii) capture into high-n shells ($n \geq 3$) is a minor contribution to the total cross section; iii) capture into the $n = 2$ shell ($\sigma_{em}(2p-1s)$ and $\sigma_2$) is the dominant channel at higher energies, but decreases rapidly for energies below ~3 keV/amu; iv) at energies below ~1 keV/amu, capture into the ground state $\sigma(n = 1)$ dominates. The same trends have been observed for collisions on H$_2$ (see e.g. Hoekstra et al. (1994), Hodgkinson et al. (1995))
Figure 5.3: Single-electron capture related cross sections for He$^{2+}$ – CH$_4$ collisions. Present data: $\bullet$ – $\sigma_{em}(2p-1s)$, $\nabla$ – $\sigma_{em}(3p-1s)$, $\bigcirc$ – $\sigma$ (n=2), $\bigtriangledown$ – $\sigma$ (n=3), and $\triangle$ – $\sigma$ (n=1). Total single electron capture cross sections: $\blacksquare$ – Rudd et al. (1985a), $\square$ – this work. Curves - cross sections used for calibration and modeling purposes, see text.

Figure 5.4: Single-electron capture related cross sections for He$^{2+}$ – CO collisions. Present data: $\bullet$ – $\sigma_{em}(2p-1s)$, $\nabla$ – $\sigma_{em}(3p-1s)$. Kearns et al. 2001: $\bigcirc$ – $\sigma$ (n=2), $\bigtriangledown$ – $\sigma$ (n=3), and $\triangle$ – $\sigma$ (n=1). Total single electron capture cross sections: $\blacksquare$ – Rudd et al. (1985a), $\square$ – Cadez et al. (2002), $\lozenge$ – Ishii et al. (2002). Curves – cross sections used for calibration and modeling purposes, see text.
Collisions between He$^{2+}$ and Various Cometary and Planetary Molecules

The aforementioned points also hold for atomic hydrogen, except that no population of the He$^{2+}$ (1s) ground state is observed (see e.g. Shah and Gilbody, 1974, 1978; Hoekstra et al., 1991), not even at low energies. For atomic hydrogen the total single-electron capture follows a similar steep decrease at low energies as observed in the present cases for capture into He$^{2+}$ ($n=2$). This is a direct manifestation of the fact that resonant charge transfer is not feasible (Janev and Winter, 1985; Fritsch and Lin, 1991). Using a simple ‘resonant’ charge transfer model as the Over-the-Barrier model (Niehaus, 1986) one finds the following relation between the final state energies and the ionization potential, $I_{pot}$, of the electron donor:

$$E_{final} = (1 + \frac{q-1}{2\sqrt{q}+1})I_{pot}$$

(5.4)

with $q$ the charge state of the ion. For the collision systems under consideration the final binding energies for resonant electron capture are given in Table 5.1. From the energies it is obvious that the He$^{2+}$ ($n=2$) shell is most likely populated, but there is an energy mismatch of 2 – 4 eV depending on target species. Due to this energy difference the cross sections decrease at lower collision energies.

This argumentation is in apparent contradiction with the increase of the cross sections for capture into the He$^+$ ($n=1$) ground state at low energies, because the energy mismatch is very large, almost 40 eV. However, for molecular targets the considerable amount of electronic excess energy associated with charge transfer into the ground state can be absorbed and released via dissociative processes (Hoekstra et al., 1991; Hodgkinson et al., 1995; Kearns et al., 2001; Seredyuk et al., 2005a). As these so-called dissociative electron capture processes involve a kind of energy equilibration between ion and target, they are most efficient at lower collision energy for the interaction time is longer.

Finally, it is of note that in the energy range of 1 – 2 keV/amu in which TES and PES data overlap, the ratio of $\sigma(n = 2)$ and $\sigma_{em}(2p – 1s)$ is consistent with a statistical $\ell$-state distribution.

### 5.3 EUV Line Emission Data for Alpha Particles

The interaction of solar wind alpha particles with cometary gases shows up in the EUV spectral range via line emission at 30.4 nm (HeII (2p $\rightarrow$ 1s)) and 58.4 nm (HeI (1s2p $^3P$ $\rightarrow$ 1s $^1S$)) (Krasnopolsky et al., 1997; Krasnopolsky and Mumma, 2001; Bodewits et al., 2004). For predicting line intensities at 30.4 nm in astrophysical environments one can not directly use the measured $\sigma_{em}(2p – 1s)$ cross sections because of additional contributions from the He$^+$ (2s) state. The lifetime of the metastable He$^+$ (2s) is so long that, in contrast to cometary environments, its decay (via state mixing with the He$^+$ (2p) level) is not observed in field-free laboratory experiments (Shah and Gilbody, 1978; Hoekstra et al., 1991). However, the overall cross section for 30.4 nm emission, i.e., the cross section for ‘infinitely’ long observation times, can be constructed from the laboratory data as follows:

$$\sigma_{em}(30.4\text{nm}) = \sigma_{sec} - \sigma(n = 1) - \sigma_{em}(3p – 1s)$$

(5.5)
5.3 EUV Line Emission Data for Alpha Particles

Figure 5.5: Single-electron capture related cross sections for He$^{2+} - \text{H}_2\text{O}$ collisions. Present data: • $\sigma_{em}(2p-1s)$, ▼ $\sigma_{em}(3p-1s)$, ◦ $\sigma(n=2)$, ▽ $\sigma(n=3)$, and △ $\sigma(n=1)$. Total single electron capture cross sections: ■ – Rudd et al. (1985b), □ – Greenwood et al. (2004). Curves – cross sections used for calibration and modeling purposes, see text.

Figure 5.6: Cross sections for HeII line emission at 30.4 nm for ‘infinite’ observation times, see text.
The cross sections for 30.4 nm emission determined in this way are compiled in Fig. 5.6. For reference the data for atomic hydrogen are added (Shah and Gilbody, 1978; Hoekstra et al., 1991). Except for water molecules, the velocity behavior of the HeI line emission at 30.4 nm is found to be remarkably similar for all targets. The values used for $\sigma_{sec}$, $\sigma(n = 1)$, and $\sigma_{em}(3p - 1s)$ are indicated by the smooth curves in Figures 5.2, 5.3, 5.4, and 5.5.

The competing line emission at 58.4 nm, resulting from simultaneous two-electron capture into HeI ($1s2p \, ^1P$), is almost independent of the He$^{2+}$ collision velocity (see Fig. 5.7). As the 30.4 nm line emission depends strongly on velocity the ratio between the two lines may be used as velocity diagnostics (Bodewits et al., 2004).

In the interaction between comets and the solar wind, collision between He$^{2+}$ and water play a key role. Helium charge exchange can be traced by line emission in the extreme-ultraviolet and the ratio between the Ly-$\alpha$ and K$\alpha$ emission lines of HeII and HeI at 30.4 nm and 58.4, respectively provides a direct measure for projectile velocities that are typical for the solar wind. For solar wind velocities, the line ratio for the system He$^{2+} - \text{H}_2\text{O}$ collisions is higher than the line ratios found for CO and H$_2$. This implies that for those cases where water is the dominant collision partner for solar wind He-ions, diagnostics based on CO and H$_2$ helium line emission ratios probably overestimate the solar wind velocity (Bodewits et al., 2004).

### 5.4 Additional Charge Exchange Data

To model the line emission, one needs to track the evolution of the charge state distribution of helium ions entering in the gas cloud of the comet (Chapter 8). Besides the single electron capture (SEC) process by He$^{2+}$

$$\text{He}^{2+} + B \rightarrow \text{He}^+ + B^+$$

(5.6)

one also has to consider bound double-electron capture (B2C) by He$^{2+}$:

$$\text{He}^{2+} + B \rightarrow \text{He} + B^{2+}$$

(5.7)

and sequential one-electron capture (SEQ) by He$^+$:

$$\text{He}^+ + B \rightarrow \text{He} + B^+$$

(5.8)

These three processes control both the charge state distribution and the line emission. For total bound double capture (Eq. 5.7) we used data of Rudd et al. (1985a); Greenwood et al. (2000) and for one-electron capture by He$^+$ (Eq. 5.8) we used data of Rudd et al. (1985c,b); Greenwood et al. (2000, 2004). For the 58.4 nm line emission following single-electron capture by He$^+$ we used data of Juhász (2004). Because of the absence of the relevant data for interactions on atomic oxygen, the following cross section estimates were used: for direct and sequential single-electron capture (Eqs. 5.6 and 5.8) we used the data for atomic hydrogen because O and H have the same ionization potential; for double-electron capture we used the CO data because it has a similar second ionization potential.
5.5 Helium Line Ratio

The experimental setup used for the PES measurements described in this chapter was not yet equipped with decelerating ion optics. Direct measurements of cross sections were therefore only possible between 1.5 – 12 keV/amu (or 535 – 1500 km/s), slightly above slow solar wind velocities ($\leq$ 400 km/s). For these velocities, the ratio between the 30.4 nm and 58.4 nm emission lines is more or less constant as is shown in Fig. 5.8. Because the cross section for capture into the HeI(1s2p) state has been seen to be roughly constant with velocity in collisions between both CO and H$_2$ (Bodewits et al., 2004), we estimated 58.4 nm double electron capture cross sections for velocities below 1.5 keV/amu by extrapolation from our results. By assuming a statistical distribution over the angular momenta, the 30.4 nm/58.4 nm line ratio can then be estimated from total HeII (2$\ell$) cross sections in He$^{2+}$ – water molecule collisions (Seredyuk et al., 2005a; Abu-Haija et al., 2003).

In Fig. 5.8, the He$^{2+}$ – water molecule line ratio is compared with the line ratios obtained with H$_2$ and CO targets. Although the line ratios for collisions with the latter two molecules overall show the same behavior, the line ratio of water shows a rather different behavior over the whole range of typical solar wind velocities. The helium line ratio changes orders of magnitude for only a relatively small increase of velocity. This suggests that the 30.4/58.4 nm ratio could be used as velocity diagnostics for charge exchange interactions, but also that one should distinguish the contribution of different target species. This will be further discussed in the Chapters 8 and 9.

**Figure 5.7:** Cross sections for HeI line emission at 58.4 nm. • - CO$_2$, ○ - CO, ■ - H$_2$O, and □ - CH$_4$.  

5.5 Helium Line Ratio
Collisions between He$^{2+}$ and Various Cometary and Planetary Molecules

Figure 5.8: Dependency of line emission on the projectile velocity. **Upper panel:** He$^{2+}$ colliding on H$_2$O. Present data for state selective cross sections for He II (2p) are indicated by black squares, state selective cross sections for He II (2ℓ) by open circles (Seredyuk et al., 2005a) and grey triangles (Abu-Haija et al., 2003). Present data for He I (1s2p) are indicated by black circles. **Lower panel:** Experimental line ratios between 30.4 nm and 58.4 nm emission for He$^{2+}$ colliding on H$_2$ (white triangles), CO (grey circles – Bodewits et al., 2004) and H$_2$O (measured – black squares, estimated – grey diamonds). At low velocities, the He I cross section is estimated by extrapolation, see text. Lines are drawn to guide the eye.