Single and double electron capture by slow He$^{2+}$ from atoms and molecules

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Abstract. Impact of slow alpha particles (He$^{2+}$) on H$_2$ and O$_2$ is relevant for radiation cooling in future magnetically confined burning fusion plasmas. A new compact experimental setup has been utilized for measuring absolute cross sections for single (SEC) and double electron capture (DEC), and transfer ionization (TI) in collisions of slow (impact energy typically 0.1 – 1 keV times ion charge) singly and multiply charged ions with atoms and molecules. Our method combines collection of slow product ions and electrons with primary ion beam attenuation and stopping in a differentially pumped target gas chamber. Reliability of the new setup has been checked by measuring well established SEC and DEC cross sections for impact of slow singly and doubly charged noble gas ions on their atoms (He, Ne, Ar). We have then measured absolute cross sections for SEC by both $^3$He$^{2+}$ and $^4$He$^{2+}$ from Ne, and in further consequence will study fusion relevant SEC and DEC by He$^{2+}$ from H$_2$ and O$_2$.

1. Introduction
For an improved understanding and control of magnetically confined fusion plasmas, it is necessary to learn still more about the influence of multicharged impurity ions residing in these plasmas. In the present work, a compact experimental setup has been constructed and utilized for measuring absolute cross sections for single (SEC) and double electron capture (DEC) by slow singly and multiply charged ions from gaseous atoms and molecules. Our technique combines the collection of slow product ions with primary ion beam attenuation and stopping in a differentially pumped target gas chamber. The target gas pressure is measured by an absolutely calibrated capacitance manometer. Primary ions are obtained from a 14.5 GHz all-permanent magnet ECR ion source [1]. The reliability of the new experimental setup has been checked by measuring well established SEC and DEC cross sections for impact of slow doubly charged noble gas ions on their atoms (He, Ne, Ar), where resonant DEC is the clearly dominant reaction. We have also studied SEC and DEC for slow He$^{2+}$ collisions with Ne, where SEC is expected to proceed via a single reaction channel only [2].

2. Experimental technique
The collision chamber geometry is sketched in figure 1. An insulated aperture ($A_1$) at the entrance monitors the incoming ion beam current. A first Faraday cup (FC$_1$) with 1 mm aperture serves for normalizing the ion current measured in the second Faraday cup (FC$_2$) to the incoming ion current. The collision region is surrounded by a cylindrical mesh and a slow particle collector electrode.
At the end of the collision region a biased aperture $A_2$ discriminates singly charged ions produced via SEC from primary doubly charged ions. The aperture $A_2$ with 10 mm diameter permits a mean scattering angle of $\pm 8^\circ$. Behind $A_2$ a negatively biased ring keeps secondary electrons within FC$_2$ which registers the attenuated ion current. The pressure in the target gas cell is measured by a capacitance manometer (Baratron), with typical values in the $10^{-4}$ to $10^{-3}$ mbar range for assuring single collision conditions. SEC, DEC and TI cross sections were obtained by combination of the followings techniques.

![Figure 1. Scheme of the charge exchange setup.](image)

First aperture ($A_1$) with 2.5 mm diameter opening, Faraday cup for incoming current normalization (FC$_1$) with 1.0 mm aperture, insulated second aperture ($A_2$) for final ion selection with 10 mm diameter aperture. FC$_2$ serves for attenuated ion current measurement.

### 2.1. Beam attenuation measurement
Fast primary ions and product ions from charge-changing collisions are detected in FC$_2$. Decreasing doubly charged ion current and correspondingly increasing singly charged ion current vs. sufficiently low target thickness $\pi$ (gas density times target length) give a total attenuated current as

$$I_{FC} (\pi) \approx I_0 \left(1 - \sigma_{at} \pi \right), \text{ with } \sigma_{at} = \sigma_{20} + \frac{\sigma_{21} + \sigma_{TI}}{2}$$

(1)

where $I_0$ is the primary ion current measured in FC$_2$ without attenuation, and $\sigma_{20}$, $\sigma_{21}$ and $\sigma_{TI}$ are the DEC, SEC and transfer ionization cross sections, respectively.

### 2.2. Retarding-field measurement
After passing the target gas cell the fast primary and charge-exchanged ions are separated by a retarding field. For initial ion acceleration voltage $U_a$ primary ions are reflected by a slightly higher retarding potential, while ions which have captured $j > 1$ electrons can only be reflected with a higher potential $U_R > q U_a / (q - j)$. For primary doubly charged ions the SEC cross section is obtained from the separated current of fast singly charged ions as

$$I'_{FC} (\pi) \approx I_0 \sigma' \pi, \text{ where } \sigma' = \frac{\sigma_{21} + \sigma_{TI}}{2}$$

(2)

### 2.3. Collection of slow ions and electrons
Slow charged secondary particles are collected on the shielded cylindrical electrode surrounding the collision region (see figure 1). We distinguish slow ions and electrons by different bias of the collector with respect to the cylindrical mesh. For negative bias the dependence of slow ion current on $\pi$ is

$$I'_{coll} (\pi) \approx \varepsilon I_0 \sigma_s \pi, \text{ where } \sigma_s = \frac{\sigma_{20} + \sigma_{21} + \sigma_{TI}}{2}$$

(3)

with $\varepsilon$ the transmission factor ($0 \leq \varepsilon \leq 1$) for the collector electrode. Such slow ion measurements provide approximately the same information as the attenuation measurements (see section 2.1) and are therefore useful as a cross-check, especially at lower impact energy where the scattering angle may exceed the acceptance angle of FC$_2$. The factor $\varepsilon$ takes into account the mesh design (coiled 0.1 mm molybdenum wire with 2 mm separation of each turn, corresponding to 98% transparency, and the slits in the inner cylinder on which the mesh is fixed). We have determined $\varepsilon$ by measuring the well
established resonance SEC cross sections for Ar\(^+\), Ne\(^+\) and He\(^+\) impact at different ion energies and target gas pressures, resulting in \(\varepsilon = 0.46 \pm 0.02\). The slow electron current on the positively biased collector as function of \(\pi\) (no direct ionization expected in our impact energy range) is given by

\[ I_{coll}(\pi) \approx -\varepsilon I_0 \frac{\sigma_{II}}{2} \pi \]  

from which \(\sigma_{II}\) can be determined. Proceeding in this way, SEC and DEC cross sections are obtained from equations (1), (2) and (4) as

\[ \sigma_{21} = 2\sigma' - \sigma_{II} \]  
\[ \sigma_{20} = \sigma_{att} - \sigma' \]

3. SEC and DEC cross section measurements for X\(^{2+}\) - X collisions (X = Ar, Ne, \(^4\)He)

In order to check the reliability of the new setup, total SEC and DEC cross sections for Ar\(^{2+}\), Ne\(^{2+}\) and \(^4\)He\(^{2+}\) colliding with their respective atoms were measured for impact energies up to 10 keV. The statistical error for these measurements is typically 18 % for \(\sigma_{att}\), 10 % for \(\sigma'\) and 10 % for \(\sigma_{II}\). Since DEC cross sections have to be obtained from equation (6), here the error propagation causes an accuracy of about 20%. For all three collision systems the SEC cross sections are very small below 10 keV/amu and DEC is the by far more important reaction. The data agree with previously published ones and show that SEC is indeed less important than DEC. SEC and DEC cross sections for \(^4\)He\(^{2+}\) on He are shown in figure 2 as function of impact energy, in comparison to other experimental and theoretical data. To our knowledge, no measured data below 2 keV/amu have been published before.

Figure 2. Cross sections for \(^4\)He\(^{2+}\)-He collisions as function of impact energy. DEC: full circles – this work, full triangles – Berkner \textit{et al} [3], full diamonds – Bayfield \textit{et al} [4], full inverted triangles – Afrosimov \textit{et al} [5], solid line (AO calculation) – Fritsch [6]. SEC: open circles – this work, open triangles – Berkner \textit{et al} [3], open diamonds – Bayfield \textit{et al} [4], open inverted triangles – Afrosimov \textit{et al} [5], solid line (AO calculation) – Fritsch [6].

4. SEC cross sections for He\(^{2+}\) - Ne collisions

SEC for impact of He\(^{2+}\) on Ne has been used for TES calibration [2, 7]. Only a few absolute cross section measurements and no theoretical work are available. We investigated the impact energy range from 0.1 to 6 keV (cf. figure 3). The by far most probable reaction channel for SEC is [2]

\[ \text{He}^{2+} + \text{Ne} \rightarrow (2s^2 2p^6 1S) \rightarrow \text{He}^+ (1s) + \text{Ne}^{2+} (2s 2p^6 2S) \] \(\Delta E \approx 5.9 \text{ eV}\)  

and for DEC the reaction channel with the smallest energy defect is

\[ \text{He}^{2+} + \text{Ne} \rightarrow (2s^2 2p^6 1S) \rightarrow \text{He}^+ (2s \ 3S) + \text{Ne}^{2+} (2p^4 3P) \] \(\Delta E \approx -3.4 \text{ eV}\)
5. Summary and outlook
We have built an apparatus for SEC and DEC cross section measurements particularly at low impact energy (≤ 100 eV/amu). The reliability of this setup has been demonstrated by measuring some well established SEC and DEC cross sections. Absolute SEC and DEC cross sections for \( \text{He}^2+\)-Ne collisions have been obtained at low impact energy for the first time. We will continue our studies with similar measurements of the fusion relevant \( \text{He}^2+\)-H\(_2\) and \( \text{He}^2+\)-O\(_2\) SEC and DEC cross sections.

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