Photons shedding light on electron capture by highly charged ions
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SUMMARY

In this thesis charge transfer is studied in collisions of highly charged ions \( \text{A}^{q+} \) with neutral particles \( \text{B} \). When during the collision one electron is captured by the highly charged ion we can describe this charge transfer process by

\[
\text{A}^{q+} + \text{B} \rightarrow \text{A}^{\{q-1\}+}(n,l,m) + \text{B}^* \rightarrow \text{A}^{\{q-1\}+} + \text{"photons"}
\]

Because the electron is captured resonantly (i.e. without changing its binding energy) by the ion, a limited number of highly excited states (characterized by the quantum numbers \( nlm \)) is preferentially populated. These highly excited states subsequently decay to the ground state of the \( \text{A}^{\{q-1\}+} \) ion in one or more steps under emission of photons. The wavelength of a photon is characteristic for the specific highly excited state into which the electron was captured. The observed photon spectrum can be looked at as the "fingerprint" of the charge exchange process.

Photons from these charge transfer processes are observed in the spectra of supernovas, planetary nebulae and thermonuclear fusion plasmas. In both the astrophysical and thermonuclear fusion plasmas the highly charged ions collide mainly with atomic hydrogen. In order to obtain information about e.g. particle densities or ion temperatures in these plasmas from the observed intensity of the photon emission it is necessary to accurately know the cross sections for electron capture in the relevant highly excited states. In the experimental work described in this thesis we have measured these state selective electron capture cross sections by means of Photon Emission Spectroscopy. Especially, the most fundamental collision processes are studied: Highly charged ions colliding on atomic hydrogen. With these measured cross sections we can test the different theoretical models. These theories are based on different assumptions regarding the capture process and in most cases the different theoretical results do not agree with each other.

The experimental apparatus and measuring techniques are described in chapter 2. The emphasis is on (I) the wavelength dependent absolute sensitivity calibration of the photon detection systems, (II) the
production and the density calibration of an atomic hydrogen beam, and (III) a method to extend the possible collision energy range down to lower energies.

In chapter 3-7 the electron capture process is studied in more and more detail. First total charge transfer cross sections are determined, then the distribution of the captured electrons over the possible $n$ shells, the $nl$ subshells (i.e. states with different binding energies and angular momentum), and finally the distribution over the $nlm$ states (i.e. the orientation of the electron trajectory) is studied.

Chapter 3 treats the charge transfer process in collisions of multiply-charged (4+, 5+) ions with helium. Cross-sections are determined for the following processes: (I) single- and double-electron capture, and (II) single-electron capture followed by target excitation of the resulting ion. With a somewhat modified classical model we explain the general trends of the different capture cross-sections.

The fundamental one-electron systems, $C^6+$ and $O^8+$ (bare ions) colliding with atomic hydrogen, are described in chapter 4. The charge transfer process populates mainly a single $n$-shell, $n = 4$ for $C^6+$ and $n = 5$ for $O^8+$. It needs to be remarked that the $l$ states within one $n$-shell are (quasi-) degenerate because the $C^5+$ and $O^7+$ product ions are hydrogen-like. For this reason the different $nl \rightarrow n'l'$ transitions can not be spectroscopically resolved. Therefore the "sum" cross sections are measured. $\Sigma(nl \rightarrow n'l')$. Our experimental results for the dominantly populated $n$ shells are in good agreement with theoretical calculations. The results for the $n$-shell directly above the dominantly populated one are best reproduced by calculations which are based on an expansion of the electronic wave function in a basis of molecular wave functions. For higher $n$ shells there are considerable differences between theory and experiment. Exactly these transitions between high-$n$ shells with $\Delta n = 1$ are important for fusion plasma diagnostics because the wavelength of the accompanying photon is in the visible region and fiber connections can be used between the fusion reactor and the spectrometers.

In chapter 5 we show that it is possible to determine the separate $l$ cross-sections by measuring the $n \rightarrow n'$ "sum" emission profile along the ion beam axis and deconvoluting the different $nl \rightarrow n'l'$ emission profiles. In this way the different $He^+(4l)$ cross-sections are determined for the
first time from the $n=4 \rightarrow n=3$ transition in He$^+$ following charge transfer in He$^{2+} + \text{H}$ collisions. For plasma diagnostics, this transition is one of the most important $\Delta n=1$ transitions between high-$n$ states (the He$^+(n=2)$ state is dominantly populated). The experimental values did deviate strongly from the theoretical ones, which were used often in plasma-physical model calculations. Nowadays new theoretical results are used in these model calculations which do reproduce our measurements.

In chapter 6 we describe how the range of collision energies is enlarged from $2000 \times q$ eV to $150 \times q$ eV. This is done by decelerating a fast $4000 \times q$ eV beam with a system of five electrostatical lenses of which the last one encloses the collision center. Experiments have been done for C$^4+-\text{H}$ (and H$_2$) collisions. The state-selective cross-sections show that the long existing discrepancies between theoretical and experimental total charge transfer cross-sections (around 1.8 keV collision energy) are mainly caused by a theoretical overestimation of the C$^3^+(3p)$ capture. Although total cross-sections are in good agreement with theory for energies below 1.2 keV there exist significant differences between the experimentally determined distribution over the 3l states and the theoretical 3l distribution.

In the last chapter, chapter 7, we make the final step in determining the $m$ distribution (measure for the collisionally induced alignment) within a nl subshell. A non-uniform population of the $m$ states manifests itself through polarization of the emitted radiation. From the polarization of the $3p \rightarrow 2s$ and $3d \rightarrow 2p$ transitions in C$^3^+$ produced in collisions of C$^4+$ with H$_2$ we deduce that with increasing collision energy the $m = 0$ states are preferentially populated. This is clearly in disagreement with the often made implicit assumption that l states are statistically populated, i.e. a uniform population of the $m$ states.