Hot recoils from cold atoms
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Document Version
Publisher's PDF, also known as Version of record

Publication date:
2001

Link to publication in University of Groningen/UMCG research database

Citation for published version (APA):
8 Summary

In this thesis a novel experimental method is introduced to study, on an impact parameter dependent basis, electron transfer processes in highly charged ion-atom interactions. This technique combines a cold target of atoms, trapped and cooled in a Magneto-Optical Trap (MOT), with Recoil Ion Momentum Spectroscopy. As a proof of principle we have applied the method to study (multiple) electron capture from sodium by O$^{6+}$ and C$^{6+}$ impact. Theoretical results were obtained with the Classical Trajectory Monte Carlo (CTMC) and the Over-the-Barrier method. Besides the presentation of the experimental and theoretical results this work also contains a detailed discussion of the Magneto Optical Trap (MOT) and the recoil ion momentum spectrometer, both as used in our COld Target Recoil Ion Momentum Spectroscopy (COLTRIMS) experiments.

Also discussed in this work are results of lithium target excitation by slow H$^+$ and He$^{2+}$ impact obtained with the Photon Emission Spectroscopy (PES) experimental and the Atomic Orbital Close Coupling (AO-CC) theoretical method (Chapter 4). These data were taken with an existing set-up during the design and construction phase of our COLTRIMS experiment. With the semi-quantummechanical AO-CC theory we obtained excellent agreement with experiment and intricate ion-atom collision dynamics were observed. We saw that the Li de-excitation spectra after H$^+$ and He$^{2+}$ impact displayed a behaviour which can be ascribed to the competition of electron excitation and capture channels i.e. the former loosing flux to the latter.

In Chapter 5 we discuss the principles of laser cooling in general and our Magneto-Optical Trap (MOT) in particular. Our MOT was found to be similar to those described in literature albeit that our MOT operates at somewhat lower laser powers. Temperatures were determined to be 300±100 $\mu$K, the number of
trapped atoms in the order of $10^{6\pm1}$ and the MOT size in the order of 0.5 mm. These numbers correspond to a typical target density of about $10^{10}$ atoms/cm$^3$.

The MOT cloud is located at the heart of our recoil ion momentum spectrometer. We show in Chapter 6 that our recoil spectrometer has spatial and time focusing properties and moreover that it is "self calibrating", i.e. its characteristics can be reconstructed completely from experimentally obtained information. We can for example determine Na$^{q+}$ recoil momenta from first principles by using Na$_2^+$ MOT-ions as the zero-momentum marker. This eliminates to a large extent the need for a "benchmark collision experiment" to be part of the detector calibration, as was common in the COLTRIMS experiments up to now.

In Chapter 7 we discuss the first results of COLTRIMS with a laser cooled Na target. Na is an alkali metal with one very loosely bound outer electron and this is directly reflected in the very small momenta of the Na$^+$ recoils. The longitudinal and transversal momenta were found to be typically five times smaller than those quoted for singly charged noble gas recoils. The transversal momentum spectrum of Na$^+$ created by 3 keV/amu O$^{6+}$ impact however agreed well with the CTMC calculations, whereas the longitudinal momentum resolution needs some further attention.

Multiple electron capture from Na by O$^{6+}$ and C$^{6+}$ involves the capture of one or more core electrons and this implies much more "violent" ion-atom collisions. The typical longitudinal and transversal momenta are therefore much higher (up to two orders of magnitude as compared to Na$^+$ recoils). We compared the experimentally found final state (or Q-value) distributions to those predicted by CTMC and the Over-the-Barrier model. Both methods yield classical (continuous) final state distributions. In the CTMC method procedures have been developed to project these continuous distributions on the real (discrete) final state distribution. Although proven to be successful for one-electron processes, the consecutive use of the so-called binning procedures for many electron processes seems to lead to peculiar, unrealistic distributions. The unbinned CTMC Q-value distributions agree much better with our experiments, albeit that the mean Q-value of the CTMC calculation is somewhat larger than the mean Q-value we found experimentally. A possible cause for this larger Q-value was argued to be a reduction in the screening of the projectile charge by captured electrons in the CTMC calculations. The Over-the-Barrier model predictions agreed well with the experimental Q-value distributions.

Besides the comparison of theoretical and experimental final state (Q-value) distributions we also compared theoretical and experimental transverse momentum distributions. By doing this, we compared the predicted impact parameter dependence of the various Na$^{q+}$ ($q=2-4$) reaction channels to experiment. We found that CTMC (binned and unbinned) usually agreed very well with the experimentally found transversal momentum distributions. There were basically only discrep-
ancies between the theoretical Na\textsuperscript{3+} transversal momentum distribution and the experimentally found Na\textsuperscript{3+} momenta. Explanations for these discrepancies were obtained by using the concept of target electrons becoming active in the collision successively at smaller and smaller impact parameters. Also the experimentally found change in recoil yield when switching the projectile species from O\textsuperscript{6+} to C\textsuperscript{6+} is understandable in the context of active electrons. In collisions of O\textsuperscript{6+} with Na more Na(2p) electrons were found to become active as compared to C\textsuperscript{6+} projectiles and these extra active electrons than feed the Na\textsuperscript{3+} and Na\textsuperscript{4+} reaction channels. The end result is that O\textsuperscript{6+} produce significantly more Na\textsuperscript{4+} than C\textsuperscript{6+} projectiles.

For future developments we will be mainly looking for a higher experimental resolution (especially for the momenta of the Na\textsuperscript{+} recoils) and an improvement in theoretical methods. The former will be realized by for example increasing the path length of the spectrometer and the latter mainly by improving the CTMC binning procedure. Also considered for the future are collision experiments on Na(3p) atoms, optically pumped into a non-isotropic m-state distribution. Even a study on intense non-resonant light interacting with the ion-atom collision complex may one day be within the grasp of the experimental physicist.