

Structure and Dynamics of Atoms, Ions, Molecules, and Surfaces: Atomic Physics with High Velocity, Highly Charged Ion Beams

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The goals of this part of the J. R. Macdonald Laboratory, JRML, program are 1) to study double and triply excited states formed in high velocity, highly charged ion-neutral target collisions by state selective electron-ion resonances and by triple electron capture and 2) to study the dynamics of one and two electron processes in which electrons from bound neutral target states are brought to continuum and bound states of high velocity, highly-charged ions.

Doubly and Triply Excited States in High Z Few Electron Ions

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We continue our investigation of doubly excited states of ions via electron resonant transfer and excitation in ion-atom collisions. The process is one in which a quasi-free target electron is captured into a resonant state of the projectile ion. The process is detected by observing the Auger electron emission from the resonant state at zero degrees in the laboratory frame. This process gives rise to 180° scattering when transformed to the center of mass. The projectile electron emission spectrum can be analyzed as an electron-ion collision system by including the effects of the Compton profile of the target electrons and the kinematical transformation. It can then be directly compared with electron-ion differential elastic and inelastic scattering calculations. We have successfully demonstrated that the Auger emission from C^{5+} , N^{6+} , O^{7+} , and $F^{8+} + H_2$ collisions, when analyzed in this way, gives very good agreement with R-Matrix calculations for $C^{5+}(1s) + e^- \rightarrow C^{4+}(2p^2, ^1D) \rightarrow C^{5+}(1s) + e^-$ (and similarly for N^{6+} , O^{7+} , and F^{8+}) resonance elastic scattering[Publ. #6]. We have recently extended these measurements to the complete $2lnl$ manifold of resonance states for B^{4+} and B^{3+} projectiles. R-Matrix calculations are in good agreement for the $2p^2, ^1D$ state as indicated above and in less good agreement for the case of three electron resonance states (e.g. $1s2p^2, ^2D$).

We have also measured the inelastic scattering channel of the ion-electron scattering process by observing the Auger decays to the $2s/2p$ final states. The first manifold above the inelastic scattering threshold is the $3l3l'$ configuration. The states in the $3l3l'$ configuration decay primarily via the inelastic scattering channel. The experiment was done for $F^{8+}(1s) + e^- \rightarrow F^{7+}(3l3l') \rightarrow F^{8+}(2s/2p) + (e^-)'$. The outgoing electrons are very low in energy in the center of mass, but in the lab frame are observed at energies above and below the projectile electron cusp energy, i. e. electrons moving with the velocity of the beam. The electron group at energies greater than the cusp energy corresponds to 180° scattering in the c.m. frame and the electron group at energies less than the cusp energy corresponds to the 0° scattering in the c.m. frame. We have recently extended the measurements to B^{4+} projectiles. The resonances in this case are poorly resolved, however the gross structural features are reproduced by R-matrix calculations. These experiments are extremely time consuming. The inelastic scattering experiments were performed in our double 45° parallel plate analyzer

with retardation between the analyzers. The experiments could be performed much more efficiently using our high efficiency, high-resolution zero-degree off-axis hemispherical spectrometer with position sensitive detection on the image plane. Unfortunately we have encountered large electron backgrounds in the vicinity of the cusp, which have made these experiments impossible. We believe the background is from the scattering of the cusp electrons from the hemispheres of the analyzer. We are planning to solve this problem by introducing a high efficiency pre-analyzer to catch these unwanted electrons before they reach the position sensitive detector in the hemispherical analyzer.

In the process of studying these resonance states we noticed that for two-electron ion beams we could enhance the production of certain states by controlling the manner in which the beam was prepared. The effect is due to the $1s2s\ ^3S$ metastable component in the beam. We undertook a systematic study of the production of metastable ion beams, since what we discovered was that we could preferentially populate triply excited resonant states from the metastable beam component, e.g. $1s2s + e^- \rightarrow 2sn/nl'$ resonances. Below is a summary of these studies.

FIRST STUDY: The fraction of metastable ions in $B^3(1s^2\ ^1S; 1s2s\ ^3S)$ beams produced in collisions with thin-foil and gas targets has been measured as a function of the incident energy in the range of 0.85-9 MeV. This was done by comparing the electron yield of doubly excited states formed in the collision of B^{3+} with hydrogen and helium targets. Significant differences were observed in the energy dependence of the metastable fraction between production in foil and gas targets. It was shown that the production of $1s2s\ ^3S$ metastable ions in a foil yields a constant fraction over the investigated energy range, unlike the fraction of metastable $1s2s\ ^3S$ ions produced in collisions with gas targets, which strongly depends on the incident beam energy. A theoretical study of the processes contributing to the formation of the 3S metastable ions in collisions with foil and gas has been made. K-vacancy production in the ion-beam stripping process has been identified as a dominant mechanism and used to explain the observed difference in the energy dependence of the metastable fraction between production in collisions with gas and foil targets. A model is proposed for the calculation of the metastable fraction for He-like beams. [Publ. #4]

Z DEPENDENCE: Auger spectroscopy has been used to measure the fraction of metastable $1s2s\ ^3S$ ions in fast He-like B, C, N, O, F beams produced in collisions with thin carbon foils as a function of both the incident energy in the range of 0.5 to 2 MeV/u and the foil thickness in the range of 1-5 $\mu\text{g}/\text{cm}^2$. The method used for determination of the metastable fraction is based on measurements of the electron emission from the doubly excited states of Li-like ions formed in collisions of primary beams with hydrogen and helium targets. Some differences were observed both in the energy dependence and the absolute value of metastable fractions for different beams. In particular, the metastable content in C^{4+} ions produced in carbon foils was found to be significantly lower than that of other investigated beams. The observed deviation has been explained on the basis of K-vacancy sharing, which is known to have the highest probability for symmetric collisions. A model recently proposed for the calculation of the metastable fraction in He-like beams has been used to predict the metastable fraction of B^{3+} ions leading to good agreement with the experiment. [Publ. # 2]

NEW TECHNIQUE: An experimental technique for the determination of the metastable $1s2s\ ^3S$ fraction of two-electron ion beams has been reported. The method utilizes the electron

yields of the $1s2p^2\ ^2D$ and $1s2s2p\ ^4P$ doubly excited states, produced in collisions of two-electron ion beams with H_2 or He targets. The metastable beam fraction is determined in two successive measurements at the same beam energy but having different metastable fractions. The technique is applied to the case of B^{3+} ions in collisions with H_2 targets. The results are in good agreement with those from our recent paper on similar metastable fraction measurements [Publ. # 4]. The method can be safely applied in cases where the two different metastable fractions differ significantly. [Publ. # 3]

PRODUCTION OF TRIPLY EXCITED STATES: Triply excited states of three-electron ions have been produced by resonant transfer excitation (RTE) in metastable two-electron-ion-beam— H_2 collisions. Measurements of the Auger-electron emission in the direction of the ion beam is used to determine the absolute cross sections for formation of the triply excited states and the branching ratios of the corresponding elastic and inelastic electron scattering channels. The results are compared to existing theoretical calculations of the Auger decay rates. Accurate measurements of the double differential cross sections are made on the basis of the known metastable ion beam fractions and known cross sections for RTE from the ground-state component of the beam. The system investigated is $B^{3+}(1s2s\ ^3S) + H_2$ leading to the $B^{2+}(2s2p^2\ ^2D)$ resonance that decays to $B^{3+}(1s2s\ ^3S)$, the elastic scattering channel and to $B^{3+}(1s2s\ ^1S)$ and $B^{3+}(1s2p\ ^3P)$, two inelastic scattering channels. [Publ. # 1]

At this point in our research we observed that we could readily populate doubly and triply excited states in triple capture measurements. The first experiment involved producing states of the $1s2l2l'$ manifold. A summary of this study is given below. We later figured a way to populate more exotic and interesting triply excited manifolds, in particular the $2p^3$ states. See invited abstract by P. Richard in this conference.

TRIPLE CAPTURE: Doubly excited KLL states were populated by triple electron capture in collisions of fast ($v = 4.5\text{-}6.6$ a.u.) C^{6+} ions with Ar atoms. Measurements of the Auger electron emission in the direction of the ion beam was used to determine the absolute single differential cross sections for the triple electron capture to all autoionizing KLL states. The results were compared with cross sections calculated within the independent particle model, in which the simultaneous capture of all three-target electrons was assumed. Single electron capture probabilities, employed by the model, were calculated using the two-center semiclassical close-coupling method, based on an atomic orbital expansion. In order to allow comparison of the measured zero-degree differential cross sections with calculated total cross sections, the Auger electron emission from the doubly excited KLL states was assumed isotropic. Model calculations were found to be in a good agreement with the experimental data. The adequate description of the triple electron capture by the model implies that the projectile screening and electron-electron correlation effects in multiple electron capture are significantly reduced in fast highly charged ion-atom collisions.

Study of One- and Two-Electron Processes in Ion-Atom Collisions: Single Capture and Transfer Ionization, *R. Unal, P. Richard, N. Woody, E.P. Benis, I. Ben-Itzhak, C. L. Cocke, M. J. Singh, H. Tawara, C. D. Lin, and T. G. Lee.*

We have investigated the charge state and energy dependences of Transfer Ionization (TI) and Single Capture (SC). The main emphasis of this research is to provide reliable measured cross sections that can be compared with new state of the art calculations. The collision

systems studied are $F^{(4-9)+}$ ions interacting with helium produced in a collimated supersonic jet. The measurements were made for beam energies between 0.5 and 2.5 MeV/u, which corresponds to projectile velocities between 6 and 10 au. A recoil ion momentum spectrometer was used to separate TI and SC based on the longitudinal momentum transfer as well as the time-of-flight of the recoil ions. The ratio, σ_{TI}/σ_{SC} , was accurately obtained by this method, and the individual cross-sections for the cases of bare and hydrogen-like fluorine ions were determined by using the measured ratios and the previously measured total charge exchange cross-sections.

New calculations were undertaken to compare with this accurate data set. Previous data obtained from time of flight of the recoil ions suffer from large errors and are not in agreement with the present data or previous calculations. A more consistent independent electron model, using the two-center semiclassical close coupling method was used to calculate the SC and TI cross sections. Good agreement was found between the new measurements and the new calculations.

Publications:

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- 4) "Energy Dependence of the Metastable Fraction in $B^{3+}(1s^2\ ^1S, 1s2s\ ^3S)$ Beams Produced in Collisions with Thin-Foil and Gas Targets,"
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