Recent Measurements of Low Energy Charge Exchange Cross Sections for Collisions of Multicharged Ions on Neutral Atoms and Molecules

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At the ORNL Multicharged Ion Research Facility (MIRF), charge exchange (CX) cross sections have been measured for multicharged ions (MCI) on neutral atoms and molecules. The ORNL ion-atom merged-beams apparatus was used to measure single electron capture by MCI from H at eV/amu energies. A gas cell was used to measure single and double electron capture by MCI from a variety of molecular targets at (q x keV) collision energies.

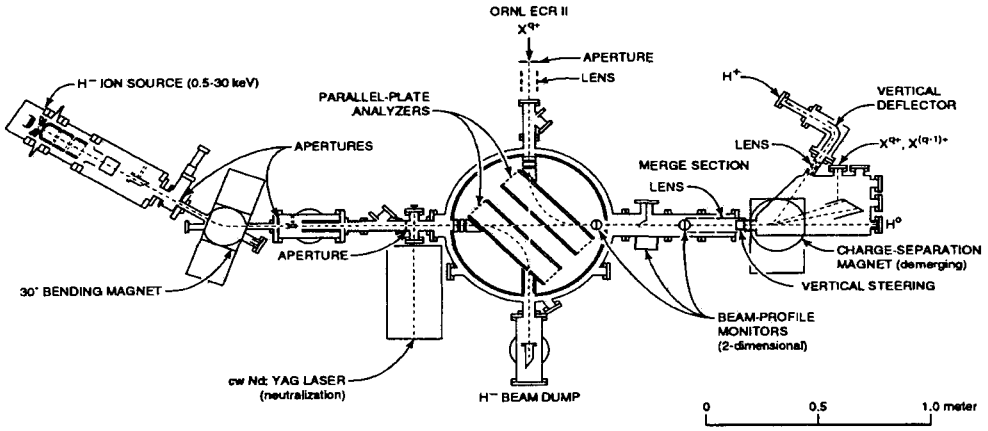

Figure 1. Schematic of the ORNL ion-atom merged-beams apparatus.

Figure 1 shows a schematic of the ORNL ion-atom merged-beams apparatus. A 6-8 keV ground state neutral atomic hydrogen or deuterium beam is produced via photo-detachment of a $H^-(D^-)$ beam as it passes through the inner cavity of a YAG laser. The neutral beam is electrostatically merged with an intense multicharged q x (8-25) keV ion beam from the ECR ion source. Measurements of the horizontal and vertical profiles of the two beams at three positions along the merge-path are used to calculate the form factor or beam-beam overlap. At the end of the merge path the signal H^+ is demerged from the primary beams and detected in a channel electron multiplier. The absolute cross section is determined directly from experimental parameters that include the primary beam intensities, form factor, beam-beam signal rate, merge path length, and velocities of the beams. Beam-beam signals are inherently low (Hz) and must be separated from large backgrounds (kHz) by a two-beam modulation technique.

The merged-beams experiment has been successful in providing benchmark total electron capture measurements for several collision systems with a variety of multicharged ions (see Table 1) on H or D. References for most measurements can be found at the web site www-cfadc. phy.ornl.gov/mirfhome or in the merged-beams reviews (Havener 97, Phaneuf 1999). The Cl^{7+} + H(D) measurements can be found in (Thompson 01) and the Mo^{q+} + H(D) in (Havener 01). The feasibility of using the merged-beams technique to measure state-selective cross sections was investigated for Si^{4+} + D (Wu & Havener 1998).

Table 1. A list of the multicharged ions used in ORNL ion-atom merged-beams measurements. Total electron capture cross sections have been measured for the above ions with H or D.

Ion q =	1	2	3	4	5	6	7	8	9	10	11
B				X							
C	X		X	X							
N		X	X	X	X						
O			X	X	X						
Ne			X	X							
Si				X							
Cl							X				
Mo				X	X		X		X		X

The following is a short discussion of some of the results pertinent to this report. Theoretical predictions of charge exchange cross sections can be very sensitive to the quasi-molecular potentials used in the calculations. This was demonstrated by merged-beams measurements (Pieksma et al. 1998) for B^{4+} + H(D) when compared to recent theory. Merged-beams measurements (Bliek et al. 1997) for C^{4+} were performed with sufficient resolution that structure was observed near the peak in the cross section where several dominant capture channels compete. The observation of this structure has led to a reevaluation (Tseng and Lin 1998) of theory, but as yet no calculation of C^{4+} has been able to reproduce the structure. More dramatic structure has been observed in merged-beams measurements (Pieksma et al. 1997) for N^{2+} + H.

There is a considerable amount of previous experimental work in ion-atom collisions at 100 eV/amu and above. While there have been recent experiments which select ions in either ground or metastable states, a significant fraction of the previous measurements did not fully characterize the metastable content of their ion beam. Merged-beams measurements [Stancil 98] for C^+ + D show that the recommended data for fusion (Janev et al. 1988) are too high at low energies and are based on previous measurements using a thermal-dissociation atomic hydrogen target (Nutt et al. 1979). These measurements used a C^+ beam, which was probably contaminated with metastables. The merged-beams measured cross section is over an order of magnitude lower at eV/amu energies and was taken with a C^+ beam essentially free of metastables. The metastable content of ion beams at ORNL can be estimated by observing electron-impact ionization below threshold. The ionization measurements were performed using the ORNL electron-ion crossed-beams apparatus (Bannister 1996). It is important to note that the electron capture process by ground state C^+ ion from H is endothermic by 2.33 eV (Stancil et al. 1998). For endothermic reactions, the cross section decreases with decreasing energy, becoming exponentially small at the lowest energies near threshold. ORNL molecular-orbital coupled-channel calculations (Stancil et al. 1998) verify this lower cross section for the C^+ ground state.

Recent measurements with the merged-beams apparatus involve heavier and higher charge state ions. Measurements with Mo^{q+}, q=4,5,7,9,11 which were limited to higher collision energies due to the 25 kV maximum acceleration voltage of the present ECR ion source, were found to generally follow the q scaling experimentally found by Phaneuf (1983) for Fe^{q+} + H, q=3-14. Our recent cross section measurements (Thompson et al. 2001) with Cl^{7+} exhibit a strong energy dependence with a decrease in the cross section toward eV/amu energies, in contrast to the slightly increasing cross section previously observed for other 7+ ions. To investigate this energy dependence MOCC calculations were performed for N^{7+} + D (calculations for Cl^{7+} are tedious due to the number of states involved). The calculated cross section for N^{7+} decreases toward lower energies and agrees with the Cl^{7+} measurements, suggesting that the Ne-like core of Cl^{7+} plays no significant role in the electron capture process for this collision system. The fact that the cross section does not remain flat toward decreasing energies shows that the actual quasi-molecular structure and associated dynamics remain important even for high charge states ions with multielecton cores.

Presently, the negative ion source on the ion-atom merged-beams apparatus is being upgraded to a new Cs negative ion sputter source which will allow measurements with a wide variety of neutral atom and molecular beams. Any negative ion whose extra electron is bound by less that 1 eV can be photodetached with the current YAG laser and used to produce a neutral beam. Such neutral beams include Li, B, Na, Al, P, K, Ca, Cr, Fe,... and molecular beams such as O_2, CH_2,....The merged-beams technique is the only technique available to explore collisions at eV/amu energies and below for these atomic targets. For vapor targets like Fe that can only be produced at high temperatures, the electron capture process is virtually unexplored. For symmetric collisions like Fe^{q+} + Fe it will be important to access the relative contribution of the single to the multiple electron capture resonant processes.

Measurements of single and double electron capture by MCI from a variety of molecular targets were performed using a gas cell for collision energies from 100 eV/amu to 3000 eV/amu. A highly collimated MCI beam was directed through a gas cell and the electron capture products, $X^{(q-1)+}$ and $X^{(q-2)+}$ were subsequently separated from the primary beam with a parallel-plate electrostatic analyzer. Measurements were performed with As^{2+} + O_2, N_2, H_2; P^{2+} + O_2, N_2, H_2; B^+ + CH_4, CO_2, CO, H_2, N_2; B^{3+} + H_2; and $S^{5+,7+}$ + CO_2, CO, H_2, H_2O. In general the ion-molecule CX measurements show the same trends with the ionization potential as the classical over barrier model, especially for larger q. For B^{3+} + H_2, single and double CX measurements show fair agreement with existing molecular-orbital close-coupling calculations (Bacchus-Montabonel 1999).

This work has been supported by the U.S. Department of Energy , Office of Fusion Energy Sciences and Office of Basic Energy Sciences, at Oak Ridge National Laboratory, which is managed by UT-Battelle, LLC, under Contract No. DE-AC05-00OR22725.

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