

Charge Transfer Experiment

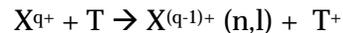
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Abstract. Low energy charge transfer is an important process in plasmas where multicharged ions and neutral atoms or molecules can exist at eV/amu energies and below. At eV/amu collision energies there are no scaling laws to characterize the charge transfer cross section and both theory and experiment are difficult. The capabilities of current experimental techniques used to measure low energy total and state-selective cross sections are discussed.

1 Introduction

Charge transfer from a multicharged ion, X^{q+} with charge q , to a neutral atomic or molecular target, T is defined by



where one (or more) electron is transferred from the neutral target to the multicharged ion. n,l denotes the principal and angular quantum number, respectively, of the final (typically excited) state of the product ion. For low energy collisions, the single electron transfer process dominates, with a cross section for single capture that is typically large, on the order of $10^{-16} \text{ cm}^2 - 10^{-14} \text{ cm}^2$. The electron capture process is important in many environments where multicharged ions and neutrals exist, e.g., in magnetically confined fusion plasmas, semiconductor processing, and photo-ionized nebulae (Kingdon 99) and has received a significant amount of experimental and theoretical effort. For velocities in the range $0.1 < v < 1$ a.u. the behavior of the total capture cross section has been successfully parameterized in terms of ionic charge, target binding energy, and collision velocity (Janev 85). For lower velocities, ($v < 0.1$ a.u.) less is known about electron capture by multicharged ions colliding with neutral atoms and molecules. The relative nuclear motion between collision partners is slow compared to the orbital motion of the active electrons in the system. Electrons of the temporary quasi-molecule formed in the collision have sufficient time to adjust to the changing interatomic field as the nuclei approach and separate. Fully quantum coupled-channel molecular-orbital calculations are considered the most accurate but are difficult to perform. The status and a review of current theory is given in another chapter.

Most of the experimental work on charge transfer has been based on ion-beam gas-target methods using conventional ion sources which are typically limited to collision energies above $\sim 1000\text{eV}$. At low energies this technique becomes difficult due to the energy spread and emittance of the primary ion beam. Complete collection of the primary and product ions (or photons) is limited both by the divergence of the primary ion beam and the angular scattering (Olson and Kimura 1982) that takes place during the collision.

Measurements with a H target are performed in a gas cell configuration using a thermal-dissociation atomic hydrogen target (e.g., Phaneuf 1981) or in a crossed-beams configuration using an effusive H beam from a radio-frequency (RF) discharge source (e.g., Dijkamp et al. 1985). State-selective techniques include photon emission spectroscopy (e.g., Dijkamp et al. 1985) and translational energy spectroscopy (e.g., Wilkie et al. 1986, Lepusch et al. 1997). Special low energy ion sources incorporate a “cool” source of ions extracted from, e.g., a laser produced plasma (Phaneuf 1981, Wang & Kwong 1997) or ions from recoils (Yaltkaya 1993). Such sources are able to produce beams typically as low as $q \times 10$ eV, where q is the charge state of the ion. However, beam-gas or crossed-beam techniques, which utilize these and other sources, still convert a significant portion of the beam energy into collision energy and the techniques are then limited to the energy spread, emittance, and intensity of the beams.

Special techniques are needed to measure electron capture cross sections at eV/amu collision energies. In the merged-beams technique, relatively fast (keV) beams are merged producing low energy collisions in a moving center-of-mass frame with a collision energy resolution significantly lower than the energy spread of each beam. With the intense multicharged ion beams made available by an electron-cyclotron-resonance (ECR) ion source, the merged-beams technique is currently used at ORNL to study electron capture for multicharged ions with neutral H or D from 0.02 eV/amu to 5000 eV/amu. At the University of Nevada, Las Vegas, an ion trap technique is used to measure reaction rates of stored ions interacting via charge transfer with target gas. With the introduction of an RF ion beam guiding technique to multicharged ions (Okuno et al. 1991), conventional beam-gas techniques have been extended to eV/amu energies. At the Tokyo Metropolitan University (TMU) in Japan, a mini-EBIS multicharged ion source in combination with an RF ion beam guide allows total electron capture cross sections to be measured to energies less than an eV/amu. At KVI Groningen, The Netherlands, a newly constructed cross-beams apparatus uses an RF ion beam guide and decelerated ions from an ECR ions source to measure state-selective electron capture cross sections using photon spectroscopy. By reviewing these current techniques one can appreciate the difficulties and also the current capabilities that exist for charge transfer (electron capture) experiments at eV/amu energies.

2 Merged-beams measurements

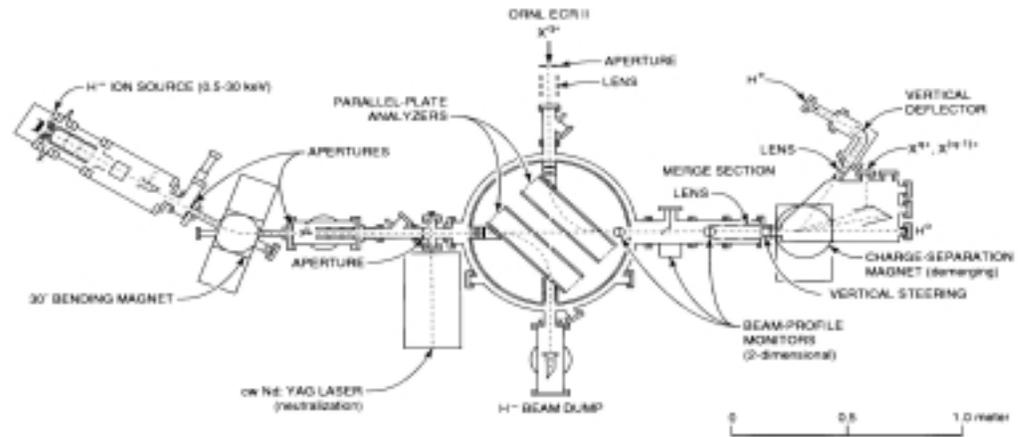


Figure 1 Schematic of the ORNL ion-atom merged-beams apparatus.

The merged-beams technique allows access to very low (thermal to keV) interaction energies. In merged-beams, relatively fast (keV) beams are merged producing low-energy collisions in a moving center-of-mass frame. Merged-beams experiments are technically difficult and early experiments were typically limited to collision systems with relatively large cross section using low charge-state beams. With the advent of the advanced ECR ion source producing high quality intense multicharged ion beams, a new class of collisions became available for study using the merged-beams technique. At ORNL, an ion-atom merged-beams apparatus (Havener 1997) was constructed to take advantage of this scientific opportunity and was used to study electron capture by multicharged ions from H and D from a low of 20 meV to 5000 eV/amu collision energies. 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 $q \times (8-25)$ 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.

The velocities of the beams are determined from their respective ion source acceleration potentials. Beam-beam signals are inherently low (Hz) and must be separated from large backgrounds (kHz) by a two-beam modulation technique.

A major advantage of the merged-beams technique [Phaneuf 99] is that relatively fast beams in the lab can be used to access eV/amu collision energies in the center-of-mass frame. Any energy spread in the primary beams, which is typically several eV, is deamplified in the center-of-mass frame, allowing the study of low energy collisions with excellent energy resolution. This deamplification increases for lower energies: for $O^{5+} + D$ collisions (Havener 1997) at 100 eV/amu, the estimated 46 eV spread in the ion beam results in only a 0.54/amu uncertainty in the collision energy, while at 0.01 eV/amu the same energy spread corresponds to only 4 meV/amu uncertainty in the collision energy. Surprisingly, the practical low energy limit for the apparatus is determined by the minimum merge angle achievable, not the energy spread of the primary beams. A merge angle of only 0.1° corresponds to an energy uncertainty of 12 meV/amu (Havener 1997).

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 on in the merged-beams reviews (Havener 97, Phaneuf 1999). The $Cl^{7+} + H(D)$ measurements can be found in (Thompson 01) and the Mo and Ne in (Havener 01). The feasibility of using the merged-beams technique to measure state-selective cross sections was demonstrated for $Si^{4+} + D$ (Wu & Havener 1998).

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

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.

The following is a short discussion of some of the results. The experimental and theoretical study (Folkerts et al. 1995) for $N^{4+} + H(D)$ found that theoretical predictions of the cross section can be very sensitive to the quasi-molecular potentials used in the calculations. Similar results were

found when merged-beams measurements (Pieksma et al. 1998) for $B^{4+} + H(D)$ were compared to recent theory. Merged-beams measurements (Bliek et al. 1997) for C^{4+} were performed with sufficient precision 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 $N^{2+} + H$.

The ion-induced dipole attraction between reactants is relatively strong at low energies and can lead to trajectory effects. When the collision energy is low enough, trajectory effects can dominate the electron capture process. This is the basis of the Langevin model (Gioumousis and Stevens 1958). According to this simple classical model, there exists a critical impact parameter b_c , such that for $b < b_c$ the trajectories follow collapsing orbits during which electron capture can occur. The Langevin model predicts that the cross section scales as

$$\sigma \propto q / v \sqrt{\alpha / \mu}$$

where v is the collision velocity, α is the polarizability of the neutral atom, and μ is the reduced mass.

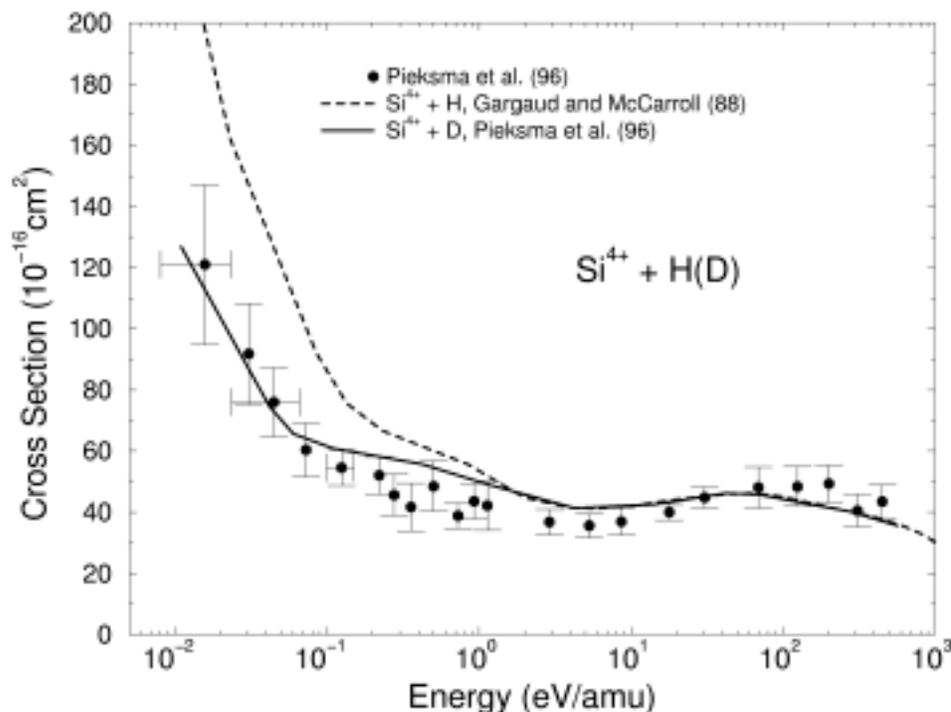


Figure 2. ORNL merged-beams measurements for $Si^{4+} + D$ compared to calculations for H and D. Error bars denote the relative error at a 90% confidence level. The relative error must be added in quadrature to the systematic error of 12% to calculate the absolute error.

Merged-beams measurements of electron capture cross sections for $\text{Si}^{4+} + \text{H(D)}$ collisions (Pieksma et al. 1996) are presented in Figure 2. These represent the first cross-section measurements in the thermal energy regime for collisions of multicharged ions with D atoms. Measurements with H could not be performed below 1 eV/amu due to the limited range of acceleration voltage of the ECR ion source. State-of-the-art molecular-orbital coupled-channel calculations (Gargaud & McCarroll 1988, Pieksma 1996) are compared in the figure to the merged-beams measurements with D on an absolute scale. Excellent agreement is found above 1 eV/amu, where strong rotational coupling between capture to the Si^{3+} (3d) and (4s) final state configurations exist. At energies below 1 eV/amu, measurements agree with the calculations for D. The cross section for H is calculated to be a factor of 1.9 larger than that for D at an energy of 0.01 eV/amu. This large isotope effect is in contradiction to the Langevin model which predicts a factor of only 1.4 (i.e., the square root of the ratio of the reduced masses). The failure of this model to predict the magnitude of the isotope effect is due to the neglect of a quantum mechanical transition probability for capture, which depends on, among other things, the radial velocity. At low enough energies, the radial velocity is determined by the ion-induced dipole attraction and the mass of the reactants. At low energies, the measurements also exhibit a $1/v$ dependence, which is also due to the attractive ion-induced dipole interaction, and which is predicted by both the molecular-orbital calculations and the Langevin model.

There is a considerable amount of previous experimental work in ion-atom collisions at 100 eV/amu and above. While there has been recent experiments (e.g., Burns et al. 1997) 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. This raises a question of utility of these data. In Figure 3, the merged-beams measurements [Stancil 98] for $\text{C}^+ +$

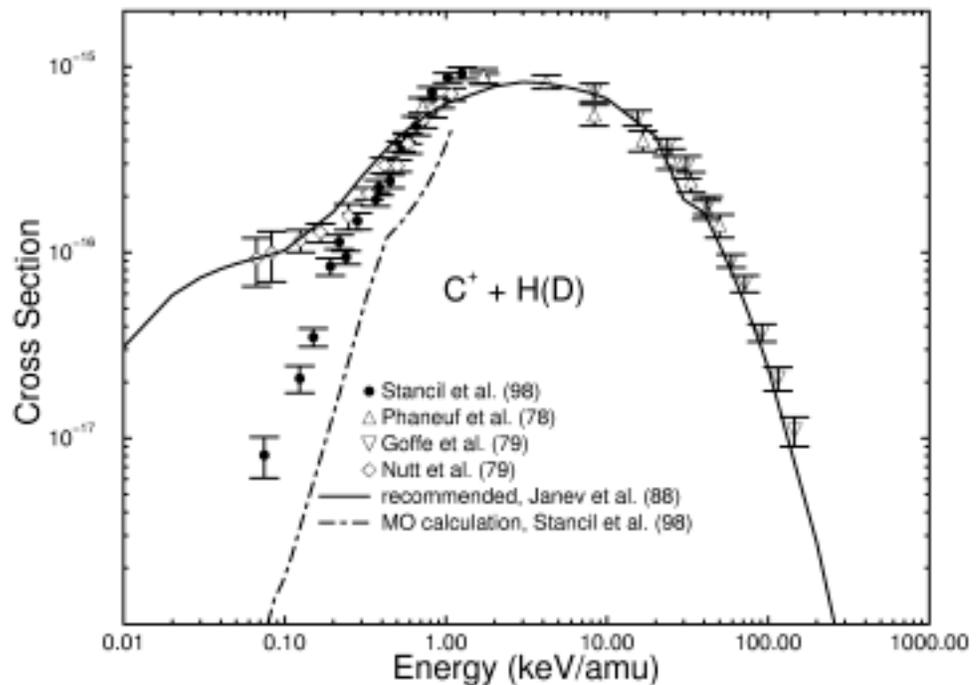


Figure 3 ORNL merged-beams measurements (Stancil et al. 1998) compared with other measurements using a hydrogen oven and with theory.

D are shown.

Note that the recommended data for fusion (solid line, Janev et al. 1988) is too high at low energies and is 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 cross section measurements are over an order of magnitude lower at eV/amu energies and were 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 98] verify this lower cross section.

Recent measurements with the merged-beams apparatus involve heavier and higher charge state ions. Measurements (Thompson et al. 2001) with Cl^{7+} show 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+} to 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 multielectron cores.

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 than 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 unexplored. For symmetric collisions like $Fe^{9+} + Fe$ it will be important to access the relative contribution of the single to the multiple electron capture resonant processes.

3 Rate measurements using an ion trap

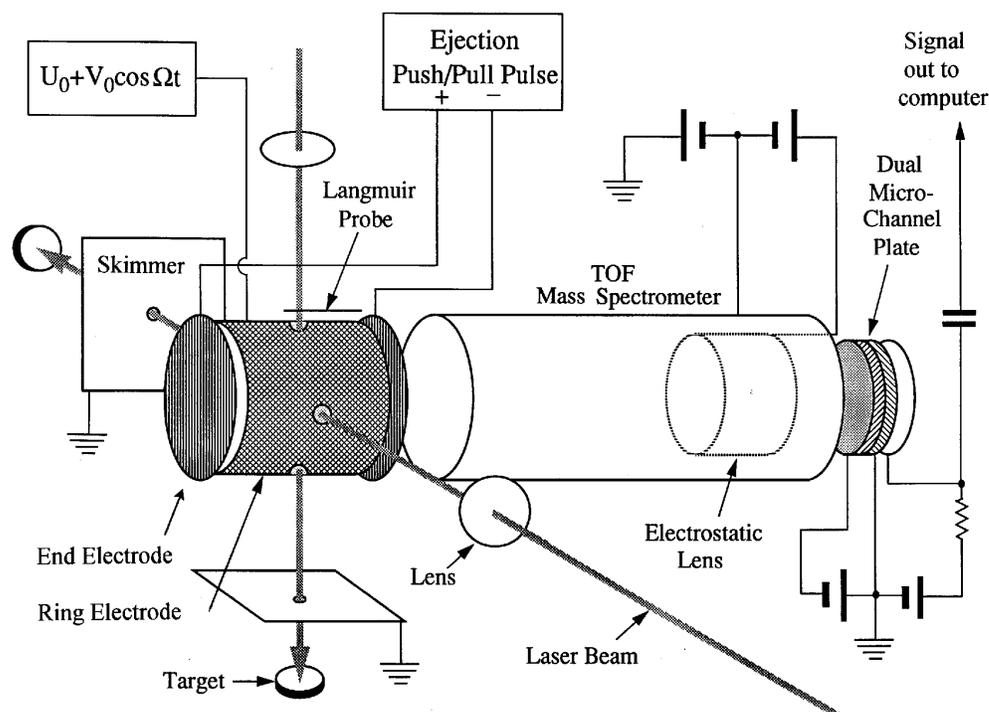


Figure 4 An overview of the laser ablation ion source and ion storage facilities.

Charge transfer rates from single or multicharged ions to gas targets are measured using an ion trap (Kwong et al. 1992). Ions are produced by a laser-induced plasma ion source and stored in the trap at an energy of a few eV for up to several seconds. Charge transfer rates are then determined by measuring the relative number of ions remaining in the trap as a function of time after their production and as a function of target gas pressure. A schematic of the apparatus is shown in Figure 4. Briefly, approximately 10^{15} ions at ~ 250 eV are simultaneously produced by laser ablation at two separate targets. Collimation of the resultant ion clouds produces two ion beams that cross at right angles inside the trap. Subsequent elastic collisions provide ions ($< 10^6$) at low enough energy to be trapped at a mean storage energy of a few eV. The trap parameters (frequency, amplitude, and d.c. bias of the RF voltage applied to the ring electrode of the trap) are adjusted to select a particular m/q . Storage times of several seconds have been demonstrated which result in most metastable ions decaying in the trap. The stored ions in the trap are analyzed by extracting the ions using voltages applied to the end caps of the trap. The extracted ions are then injected into a time-of-flight spectrometer where they are detected by a 1 in. diameter microchannel plate. The time-of-flight analysis was primarily used to determine the charge of the ions. The decay rate of the ions is measured for several target pressures. The charge transfer rate coefficient is determined from the slope of the plot of the decay rate versus target pressure.

Table 2 lists measurements using the trap and corresponding available theoretical predictions. As one can see, very little theory exists for comparison. Theory compares well with the measurement for $N^{2+} + He$, but shows a two order of magnitude discrepancy with O^{2+} and $Si^{4+} + He$. For O^{2+} , re-evaluation of the theoretical predictions by Kimura et al. (1996) shows that the measurement is consistent with there being a mixture of ground ($O^{2+}(^3P)$) and metastable ($O^{2+}(^1D)$) ions in the trap. The energy level of the metastable state is 2.51 eV higher than the ground state and has a mean lifetime of ~ 37 s. At 5000 K, the theoretical values for the ground and metastable states is 3.9×10^{-10} cm³/s and 1.0×10^{-13} cm³/s, respectively. However, experimental arguments based on plasma electron temperatures during the laser ablation process suggest that only a negligible fraction of metastables would be produced. Furthermore, only one decay curve is observed in the measurements.

Table 2. Charge transfer rate coefficient measurements and theory. Measurements with Mo⁶⁺ ions can be found in (Kwong et al. 1992); W²⁺ in (Kwong et al. 1990); O²⁺ in (Kwong & Fang 1993) N₂⁺ are found in (Fang & Kwong 1997); Si³⁺ in (Fang and Kwong 1997) ; Si⁴⁺ in (Fang & Kwong 1999); and He⁺ in (Fang, Chen & Kwong 2000).

Ion	Gas	Rate Coefficient Meas. (cm ³ s ⁻¹)	Rate Coefficient Calculation (cm ³ s ⁻¹)	Temp. K
Mo ⁶⁺	Ar	1.02(0.10) x 10 ⁻¹⁰	N/A	3500 & 20,000
W ²⁺	Ar	0.99(0.22)x10 ⁻¹¹	N/A	4100
O ²⁺	He	1.12(0.15)x10 ⁻¹²	N/A	4200
			3.9x10 ⁻¹⁰ (Kimura et al. 96) 4.5x10 ⁻¹⁰ (Gargaud et al 93) 1.0x10 ⁻¹⁰ (Butler et al 80)	5000
O ²⁺	H ₂	2.36(0.22)x10 ⁻⁹	N/A	2500
O ²⁺	N ₂	3.15(0.26)x10 ⁻⁹	N/A	13000
O ²⁺	CO	3.40(0.29)x10 ⁻⁹	N/A	13000
N ²⁺	He	8.67(0.76)x10 ⁻¹¹	8x10 ⁻¹¹ (Sun et al 96)	3900
N ²⁺	H ₂	3.38(0.35)x10 ⁻¹¹	N/A	2900
N ²⁺	N ₂	2.10(0.18)x10 ⁻⁹	N/A	13000
N ²⁺	CO	3.37(0.29)x10 ⁻⁹	N/A	13000
Si ³⁺	He	6.27(+.68)x10 ⁻¹⁰ (-.52)	4.5x10 ⁻¹⁰ (Butler et al 80) 2x10 ⁻¹⁰ (Honvault et al 95)	3900
Si ⁴⁺	He	4.54(0.48)x10 ⁻¹²	7x10 ⁻¹⁰ (Stancil et al 97) 1x10 ⁻⁹ (Opradolce et al 85) 1x10 ⁻⁹ (Butler & Dalg. 80)	4600
			2x10 ⁻¹⁰ (Bacchus-Mont. et al 98)	3000
Fe ²⁺	H ₂	< 10 ⁻¹⁴	N/A	4000
He ⁺	CO	1.33(0.15)x10 ⁻⁹	N/A	2900
		1.48(0.15)x10 ⁻⁹	N/A	8700
		1.44(0.12)x10 ⁻⁹	N/A	12000
	CH ₄	1.73(0.29)x10 ⁻⁹	N/A	8000
	N ₂	1.07(0.11)x10 ⁻⁹	N/A	8700

4 Total cross section measurements using an ion beam guide

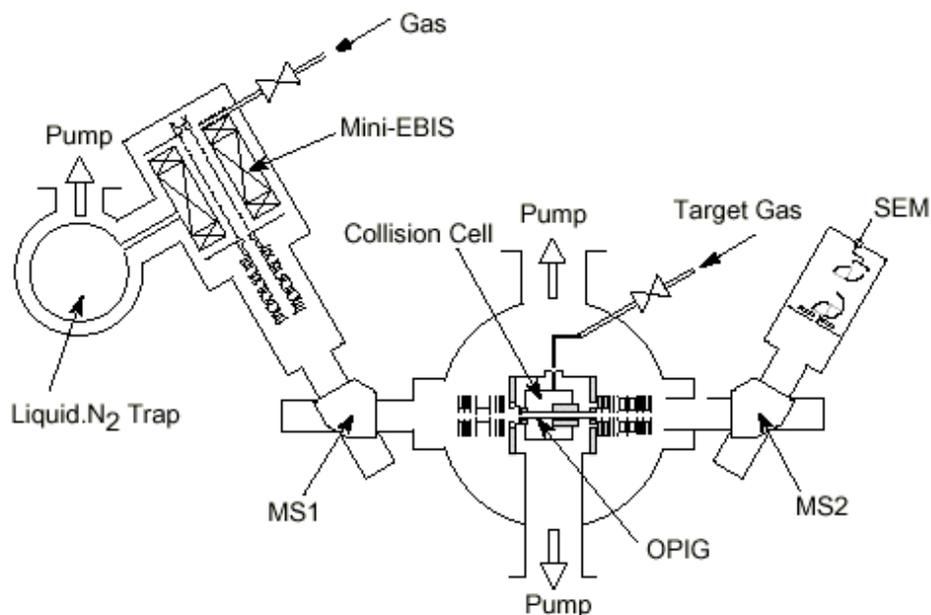


Figure 5. A schematic of the apparatus combining a mini-EBIS type ion source and an OPIG ion beam guide.

At Tokyo Metropolitan University, low energy electron capture cross sections are measured using a mini-EBIS type ion source (Okuno 1989), which is able to produce moderately intense multicharged ion beams with a small energy spread ($0.5 \times q \times \text{eV}$), and an octopole ion beam guide (OPIG) (Okuno 1986), which facilitates the collection of the scattered product ions. Figure 5 shows a schematic of the apparatus. The mini-EBIS source is a small version of an electron beam ion source (EBIS). Electrons emitted from the cathode are magnetically compressed by a rapidly increasing magnetic field of a liquid-nitrogen cooled solenoid. Cooling the solenoid allows miniaturizing it and creating a good vacuum due to cryogenic pumping.

With the mini-EBIS design, a 2 keV 12 mA electron beam can be compressed to a high current density of 10 A/cm^2 with a magnetic field of only 0.1 T. The electrons ionize the gas fed into the source, and are collected as they exit the

solenoid. The ions created in the source at low pressures (10^{-9} Torr) are confined by potential barriers at the ends of the solenoid. By lowering the barrier at the exit, ions are extracted out of the source. The source can be operated in pulsed or d.c. mode. The d.c. mode has been observed to minimize the energy spread of the source. The mini-EBIS source can produce the fully stripped ions C^{6+} , N^{7+} , and O^{8+} at the modest intensities of 5×10^4 , 4×10^4 , and 1×10^4 ions/sec. These ions are mass analyzed, focused and decelerated down to the desired collision energy before they are injected into the OPIG. The OPIG is set inside the collision cell where the target gas is bled in. An applied RF voltage to the OPIG creates an oscillatory electric field which confines the radial motion of the ions without affecting the drift motion along the central axis. The primary and product ions are accelerated out of the OPIG, magnetically analyzed, and counted by single particle counting detectors. The total electron capture cross sections, with errors of 30% at most, are determined from the initial growth of the product ion intensity as the target pressure is increased. Early work on C^{4+} , N^{4+} , and O^{4+} with He (Okuno et al. 1991) have been performed in a wide range of energy from 0.5 eV/amu to 2000 eV/amu. Later work includes $Kr^{(3-9)+} + CO$ (Ishii et al. 1996); $Kr^{(7-9)+} + Ne$, N_2 , O_2 , and CO (Ishii et al. 1999); $Ar^{(6-11)+} + He$, H_2 (Okuno et al. 1995); and $Ar^{(4-9)+} + Ne$ (Suzuki et al. 1997).

The $Kr^{q+} + CO$ measurements are presented in Figure 6 as an example. As is usually the case, the cross section for single electron capture is greater than that for double, the cross section for double greater than triple, etc. Capture from molecules is typically larger than from atomic targets and less sensitive to the particular molecular species due to the number of band-like energy levels associated with the final states (Ishii et al. 1999). The cross sections for multiple electron capture show a minimum in the cross section as a function of collision energy. The structure (see figure) gets deeper and shifts toward higher energy with an increasing number of transferred electrons. Currently there are no molecular orbital close coupling calculations to compare with these measurements. The solid lines in the figure show the Langevin $1/v$ cross section energy dependence. Especially for the higher charge state ions, the cross section shows the $1/v$ energy dependence at the lower energies. The existence of the structure in the cross sections can be understood by means of a modified over-barrier model (Ishii et al. 1999) which takes into account the induced-dipole interaction potential. Predictions using this model have shown qualitative agreement with the measurements for Ar^{q+} and Ne^{q+} on the atomic targets of He and Ne (Okuno 2001).

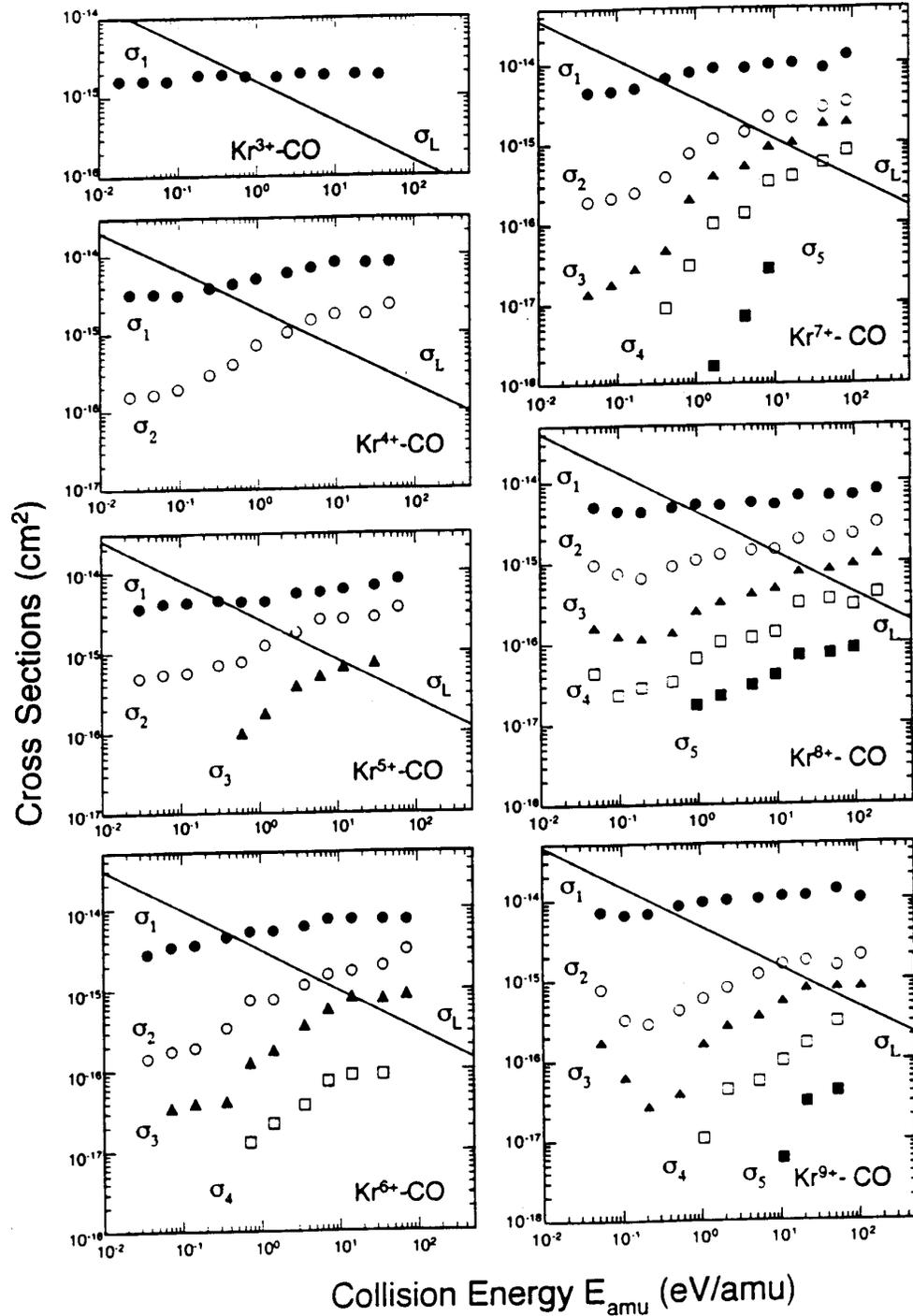


Figure 6. Log-log plot of the single and multiple electron capture cross section as a function of energy for $\text{Kr}^{(3-9)+} + \text{CO}$. The solid line denotes the energy dependence predicted by the Langevin cross section.

5 State-selective cross section measurements using an ion beam guide

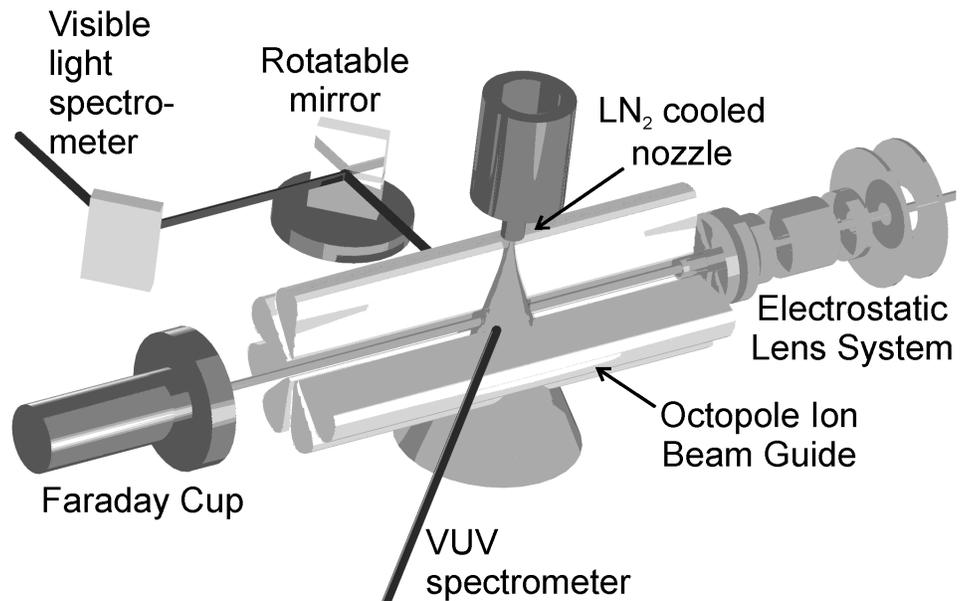


Figure 7. An artist's conception of the Octopole Ion Beam Guide at KVI, Groningen which is used to measure state-selective electron capture cross sections at eV/amu energies

At KVI Groningen, a new crossed-beam apparatus is used to measure state-selective cross sections down to eV/amu energies. Early crossed-beams measurements at KVI (e.g., Dijkamp et al. 1985) using ion beams from an ECR ion source reached collision energies as low as 1000 eV/amu. With the addition of a deceleration stage (e.g., Hoekstra et al. 1990) measurements could be performed down to 100 eV/amu. The current apparatus with the addition of an ion beam guide allows measurements to 5 eV/amu and is

shown in Figure 7. Ions that are extracted from an ECR ion source at keV energies enter the electrostatic lens system where the ions are decelerated and injected into the octopole ion beam guide. The low energy limit of $\sim 5\text{eV}/\text{amu}$ is determined by the energy spread of the ion beam from the ECR ion source. Applying a radio-frequency (RF) voltage to the octopole confines the ion beam radially as it crosses a gas target effusing through a liquid-nitrogen-cooled nozzle. Testing of the ion beam transmission shows that the ion beam can be transmitted through the apparatus without apparent loss at energies as low as a few eV/amu . The minimum collision energy is determined by the energy spread of the primary beam, which for N^{5+} is 4.2 V. During the collision of the multicharged ions with the target, capture occurs into an excited state which can decay by photon emission. A measurement of the emitted photons along with a knowledge of the branching ratios and cascade contributions allows a determination of state-selective cross sections. A VUV spectrometer can measure in the 10-90 nm wavelength range and a visible spectrometer measures 300-600 nm. Measurements can be performed with a systematic absolute uncertainty of 20%.

The first measurements with the new apparatus have been performed for He-like C^{4+} , N^{5+} , and O^{6+} ions in collisions with H_2 ; the measurements for N^{5+} are shown in Figure 8. The current measurements agree well with the previous experiment at KVI (Dijkamp 85) which only went down to 1 keV/amu. Other total cross section measurements (not shown) at 1 keV/amu (e.g., (Crandall 1979)) were above the summed measurements due to the presence of double capture to autoionizing states (transfer ionization). These states decay by emission of an electron, thereby increasing the charge on the product ion and appearing as single capture to experiments that only detect the product ion. As can be seen in the figure, the semi-classical state-selective electron capture calculations (Kumar & Saha 1999) agree fairly well with the measurements above 200 eV/amu. Below 200 eV/amu, however, the state-selective measurements show a much different energy dependence. This large discrepancy between theory and experiment points to the difficulty of theory at eV/amu energies and the need for benchmark measurements. Comparing the summed partial cross sections (total) with those of Kumar and Saha (1999), fully-quantum molecular-orbital calculations of Gargaud and McCarroll (1998), and semi-classical ab-initio molecular-orbital calculations of Elizaga et al. (2001) also shows a discrepancy below 200 eV/amu.

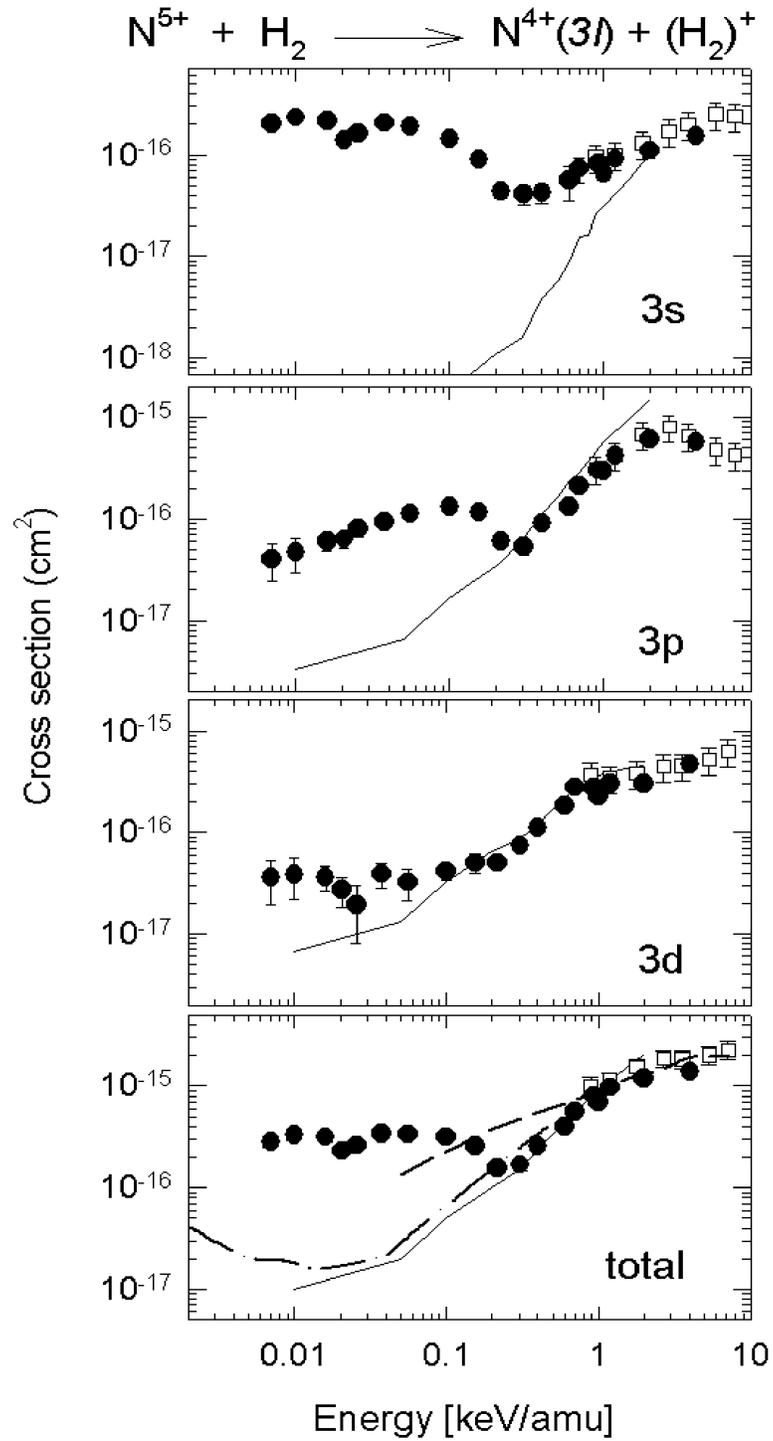


Figure 8. State selective measurements solid circles, (Lubinski 2000); open squares, (Dijkkamp et al. 85) compared to theory, solid line (Kumar & Saha 1999); dashed-dot line (Gargaud & McCarroll 85); and dashed line (Elizaga et al. 2001). The error bars represent relative error at a 90% confidence limit.

6 Summary

Electrons undergoing the electron capture process at eV/amu energies have time to adjust to the changing interatomic potentials of the quasimolecule formed during the collision. No scaling laws exist at these low energies. Due to the energy spread and divergence of the ion beams from ordinary ion sources and the additional scattering after the collisions, special experimental techniques must be used to perform measurements at these energies. These include ion trap, ion beam guide, and merged-beam techniques. Current experiments using these techniques have been discussed. The following general observations can be made concerning the comparison of experiment and theory made available by these and other measurements. For $X^{q+} + H$ collisions there is general agreement between experiment and theory for the total cross section and for the dominant state-selective channel. Calculations, however, need accurate quasi-molecular potentials. For $X^{q+} + He$ there is less experiment to benchmark theory; some large discrepancies exist in comparison of rates, e.g., $O^{2+} + He$. For $X^{q+} +$ molecules there is less theory to benchmark experiment and discrepancies exist in the total and dominant state-selective channel, e.g., $N^{5+} + H_2$. For multielectron capture, a qualitative understanding of the structure observed in the cross sections is possible with a simple over-the-barrier model that includes the effect of the ion-induced dipole attraction. With the experimental techniques currently available, new measurements are possible at eV/amu energies for a variety of multicharged ions with various atomic (H, He, Ne, Ar,...) and molecular gas targets. With the upgrade to a Cs sputter source, the ORNL ion-atom merged-beams apparatus will soon be able to perform measurements for multicharged ions with a variety of neutral atom and molecular targets.

7 Acknowledgments

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. CCH would like to thank R. Hoekstra, K. Okuno, and V. Kwong for providing information and figures.

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