Energy Dependence of Electron Loss Cross Sections for Xe^{18+} in Nitrogen

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The ionization and electron transfer mechanisms that determine the charges of energetic ions passing through matter have been of continuing interest since the discovery of natural radioactivity. The close connection between the charge of an ion and the strength of its Coulomb interaction with atoms of the medium makes it one of the most important factors in determining the rate of energy loss or stopping power. The present report describes an experimental program designed to investigate the systematic behavior of electron capture and loss cross sections for ions with relatively high energy and atomic number. This work is primarily motivated by a fundamental interest in developing a better understanding of the collision dynamics of ionization and charge exchange processes in fast, heavy ion collisions and partly by the current need for such cross sections in order to evaluate the prospects of heavy-ion fusion as a possible energy source (see the following report). The objectives of this work are twofold; (a) to provide cross sections for model systems that can be used to test theoretical methods, which (if successful) can be applied to the low charge state beams of interest to the fusion problem, and (b) to experimentally delineate the dependence of electron capture and loss cross sections on projectile energy and charge in sufficient detail to enable the development of empirical scaling laws.

During the present reporting period, electron capture and loss cross sections for 3.4, 6.0, and 8.0 A-MeV Xe^{18+} in N_2 have been measured and compared with preliminary results of classical trajectory Monte Carlo (CTMC) calculations. A brief description of the experimental method follows. The desired beam is extracted from the cyclotron and (if necessary) sent through a thin carbon stripping foil. Ions having the charge state of interest are selected using a 22° bending magnet and directed into the target chamber. The beam then passes through a series of collimators having diameters ranging from 1 to 3 mm and on into a windowless, differentially pumped gas cell operated at target gas pressures in the 1 to 100 mTorr region. After emerging from the gas cell, the beam passes through a charge dispersion magnet into a one-dimensional position sensitive microchannel plate detector.

Each charge state peak appearing in the position spectrum of projectile ions is integrated and divided by the total number of incident ions to obtain the fraction F_i of projectile ions that exited the gas cell in charge state i. The rate of change of charge fraction F_i as the projectile traverses a gas cell of length R cm containing gas atom density D cm$^{!3}$ is given by

$$\frac{dF_i}{d\pi} = \sum_k F_k \sigma_{ki} - F_i \sum_j \sigma_{ij}, \quad (1)$$

where $B = DR$,

and F_{mn} is the cross section for changing from charge m to charge n due to electron capture (m > n) or electron loss (m < n) in a collision. The solutions to this coupled set of equations are rather complicated, but for low enough pressures that $F_{mn}B << 1$, they may be expressed as follows

[1,2]:

$$F_i = a + bB + cB^2 + \ldots\ldots.., \quad (2)$$

where

$a = F_i(B=0)$

$b = F_{qi}$ (cross section for changing from incident charge q to charge i in a single collision)

$c =$ products of cross sections for producing charge state i in double collisions.

The first term in Eq(2) is the background fraction of ions in charge state i (i.e., the fraction of incident ions that change to charge state i as a result of collisions with the residual gas in the beamline when there is no gas in the gas cell). In the pressure range employed, higher order terms representing contributions from more than two collisions were negligible.

The cross section for removing i electrons in a *single* collision with a target gas atom or molecule was determined using the growth-rate method [1]. In this method, the charge fractions are measured over a range of pressures and second order polynomials are fit to the data. The cross sections F_{qi} are [according to Eq(2)] given by the coefficients of the linear terms.

The theoretical calculation of electron capture and loss cross sections for the complex many-body systems considered here is an extremely difficult task. Previous attempts generally have been limited to light ion projectiles colliding with H_2 and He targets. In the case of single-electron capture, two models have been applied with some success; one is based on the Eikonal approximation [3] and the other utilizes a semiclassical approximation [4]. Single-electron loss traditionally has been treated by means of the plane wave Born approximation [5]. A very promising approach to the calculation of *multi-electron* capture and loss cross sections for the complex systems of current interest utilizes the classical trajectory Monte Carlo (CTMC) method developed by R. E. Olson [6].

A calculation of the stripping cross sections for the X^{18+} + N system was made using the n-body classical trajectory Monte Carlo (nCTMC) method. For the system under study, explicitly included in the computations were all 7 electrons on the N target, and 18 electrons on the Xe^{18+} projectile. For Xe^{18+}, this includes the eight outer 4s and 4p electrons and the ten 3d subshell electrons. For each trial trajectory, 162 coupled first order equations are integrated in order to follow the positions and momenta of the 27 particles. Simultaneous ionization from each center is noted, along with electron capture at the lowest energies. The model includes the electron-electron interactions between nuclear centers and all electron-nuclear interactions.

The experimental results are shown in Fig. 1, where they are compared to the cross sections predicted by the nCTMC calculations for 3.4 and 8.0 A-MeV. Theory and experiment are in reasonable agreement for the loss of one through eight electrons at 3.4A MeV, and for single, double, and triple electron loss at 8.0A MeV. However, the theoretical cross sections for the loss of four or more electrons decrease much more rapidly with projectile energy than do the experimental cross sections. Cross sections for high stages of ionization are extremely difficult to estimate because of significant contributions from Auger and radiative deexcitation processes. In the near future, the 3s and 3p electrons on the Ar^{18+} will be incorporated into the calculations in order to test convergence of the computed results.

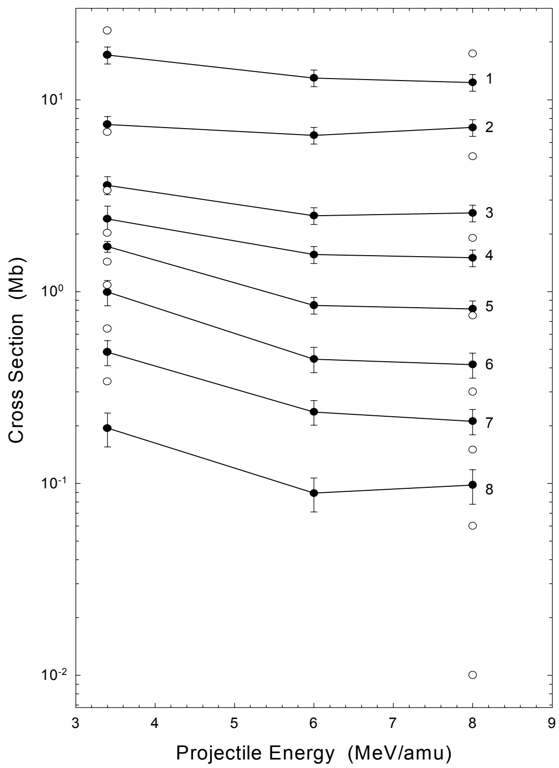

Figure 1: Experimental cross sections per atom (filled circles) for the loss of one through eight electrons from Xe^{18+} ions in single collisions with N_2 molecules. The empty circles show theoretical cross sections calculated for 3.4 and 8.0 A-MeV using the nCTMC method.

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