Laboratory Measurements of Charge Transfer on Atomic Hydrogen at Thermal Energies

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Abstract

We describe our ongoing program to measure velocity dependent charge transfer (CT) cross sections for selected ions on atomic hydrogen using the ion-atom merged-beams apparatus at Oak Ridge National Laboratory. Our focus is on those ions for which CT plays an important role in determining the ionization structure, line emission, and thermal structure of observed cosmic photoionized plasmas.

1. Introduction

We are carrying out charge transfer (CT) measurements for selected ions on atomic hydrogen using the ion-atom merged-beams apparatus (Havener 1997) at the Oak Ridge National Laboratory (ORNL) Multicharged Ion Research Facility. Our focus is on those ions for which CT is known to play an important role in determining the ionization structure, line emission, and thermal structure of observed cosmic plasmas. Objects for which these measurements are important include active galactic nuclei (AGN), galactic halos, H II regions, the intergalactic medium (IGM), planetary nebulae (PNe), and shocks in supernova remnants and Herbig-Haro objects. Our work is relevant to the past and present NASA flight missions IUE, HST, FUSE, ISO, Chandra/LETG and the upcoming missions GALEX, SIRTF, SOFIA, FIRST, and NGST. The ORNL merged-beams apparatus is the only apparatus in the world currently capable of measuring CT cross sections with H at the thermal energies important for interpreting spectra from photoionized cosmic plasmas such as those found in AGN, the IGM, H II regions, and PNe.

Our measurements are used to produce accurate CT rate coefficients and to benchmark state-of-the-art theoretical techniques. An example is given by our merged-beams measurements and rate calculations for C^+ + H (Stancil et al. 1998). Using these results the rate coefficient for the reaction H^+ + C was also calculated and found to differ from previous calculations by orders of magnitude (Stancil et al. 1998). The majority of thermal CT rates used in astrophysics are from Landau-Zener (LZ) calculations (Kingdon & Ferland 1996). These calculations are inappppropriate for collisions at eV energies and serve only as estimates, reliable, at best, to only a factor of three.

2. Merged-Beams Technique

At ORNL, an ion-atom merged-beams apparatus is used to study charge transfer by multicharged ions from ground-state H or D atoms at collision energies from 20 meV/amu to 5000 eV/amu. Relatively fast (keV) beams are colinearly merged producing low energy collisions in a moving center-of-mass frame. A 6-8 keV neutral hydrogen (deuterium) beam is produced via photodetachment 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 an Electron Cyclotron Resonance (ECR) ion source. Absolute charge transfer cross sections are determined at each collision energy directly from experimental parameters that include the primary beam intensities, beam-beam overlap or form factor, beam-beam signal rate, merge path length, and velocities of the beams.

3. Measurements

Figure 1 shows our merged-beams data for Si^{4+} (Pieksma *et al.* 1996), C^{4+} (Bliek *et al.* 1997), and N^{4+} (Folkerts et al. 1995) ions on H(D) with an energy scale from 10^{-2} to 10^3 eV/amu. As can be seen in the figure, at the higher energies all three ions have approximately the same cross section, agreeing to within 25% of the experimentally observed (Phaneuf *et al.* 1982) empirical scaling formula $q \times 10^{-15}$ cm^2. At lower energies (eV/amu), the cross sections vary by more than an order of magnitude. No simple scaling law is known that can predict the charge transfer cross section at eV/amu energies. Landau-Zener calculations can be used to estimate the energy dependence of the cross section but are not considered accurate.

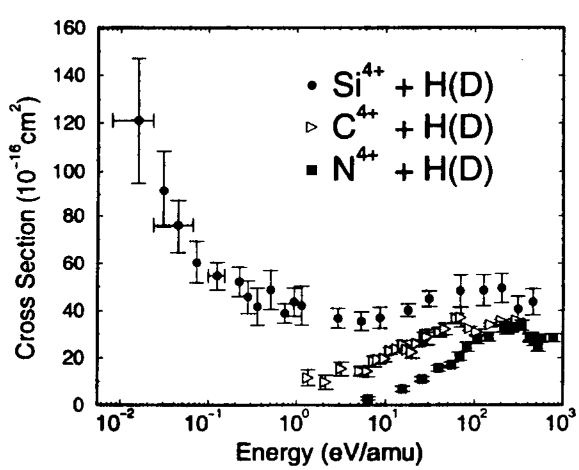

Fig. 1.— ORNL ion-atom merged-beams data for various quadruply- charged ions with H (D). The error bars correspond to the relative error at a level of two standard deviations. The decrease in the error bars for the C^{4+} data are in part due to improvements to the apparatus and an improvement in the intensity and quality of the beams produced by the ECR ion source. The absolute uncertainty is typically 15% at a level of two standard deviations.

Coupled-channel molecular-orbital fully-quantal calculations (Stancil et al. 1998; Gargaud & McCarroll 1988) are considered most appropriate at these energies but are difficult to perform. At energies below 10 eV/amu the Si^{4+} cross section is seen to increase as $1/v$, where v is the relative collision velocity, due to trajectory effects arising from the ion-induced dipole attraction. These measurements (which below 10 eV/amu had to be performed with D due to the limited dynamic energy range of the ECR source) agree with MOCC calculations (Pieksma *et al.* 1996) for Si^{4+} + D. Our measurements verify the accuracy of the theory for this system. The MOCC calculation (Gargaud & McCarroll 1988) for collisions with H when compared to the calculation with D, predict a strong isotope effect for this collision system. The theoretical cross section for H is predicted to be 1.9 times that for D at the lowest energies.

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