Measurement of Absolute Excitation Cross Sections in Highly-Charged Ions Using Electron Energy Loss and Merged Beams

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There is increasing emphasis during this decade on understanding energy balance and phenomena observed in high electron temperature plasmas. The UV spectral return from FUSE, the X-ray spectral return from the HETG on Chandra and the LETGS on XMM-Newton are just beginning. Line emissions are almost entirely from highly-charged ions (HCIs) of C, N, O, Ne, Mg, S, Si, Ca, and Fe. The Constellation-X mission will provide X-ray spectroscopy up to photon energies of 0.12 nm (10 keV) where primary line emitters will be HCIs. A variety of atomic parameters are required to model the stellar and solar plasma. These include cross sections for excitation, ionization, charge-exchange, X-ray emission, direct and indirect recombination, lifetimes and branching ratios, and dependences on l, m mixing by external E and B fields[1]. In almost all cases the atomic quantities are *calculated*, and few comparisons to experiment have been carried out.

Collision strengths and Einstein A-values are required to convert the observed spectral intensities to electron temperatures and densities in the stellar plasma. The JPL electron energy-loss and merged-beams approach [2] has been used to measure absolute collision strengths in a number of ions, with critical comparison made to the best available theories. Experimental comparisons to R- Matrix and Breit-Pauli theoretical results have been presented for C^{3+} [3], O^{2+} [4], O^{5+}[5], S^{2+}[6] and Fe^{9+} [7]. Work is planned in the targets Mg^{7+} and in the higher charge states $Fe^{(10-15)+}$. A schematic diagram of the JPL Highly-Charged Ion Facility (HCIF) is shown in Fig. 1. Details are given in Refs. [1,2]. The three available beam lines are for measurements of metastable lifetimes in HCIs [8], HCI-neutral X-ray emission and charge-exchange cross sections [9], and absolute excitation cross sections [4,7].

We give two representative examples, in O^{2+} and Fe^{9+}, of the absolute excitation work at the HCIF. Transitions in O^{2+} are detected in diffuse nebulae-HII regions, planetary nebulae, in our own Sun, and in the Io torus. Show in Fig 2 are absolute excitation cross sections for the $2s^22p^2\ ^3P_{0,1,2} \rightarrow 2s^22p^2\ ^1D_2$ transition. Relevant points are: (a) the experiments extend through the theshold region; (b) the cross sections are absolute; (c) one can measure cross sections to about 2.5 times the threshold energy. Also, these above-threshold cross sections are "nearly absolute" in that a small correction must be applied to account for high-angle, elastically-scattered electrons whose velocities can alias those of low-angle inelastically- scattered electrons. (d) One detects rich resonance structure throughout this energy range. Upon comparison with an accurate R-matrix calculation [10] experiment confirms the presence of the resonances near 2.7 and 4.2 eV, but does not detect the resonance near 3.1 eV, perhaps because this resonance is weaker and narrower than is calculated.

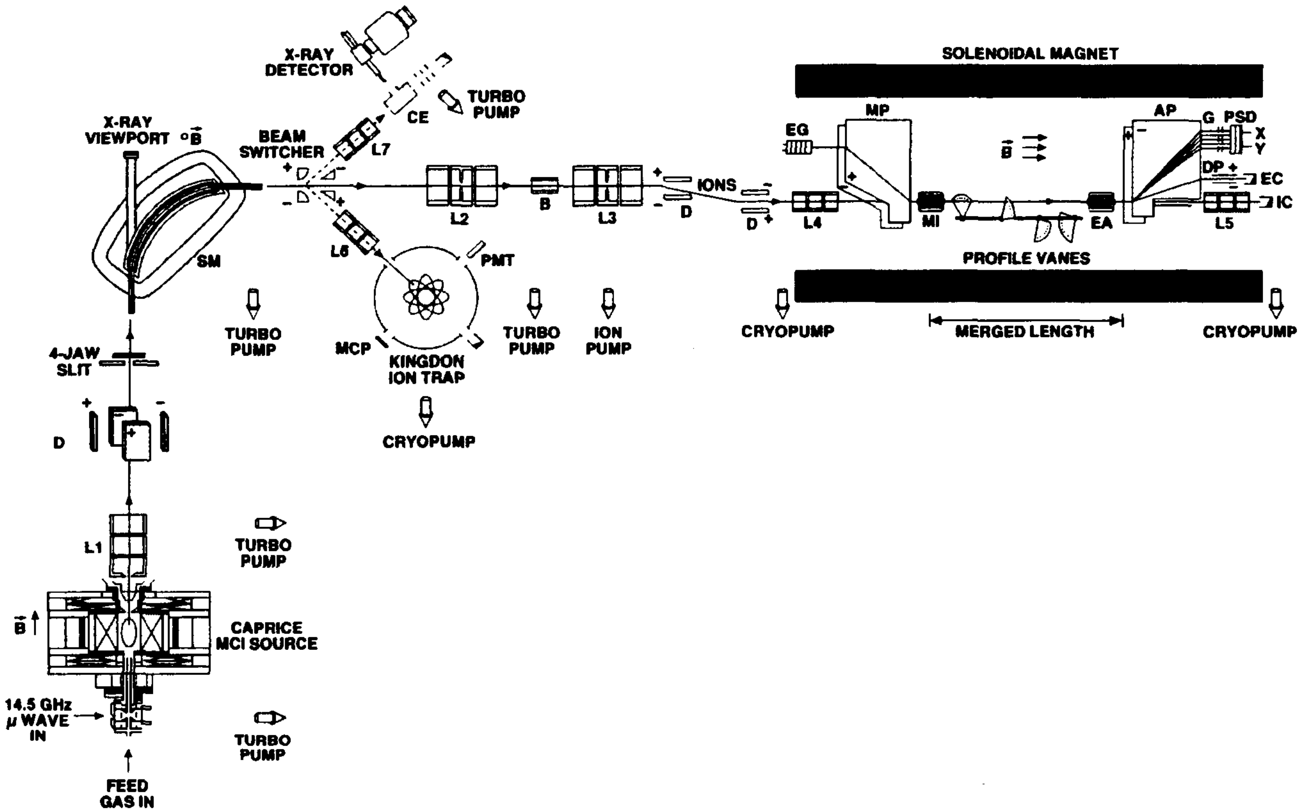

Figure 1. Experimental arrangement of the JPL Highly-Charged Ion Facility (HCIF). (L1-L7) three-element focusing lenses, **(SM)** mass/charge selection magnet, **(B)** differential pumping baffle, **(D)** deflector plates, **(MP)** electron-merging trochoidal plates, **(AP)** electron-analyzing trochoidal plates, (MI) electron mirror to reflect backward-scattered electrons, **(EA)** electronic aperture to discriminate against elastically-scattered electrons **(DP)** trochoidal plates to deflect parent electron beam out of the scattering plane, **(PSD)** position-sensitive detector, **(G)** electron-retarding grids for discrimination against elastically-scattered electrons, **(EC)** electron Faraday cup, **(IC)** ion Faraday cup, **(CE)** charge-exchange cell, **(MCP)** microchannel plate, **(PMT)** multiplier phototube. The three beam lines after the switcher are for excitation, metastable lifetimes, and charge-exchange/ experiments.

Emission lines in Fe IX-Fe XIV are detected in stellar and solar spectra [11]. The fine-structure line at λ 6376 $\mathring{A}$ in Fe^{9+}, the so-called coronal red line, corresponds to the forbidden transition $2s^22p^5\ ^2P^o{}_{3/2} \rightarrow 3s^23p^5\ ^2P^o{}_{1/2}$. Examples of its use in astrophysical diagnostics can be found in Ref. [12]. Recent HCIF results are shown in Fig. 3, with comparison to results in a 49-state Breit-Pauli theory. These are the first measurements of an absolute excitation cross section in an iron ion. Comments in (a)-(d) above apply here. The strong resonance at 4.35 eV (theory) is seen at 4.6 ± 0.1 eV (experiment). This agreement is resonable, given the error in the energy scale, and effects in the calculation (number and type of bound and continuum orbitals, electron correlation and relativistic effects *etc.*) that can shift the resonance-peak by tenths of an eV. The impressive return of high-resolution X-ray spectra from the Chandra and Newton telescopes has revealed the rich X-ray life of the Universe. Iron emission lines are a major contributors to the spectra, but high charge states of C, N, O, Mg, Si, S, rare gases, *etc.* are also detected. Almost all quantities in these HCIs, especially collision strengths, are calculated, with few comparisons to experiment. The JPL HCIF will measure critical collision strengths in these ions.

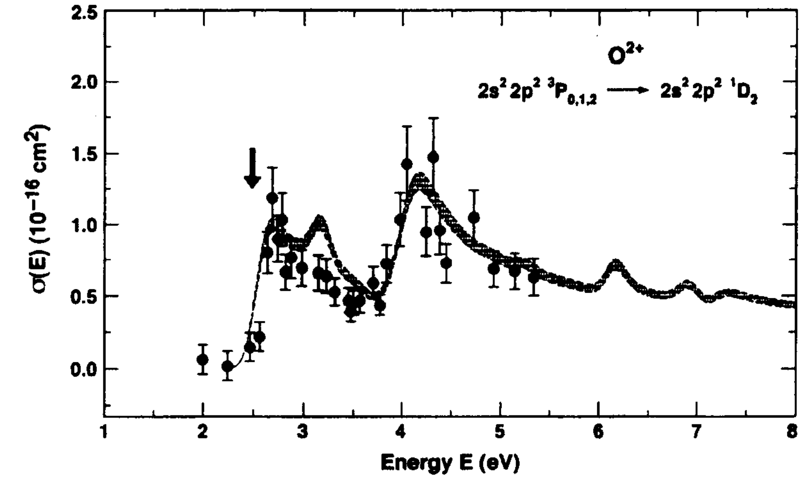

Figure 2. Comparison of experimental absolute excitation cross sections for the $2s^22p^2\ ^3P \rightarrow 2s^22p^2\ ^1D_2$ transitions in O^{2+}(solid circles) [4], with theoretical results in the 26-state R-matrix calculation [10]. The sharp resonance structures in the calculation have been convoluted with an energy-dependent resolution, as given by experimental conditions (3). These results are drawn with a 5% "theoretical accuracy" error band. Experimental error limits are shown at the 1.7σ (90%) confidence level. The arrow indicates the energy threshold of this transition.

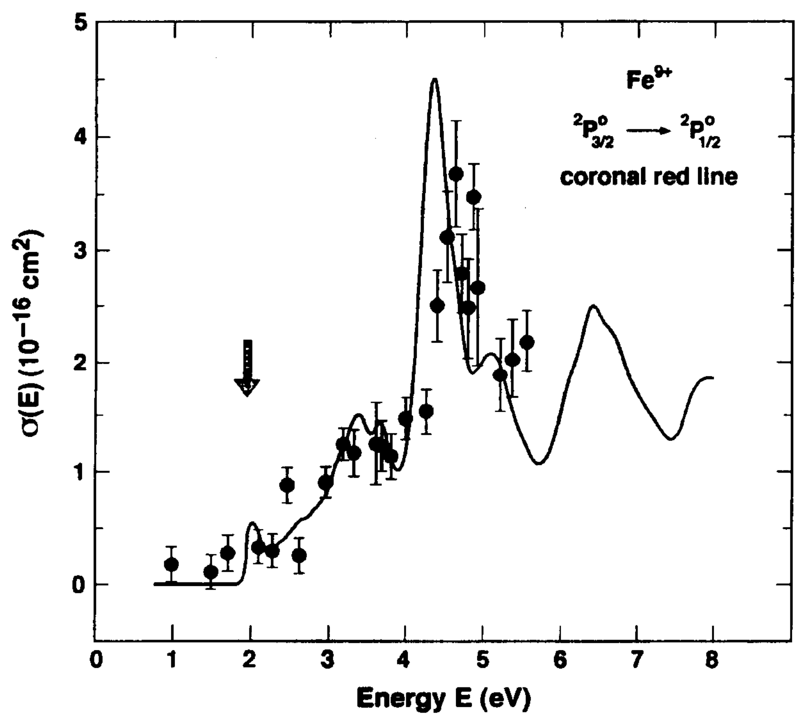

Figure 3. Comparison of the convoluted 49-state Breit-Pauli R-Matrix results (solid line) and measured absolute experimental cross sections (solid circles) for the Fe^{9+} coronal red-line transition (λ 6376 Å) [7]. Experimental errors are shown at the 1.7σ (90%) confidence level [18% or less, depending on the number of measurements (1-5) of each cross section]. The energy scale is accurate to 0.1 eV, and the vertical arrow denotes the transition threshold at 1.945 eV.

Acknowledgments

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