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Recent Excitation, Charge Exchange, and Lifetime Results in Highly Charged Ions Relevant to Stellar, Interstellar, Solar and Comet Phenomena

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ABSTRACT

Recent JPL absolute excitation and charge exchange cross sections, and measurements of lifetimes of metastable levels in highly-charged ions (HCIs) are reported. These data provide benchmark comparisons to results of theoretical calculations. Theoretical approaches can then be used to calculate the vast array of data which cannot be measured due to experimental constraints. Applications to the X-ray emission from comets are given.

1. Introduction

Fundamental to the understanding of solar heating and radiation mechanisms is the availability of reliable diagnostics of electron density (N_e) and temperature (T_e). This need has provided a challenge to experimentalists and theoreticians to measure or calculate HCI collision strengths, lifetimes, X-ray emission intensities and wavelengths; and charge-exchange, ionization, & recombination (direct and dielectronic) cross sections. The significance of these phenomena is discussed in reviews (ADNDT 1999). For diagnostic emission lines the most important and least-well measured atomic parameter is the collision strength. In equations of statistical equilibrium the collision strength plays a central role in determining the excited-state population. For the case of coronal equilibrium one has the expression (useful in the determination of T_e) for the excited-state population N_i, given by $N_i = N_e\ N_g\ C(g \rightarrow i)/A(i \rightarrow g)$ where g refers to the ground state, and $C(g \rightarrow i)$, $A(i \rightarrow g)$ are the collisional excitation rate coefficient (cm^3/s) and the spontaneous radiative decay rate (sec^{-1}), respectively, for transitions between g and i. Other expressions for N_i exist for emissions involving several excited states, or when coronal equilibrium is not valid. These expressions are sensitive to the collisional rates $C(g \rightarrow i)$, $C\ (g \rightarrow j)$ .... for excited levels i, j.... It has been pointed out that a 20-25% error in the collision rates can lead to order-of-magnitude uncertainties in N_e (Keenan 1993). The motivation of the JPL program is that: **(a)** *Almost all collision strengths used in astrophysics are calculated, with only isolated experimental data for comparison* [see the *OPACITY* (Badnell and Seaton 2003) and *IRON* (Nahar 2004) projects]. **(b)** Resonance contributions to collision rates can be factors of 2-5 times the direct rate; it is not possible to scale collision strengths, as the contributions do not scale with charge. **(c)** Uncertainties in the target wave function, inclusion of resonances and pseudostates are difficult to assess *a priori*, and are usually derived from a consensus of the various distorted-wave, $R-$Matrix close-coupling, or Flexible Atomic Code calculations. *There are very few cases where experimental data are available for comparison.*

2. Representative Results

The JPL facility has three beam lines dedicated to measurements in HCIs of absolute excitation cross sections using electron energy-loss scattering; X-ray emission spectra using either a germanium detector or a high-resolution grazing incidence X-ray monochromator; absolute single and multiple charge exchange cross sections using a gas cell and retarding-potential analysis of the transmitted ions; and metastable lifetimes using a Kingdon trap [see a facility schematic in Fig. 3 of Chutjian et al. (1999)].

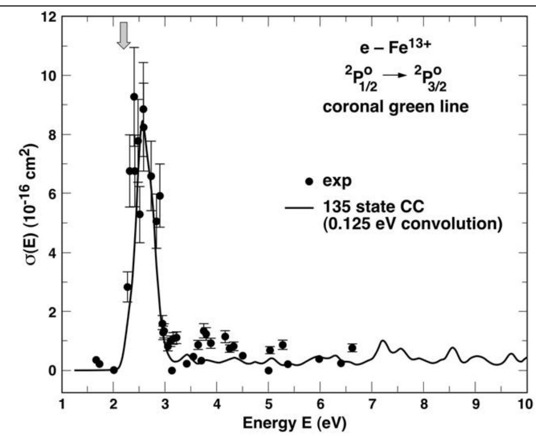

Figure 1. Absolute excitation cross sections for excitation of the forbidden M1 coronal green line in Fe^{13+}, with comparison to a 135 state R-Matrix calculation. Arrow indicates the threshold for this excitation (Hossain et al., unpublished).

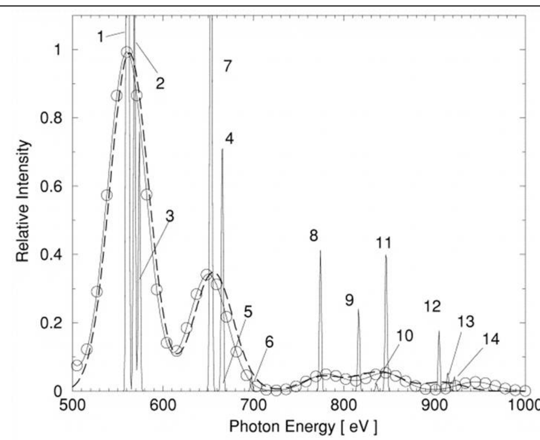

Figure 2. X-ray emission spectra from comet McNaught-Hartley. Solid circles and solid line are best fits to the observational data, and dashed curve is the calculation (Kharchenko et al. 2003).

2.1. *Excitation*

The Fe^{13+} coronal green line (530.3 nm) is the strongest forbidden line in the coronal spectrum, and brightest of all coronal emission lines in the visible spectrum; it is useful as a tracer of *Fe* abundance in galactic emission spectra. Shown in Fig. 1 are the first results of the absolute electron excitation cross section of the $3s^2 3p\ ^2P^o_{1/2} \rightarrow {}^2P^o_{3/2}$ transition. There is good agreement with results of a recent accurate 135 state *R*-matrix calculation.

2.2. *Ion Lifetimes*

JPL Kingdon trap measurements have been recently reported in the ions $Fe^{9,10,13+}$ (Smith et al. 2005). These results include the lifetime of the upper $Fe^{13+}\ ^2P^o_{3/2}$ level (coronal green line). The result of 17.0±0.2 ms compares well with an EBIT value of 16.74±0.12 ms (Beiersdorfer et al. 2003), and with a less-accurate storage-ring measured lifetime of 18.0±1.2 ms (Träbert et al. 2002). The range of ten calculated lifetimes is 16.51-16.66 ms, which is in very good agreement with measurements in this transition.

2.3. *Charge Exchange and X-Ray Emission*

The detection of X-rays from comets (Lisse et al. 1996) has been successfully interpreted by Cravens (2002) in terms of charge exchange of solar-wind ions with neutrals in the cometary coma, followed by relaxation of the electronically-excited ion by X-ray emission. Shown in Fig. 2 are results of modeling the X-ray emission (Kharchenko et al. 2003) observed by *Chandra* from the comet McNaught-Hartley, in terms of the relative abundances of the ions O^{7+}, O^{8+} and Ne^{9+} in the solar wind, and the total single charge exchange cross sections of Greenwood et al. (2000, 2001). Representative laboratory X-ray spectra are shown in Fig. 3. The excellent agreement between observation and model stems from understanding the underlying solar physics and atomic physics unique to this astrophysical plasma.

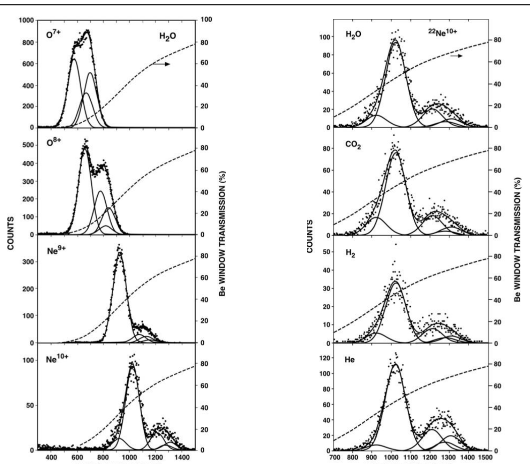

Figure 3. Laboratory X-ray spectra of HCIs colliding with H_2O (left) and $^{22}Ne^{10+}$ colliding with comet gases (right) (Greenwood et al. 2001).

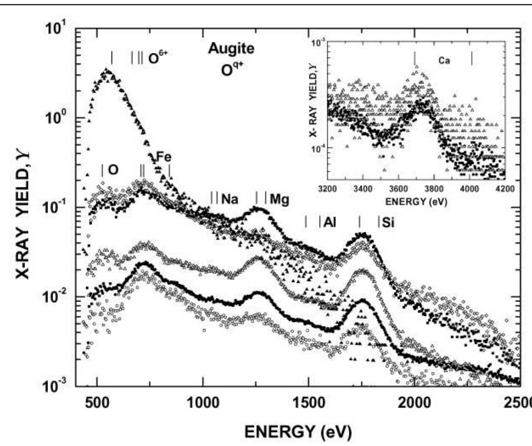

Figure 4. X-Rays emitted from augite [(Ca,Na) (Mg,Fe,Al) $(Al,Si)_2O_6$] bombarded by O^{q+} ions at energies of 7.0q keV. Charge states are given by: ● (q=2), △ (q=3), ○ (q =4), ■ (q=5), ◇ (q =6), and ▲ (q =7) (Djuric et al. 2005).

2.4. *Mineral Prospecting*

Absent in discussions of the interaction of solar wind HCIs with comets and other planetary objects is the role of surfaces. Under what circumstances does a surface contribute to X-ray production, and what wavelengths should be observed? To address these questions studies were carried out on X-rays observed during the collision of O^{q+} ions (q=2-7) [total energies of (2-7) q keV] with augite and olivine, simulants of a comet or planetary surface (Djuric et al. 2005). Spectral X-ray yields for olivine are shown in Fig. 4. Here the K-$L_{2,3}$ and K-$M_{2,3}$ transitions for the olivine components Na, O, Al, Mg, Si, and Ca are seen; as well as the L-M transition in Fe. Good agreement is found in the ratio of X-ray yields for Mg and Si, and the corresponding K-shell ionization cross sections. It appears that X-rays are being produced by electron acceleration into a surface that has been charged to a high positive potential by the HCI beam. One would search for these surface X-rays from a comet located at solar distances where gas evolution is not pronounced – regions with little or no cometopause. In these cases no blockage of the solar wind HCIs occurs, hence HCIs reaching the surface may induce a large surface charge (Lisse et al. 2005; Cravens 2006, private communication). This work was carried out at JPL/Caltech, and was supported through agreement with NASA.

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