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Measurements of Electron Impact Excitation Cross Sections at the Harvard-Smithsonian Center for Astrophysics

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ABSTRACT

The analysis of absolute spectral line intensities and intensity ratios with spectroscopic diagnostic techniques provides empirical determinations of chemical abundances, electron densities and temperatures in astrophysical objects. Since spectral line intensities and their ratios are controlled by the excitation rate coefficients for the electron temperature of the observed astrophysical structure, it is imperative that one have accurate values for the relevant rate coefficients. Here at the Harvard-Smithsonian Center for Astrophysics, we have been carrying out measurements of electron impact excitation (EIE) for more than 25 years. We will illustrate our experimental approach and apparatus by discussing a measurement of EIE in C^{2+} ($2s2p\ ^3P^o \rightarrow 2p^2\ ^3P$).

1. Introduction

Electron impact excitation (EIE) is the dominant mechanism for the formation of emission lines in many astrophysical and laboratory plasmas. Intensities of spectral lines arising from EIE can provide diagnostics of the temperature and density of an emitting plasma, and of the abundance of elements in the plasma. In the cases where the decay photon comes from a state excited from a metastable state of a particular ion, the ratio of the intensity of this emission to other emission lines from the same ion can provide a valuable density diagnostic for solar plasmas (Keenan & Warren 1993, Orrall & Schmahl 1976), for cool stars (Guinan *et al.* 2003, Jordan *et al.* 2001), and for cataclysmic variable binary systems (Prinja *et al.* 2003). The C^{2+} ($2s2p\ ^3P^o \rightarrow 2p^2\ ^3P$) multiplet at λ 117.6 nm compared to the C^{2+} ($2s^2\ ^1S^o \rightarrow 2s2p^2\ ^1P_1^o$) line at λ 97.7 nm is just such an example. Although density diagnostics require accurate knowledge of the cross section for EIE out of metastable levels, few measurements of such cross sections have been performed (Janzen *et al.* 2003, Bannister *et al.* 1999). Using the unique capabilities of the synchronous photon detection with modulated inclined beams technique, we have carried out the first measurement of the EIE cross section for C^{2+}

($2s2p\ ^3P^o \rightarrow 2p^2\ ^3P$) that covers the energy range required to determine rate coefficients for density diagnostics (Daw *et al.* 2006). We are currently working on measuring the EIE cross section and rate coefficient for C^{2+} ($2s^2\ ^1S^o \rightarrow 2s2p^2\ ^1P_1^o$).

2. Apparatus and Technique

The method used entails the measurement of the absolute intensity of the light emitted from ions excited by electron impact. A carefully prepared beam of C^{2+} , generated in a 5 GHz electron cyclotron resonance (ECR) ion source and extracted at 5 kV, is charge/mass and energy/charge analyzed to remove other ions and charge states and then is crossed with an electron beam at 45° (see Figures 2 and 3 in Daw *et al.* 2006). A magnetic field is applied co-axially with the electron beam to constrain it and increase its density. The distributions of current of both beams are measured. Beams are chopped and photons are detected synchronously to enable background subtraction. A mirror below the collision volume subtending slightly over π steradians concentrates photons onto a microchannel plate detector (MCP). The mirror has a broad-band reflectance coating that optimizes the reflectance at the wavelength of the decay photon under study. Calibrations of optical elements are performed separately and, together with a three-dimensional ray-tracing of the complete system, are used to determine the overall absolute photon detection efficiency.

The fraction of C^{2+} ions in the metastable $2s2p\ ^3P^o$ state is determined with the beam attenuation method, which involves measuring the transmitted ion beam current as a function of pressure for a gas admitted to a section of the beamline. Because the electron capture cross section for C^{2+} in He is known to be significantly larger for the metastable state than for the ground state (Lennon *et al.* 1983), we can identify the fraction with the higher attenuation rate as the metastable fraction.

The cross section is determined from experimentally measured quantities via the equation:

$$\langle \sigma \rangle = \frac{R_{\text{sig}}}{\xi \bar{v}_r} \frac{1}{\int N_I(x, y, z) n_e(x, y, z) \eta(x, y, z, \tau) dx dy dz} \quad (1)$$

where R_{sig} is the signal rate, ξ is the fraction of metastable C^{2+} ions, N_I is the ion beam spatial density, n_e is the electron beam spatial density, \bar{v}_r is the average relative velocity, η is the detection efficiency for photons, and τ is the lifetime of the excited state.

3. Electron Impact Excitation Results

Measured energy-averaged EIE cross section for the C^{2+} ($2s2p\ ^3P^o \rightarrow 2p^2\ ^3P$) transition are shown in Figure 2. The heavy error bars represent the statistical uncertainty at a 90% confidence level ($1.65\ \sigma$), and the thin error bars at 12.3 and 18.1 eV represent the total

experimental uncertainty at a 90% confidence level (1.65σ). Above 16 eV the measured cross section includes small contributions from other states. The dashed blue curve shows the 6-term close-coupling R -matrix calculation of Berrington, *et al.* (1977), and the solid curve shows the 90-term R -matrix with pseudostates calculation of Mitnik, *et al.* (2003) for only the $(2s2p \ ^3P^\circ \rightarrow 2p^2 \ ^3P)$ transition. Each has been convolved with the experimental energy spread of 0.9 eV (FWHM). The solid red curve shows the sum of the theoretical contributions of all transitions to the weighted cross section, incorporating the calculations of Mitnik *et al.*, and the measured detection efficiencies and metastable fraction. Theory and experiment agree to within the experimental uncertainties. Empirical rate coefficients and effective collision strengths, calculated using the measured EIE cross sections, for temperatures of interest in astrophysics are presented in Daw *et al.* 2006).

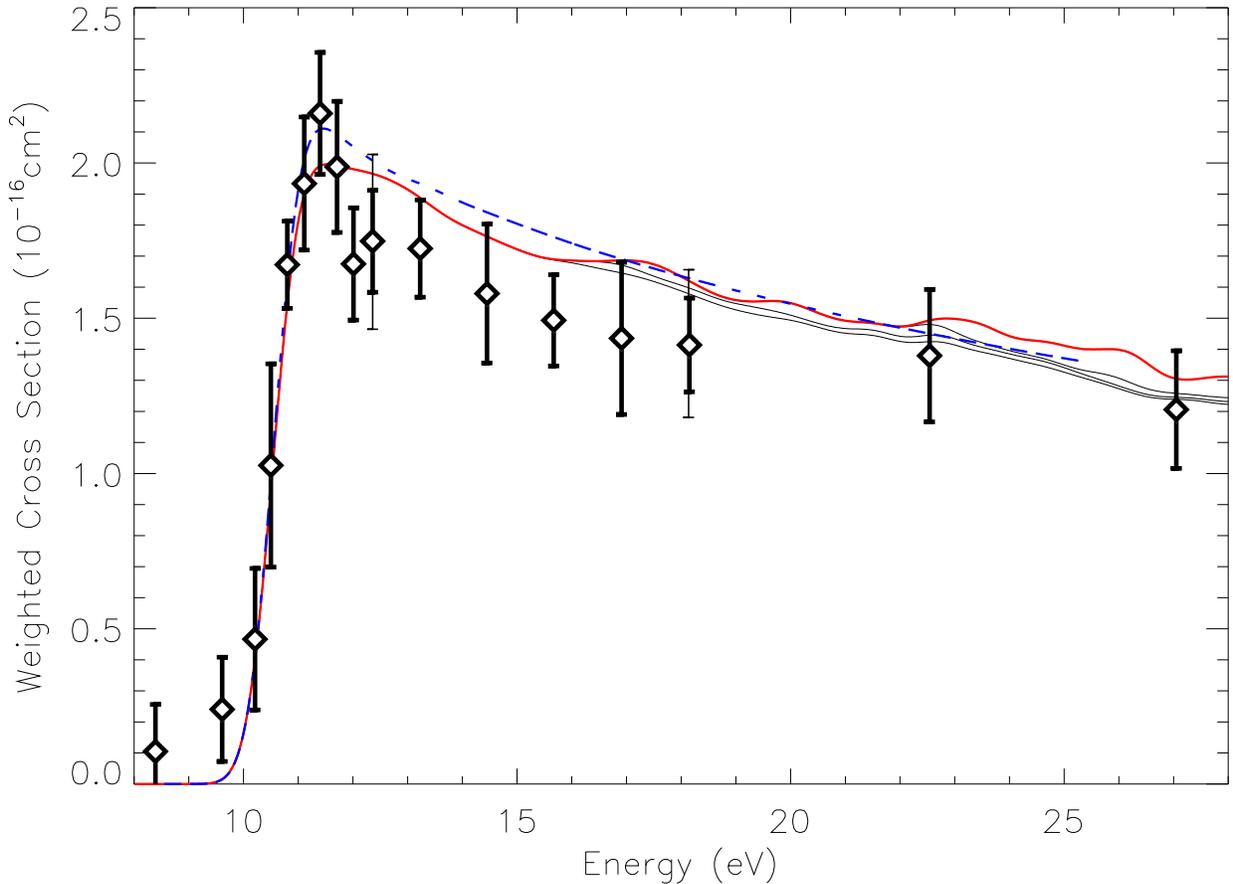


Fig. 1.— Measured energy-averaged EIE cross section for the $\text{C}^{2+} (2s2p \ ^3P^\circ \rightarrow 2p^2 \ ^3P)$ transition. See the text for explanatory information.

4. Summary

We have measured the EIE cross section for the C^{2+} ($2s2p\ ^3P^o \rightarrow 2p^2\ ^3P$) transition from threshold to more than 15 eV above. The photon detection method used in this work uniquely covers the energy range required to provide empirical rate coefficients for solar and stellar UV spectroscopy. We provide measurements of rate coefficients with an absolute uncertainty of typically $\pm 8.5\%$ (1σ).

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