Absolute cross sections for near-threshold electron-impact excitation of the $2s\ ^2S \rightarrow 2p\ ^2P$ transition in C^{3+}

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Abstract

Absolute total cross sections for electron-impact excitation of the $2s\ ^2S \rightarrow 2p\ ^2P$ transition in C^{3+} were measured from 7.35 eV to 8.45 eV using the merged electron-ion beams energy-loss technique. The results settle the discrepancy between two previous experiments using the crossed-beams fluorescence method, being in very good agreement with the older results [P. O. Taylor, D. Gregory, G. H. Dunn, R. A. Phaneuf, and D. H. Crandall, Phys. Rev. Lett. **39**, 1256 (1977)] but less so with the more recent ones [D. W. Savin, L. D. Gardner, D. B. Reisenfeld, A. R. Young, and J.

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L. Kohl, Phys. Rev. A **51**, 2162 (1995)]. The present measurements are also in good agreement with unitarized Coulomb-Born and close-coupling calculations.

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I. INTRODUCTION

Laboratory and astrophysical plasmas involve innumerable atomic processes, one of the most important of which is electron-impact excitation of ions. As a constituent in both fusion reactor [1] and stellar atmospheric [2] plasmas, carbon ions and their spectral lines are employed in diagnostic measurements for plasma parameters such as electron temperature and density, which require accurate cross sections for collisions of electrons with carbon ions for interpretation. The status of atomic data for collisions of electrons with carbon ions has been reviewed [3].

The present investigation is concerned with cross sections for electron-impact excitation of the 2s $^2S_{1/2} \rightarrow$ 2p $^2P_{1/2,3/2}$ resonance transition in C^{3+}. In 1977 Gregory and co-workers [4,5] reported cross-section measurements using the crossed-beams fluorescence technique for this transition, citing excellent agreement with theoretical values [6]. However, in 1995 in another very carefully executed experiment using a similar technique, Savin *et al.* [7] reported cross sections that lie about 26% below those of Gregory and co-workers and a like amount below the theoretical values. These later measurements, if correct, have serious implications about the reliability of theoretical calculations for electron-impact excitation of ions. In addition, the same experimental setup and calibration techniques were used by those authors to remeasure [8] the absolute cross section for dielectronic recombination (DR) of C^{3+}. They concluded that within experimental uncertainties there was now agreement between their experimental DR measurements and theoretical values, in contrast to their conclusion about their initial DR results [9] that were normalized with theoretical excitation cross sections [10]. Thus, the disparity between the recent Savin *et al.* cross sections and those of Gregory and co-workers has doubly serious implications. In the context of resolving the difference and the theoretical ramifications, the present work was undertaken using an entirely different measurement technique from those used earlier.

II. EXPERIMENT

Absolute total cross sections for near-threshold electron-impact excitation of the 2s $\rightarrow$ 2p dipole transition in C^{3+} were measured using the merged electron-ion beams energy-loss

(MEIBEL) technique. This technique has a higher detection efficiency and narrower energy distribution than the crossed-beams fluorescence technique employed by Gregory and co-workers [4,5] and Savin *et al.* [7], although the energy range is limited to the near-threshold region. Details of the apparatus and experimental method have been published previously [11,12], so only an overview will be presented here including a recent improvement to the beam profile monitor that has a direct impact on the present investigation. A schematic diagram of the MEIBEL apparatus is shown in Fig. 1. Using a trochoidal analyzer, a region of crossed **E** and **B** fields denoted the "merger," electrons are merged with ions extracted from the Oak Ridge National Laboratory electron-cyclotron resonance (ECR) ion source. After traversing an electric-field-free merge path (68.5 mm long) in the uniform solenoidal magnetic field ($\sim$ 3 mT), the electrons are separated from the ions by a second trochoidal analyzer, denoted the "demerger." The demerger deflects the primary (unscattered) electrons through a small angle where they are collected in a Faraday cup. Inelastically scattered electrons are deflected through larger angles in the demerger and strike a position sensitive detector (PSD) consisting of a pair of microchannel plates (MCPs) and a resistive anode. The ions pass through the demerger with negligible deflection and are collected in another Faraday cup after being bent through $90°$. Electrons elastically scattered through large angles could reach the PSD since their forward velocities are similar to those of inelastically scattered electrons. This is prevented by a series of five apertures located at the entrance of the demerger since these elastically scattered electrons have much larger cyclotron radii than the inelastically scattered ones.

Ion-beam purity was ensured by using isotopic $^{13}CH_4$ as the ECR source gas with helium as a buffer gas. The ions from the ECR source were extracted through a fixed 11-kV potential and then magnetically momentum analyzed so that only ions with a mass-to-charge ratio of 13/3 were in the beam. Mass spectra showed that impurities in the $^{13}C^{3+}$ beam were less than 1%. Ionization cross sections measured [13] with the ORNL crossed-beams apparatus [14] below the ground state threshold demonstrated that no metastable states were present in the ion beam.

Large backgrounds from electron and ion scattering from residual gas and surfaces are present on the PSD as well as signal from the inelastic-scattering events. In order to extract the signal from these backgrounds, both beams are chopped in a phased four-way pattern [11] and counts from the detector, with position information intact, are accumulated in four histogramming memories. The detector counts in the four two-dimensional histograms are individually corrected for the dead times of the position computer and histogram interface and of the microchannel plates and then appropriately added and subtracted to obtain the inelastic signal as a function of position on the PSD.

The excitation cross section at an interaction energy in the center-of-mass system E_{cm} is determined by

$$\sigma(E_{cm}) = \frac{R}{\varepsilon}\left|\frac{v_e v_i}{v_e - v_i}\right|\frac{qe^2}{I_e I_i}F, \tag{1}$$

where R is the signal count rate from detection of the inelastically scattered electrons, ε is the PSD detection efficiency measured to be 0.483 ± 0.018, and v_e, v_i, I_e and I_i are the laboratory velocities and currents of the electrons and ions of charge magnitudes e and qe, respectively. The form factor F is given by

$$F = \frac{\int G(x,y,z)dxdy \int H(x,y,z)dxdy}{\int G(x,y,z)H(x,y,z)dxdydz}. \tag{2}$$

The densities of the two beams $G(x, y, z)$ and $H(x, y, z)$ are measured with a movable video probe [15] at several positions along the interaction region. The probe consists of a MCP backed by a phosphor-coated coherent fiber optic bundle to convert the incident particles into an optical signal that is then digitized by a charge-injection device camera chip. Recently this probe was modified to improve measurements on electrons with laboratory energies less than 20 eV by adding a grounded grid to the front of the probe so that electrons could be accelerated before striking the probe MCP. In the present investigation, the potential between the grid and the front surface of the MCP was set at 75 V.

The data taking protocol consisted of first tuning the electron and ion beams to obtain minimum backgrounds. Concurrently, effort was made to get a reasonable overlap in front of the demerger apertures, but with no overlap beyond them in order to prevent elastically scattered electrons from reaching the PSD. A form factor was then determined from the measured beam densities. Data were collected at a given center-of-mass energy E_{cm} until the required statistical accuracy was reached. More data were then taken after E_{cm} was changed a few percent to a new value by precisely scaling the magnetic field and the voltages on the electron gun, merger, and demerger. This was repeated several times to cover a given energy range. Beam profiles were measured again at the end of this run of several energies to ensure that the form factor did not deviate significantly during the scalings.

After modifying the beam probe to give improved response to low-energy electrons, data were taken for which the form factor was measured carefully and found to be independent of probe parameters. These data consisted of two absolute cross sections, one above threshold ($E_{cm} = 8.35$ eV) and one below, and a relative curve used to determine the "contact potential" of the electron gun and hence the absolute energies of the data. The measured step height was then used to put the relative cross sections on an absolute scale. Because the 33-keV $^{13}C^{3+}$ ions have an energy equivalent to 1.4-eV electrons in the center-of-mass frame, no corrections for backscattering [12,16] were required for the present data, which extend only 0.5 eV above threshold.

Prior to modifying the beam probe, several data sets of cross section as a function of center-of-mass energy were measured. For fixed probe parameters, the measured form factors were consistent over the energy range of each set. The form factors, however, were very dependent on probe parameters and deemed to be unreliable in absolute magnitude, so that the cross sections could only be considered relative measurements. A persistent signal below threshold was observed for all of the data sets, varying somewhat from one to the next. Each set was independently fitted in a least-squares sense to the convolution of a Gaussian energy distribution of variable width with a variable-height step function at 8.00 eV, the spectroscopic threshold for the 2s $\rightarrow$ 2p transition [17]. The data were then corrected by shifting the energy the fitted amount to account for the contact potential of the electron gun and by subtracting the fitted below-threshold contribution from the cross section, assuming this contribution to be independent of energy.

Using the absolute cross section measured at 8.35 eV, the relative data from both after and before the probe modification were normalized according to their fitted step heights and then combined. The Gaussian fitted to this combined set has a full width at half maximum (FWHM) of 0.17 eV. This deduced energy distribution was then convoluted with the various theoretical predictions

[6,18], thus obtaining theory curves that can be compared directly with the measurements.

III. RESULTS

The present results [19] are shown in Fig. 2 with 90% confidence level statistical error bars. The outer bar on the absolute measurement at 8.35 eV indicates the total expanded uncertainty (17.3%) which is a quadrature sum of the statistical uncertainty and the following systematic uncertainties at a level equivalent to a statistical 90% confidence level: subtraction of below-threshold contribution (12%), form factor (8%), spatially limiting the signal on the PSD (6%), detection efficiency (4%), ion- and electron-beam currents (1% each), and ion-beam purity (1%). Also shown in Fig. 2 are three theoretical predictions, each convoluted with a 0.17-eV Gaussian representing the present experimental energy distribution. The upper solid line is the unitarized Coulomb-Born calculation (including exchange) of Magee *et al.* [6]. The other two curves are close-coupling calculations: The dashed line is the two-state calculation of Magee *et al.* [6] and the lower solid line is a more recent nine-state calculation by Burke [18]. For comparison with the present data, the results of Magee *et al.* and Burke have been shifted down in energy 0.06 eV and 0.07 eV, respectively, to agree with the spectroscopic threshold. The two-state close-coupling results of Gau and Henry [10] are almost identical to those of Magee *et al.* [6] and so are not shown. Although all three theoretical predictions are within the total expanded uncertainty of the present measurements, clearly the unitarized Coulomb-Born cross sections of Magee *et al.* [6] show the best agreement.

Figure 3 shows a comparison of the present results with prior measurements, both using the crossed-beams fluorescence method. The present data (circles) clearly show a much narrower energy distribution than the results of either Gregory and co-workers [4,5](triangles) or Savin *et al.* [7] (squares). To facilitate comparison, the Coulomb-Born calculations of Magee *et al.* [6] are convoluted with two different Gaussians, one with 0.17 eV FWHM for the present experiment and one with 2.3 eV FWHM for the experiment of Gregory and co-workers. These are the two solid curves in Fig. 3. The dashed curve is the convolution of the two-state close coupling results of

Magee *et al.* [6] with the 2.3 eV FWHM Gaussian. Savin *et al.* [7] reported an energy distribution of 1.74 eV FWHM. The error bars in Fig. 3 are 90% confidence level statistical only, except for the outer bars on one point in each set that represent the total expanded uncertainty for that experiment. The present results and those of Gregory and co-workers [4,5] are both in good agreement with all the theoretical predictions shown in Figs. 2 and 3 when the calculations are convoluted with the appropriate energy distribution. The results of Savin *et al.* [7], however, are about 20-30 % below the other measurements and are not in good agreement with the theoretical predictions. Only the nine-state close-coupling results of Burke [18] barely fall within the total expanded uncertainty of their measurements.

IV. CONCLUSIONS

In summary, the present measurements of absolute cross sections for the electron-impact excitation of the 2s $\rightarrow$ 2p transition in C^{3+} are in good agreement with the results of Gregory and co-workers [4,5] and all of the theoretical predictions, but not with the recent measurements of Savin *et al* [7]. The present results, together with the results of Gregory and co-workers, show that theoretical methods can be used and relied upon for this transition. By extension, one would conclude that theory can be relied upon for like transitions of other multiply charged ions as has also been found previously [5,11]. The implication of the present results for the DR measurements of Savin *et al.* [8] is that their DR values should be larger and thus no longer agree with theory; they had themselves reached this conclusion [9] before publishing their excitation measurements [7].

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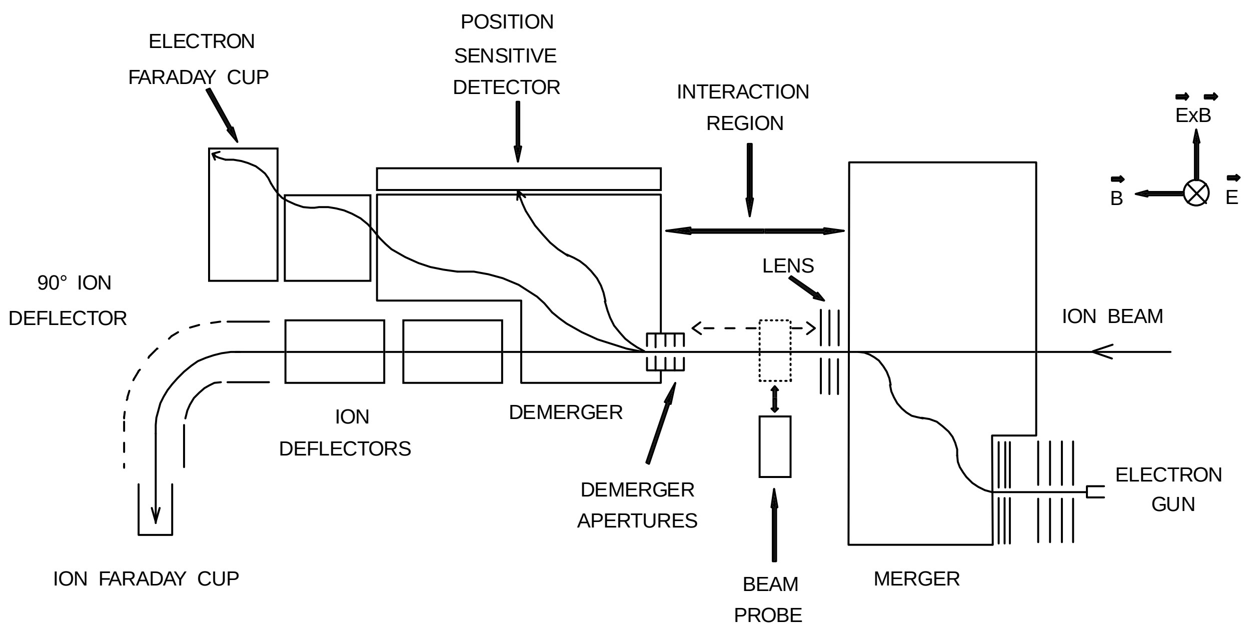

Fig. 1 Schematic diagram of the merged electron-ion-beams energy-loss apparatus (see the text for a description).

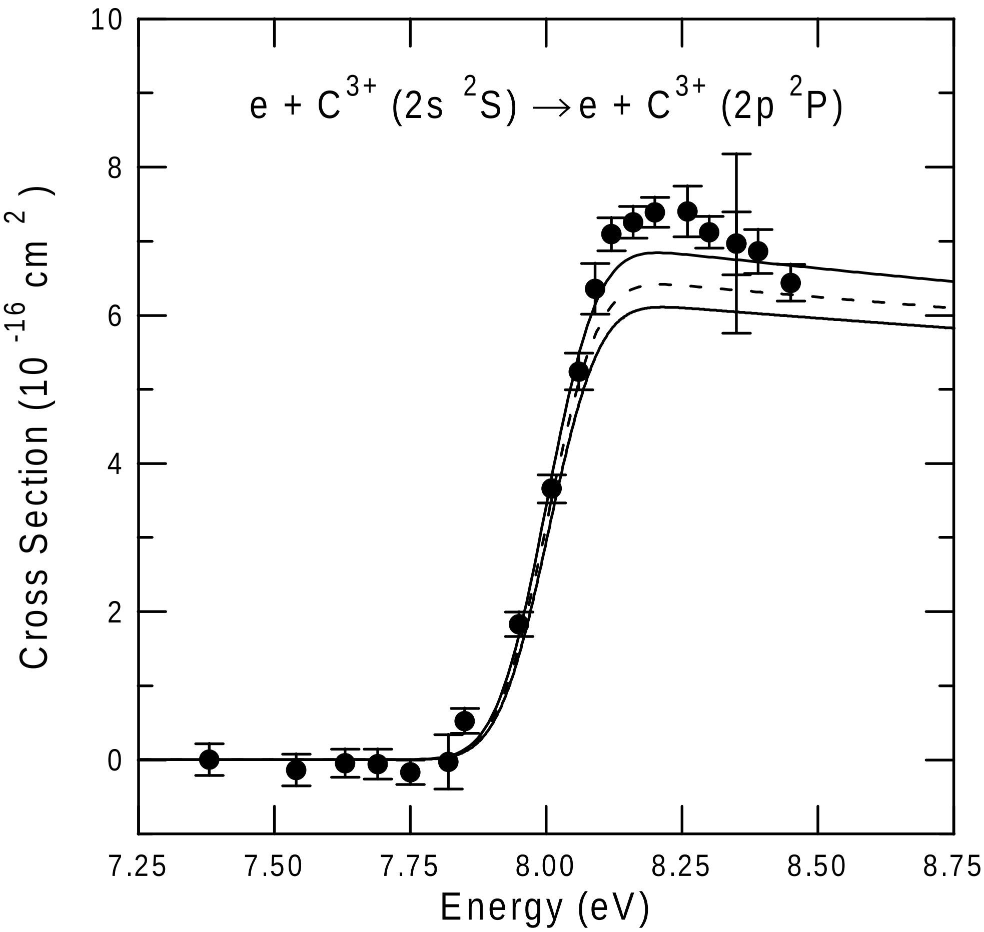

Fig. 2 Cross sections for electron-impact excitation of the 2s → 2p transition in C^{3+} as a function of the center-of-mass energy. The points are the present data with 90% confidence level relative error bars. All the present data are relative measurements, except the absolute measurement at 8.35 eV, whose outer bar represents the total expanded uncertainty. All three of the theoretical curves have been convoluted with a 0.17 eV FWHM Gaussian representing the experimental electron energy distribution: The upper solid curve is the unitarized Coulomb-Born calculation of Ref. [6], the dashed curve is the two-state close-coupling calculation of Ref. [6], and the lower solid curve is the nine-state close-coupling calculation of Ref. [18]. The close-coupling calculations have been shifted to the spectroscopic threshold for comparison with the present data (see the text).

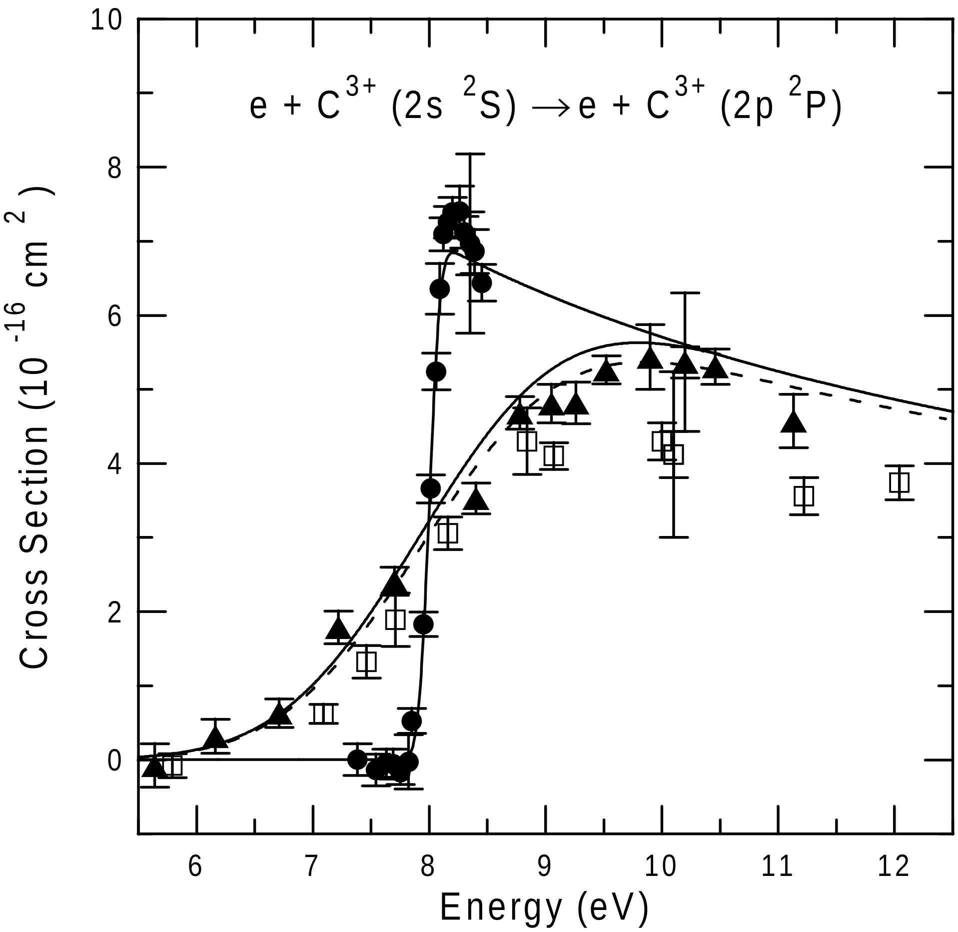

Fig. 3 Cross sections for electron-impact excitation of the 2s → 2p transition in C^{3+} as a function of the center-of-mass energy. The circles are the present data, the triangles the measurements of Refs. [4,5], and the squares the measurements of Ref. [7]. Error bars are as in Fig. 2. The solid curves are the unitarized Coulomb-Born calculations of Ref. [6] convoluted with 0.17 eV FWHM and 2.3 eV FWHM Gaussians representing the energy distributions of the present work and that of Refs. [4,5], respectively. The dashed curve is the two-state close-coupling calculation of Ref. [6] convoluted with a 2.3 eV FWHM Gaussian and shifted to the spectroscopic threshold for comparison with the measurements (see the text).