Child, *Molecular Collision Theory* (Academic, New York, 1974).

[12] Note that $\gamma = n\sigma v_r$, where n is the perturber density and $v_r = (8kT/\pi\mu)^{1/2}$ is the relative speed.

[13] The width of the Gaussian kernel reasonably approximates the true kernel width for diffractive scattering since the scattering amplitudes are nearly Gaussian (see Refs. 3 and 11).

Dielectronic-Recombination Cross-Section Measurements for C^+ Ions

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With use of a merged electron-ion beam apparatus, a lower limit of dielectronic recombination cross section for $\mathrm{C}^+(^2P) + e$ has been obtained from 9.04 to 9.32 eV. The measured cross section exceeds the theoretically predicted value by more than a factor of 3. This lies well outside the stated experimental and theoretical uncertainties.

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Dielectronic recombination, first proposed by Massey and Bates[1] to explain rapid electron-ion recombination rates in the ionosphere, is found instead to play a significant role in determining the energy balance in the solar corona[2] and in thermonuclear fusion plasmas.[3] This process, which proceeds via the excitation of an electron in the ion and the subsequent resonant capture of the incident electron into a doubly excited or resonance state of the resulting atom (the recombined ion), is stabilized by the emission of a photon when the inner excited electron relaxes thus bringing the total energy of the system below the ionization limit (see Fig. 1).

In this paper, we report the dielectronic recombination cross section for $\mathrm{C}^+(^2P)$ ions using a merged electron-ion beam apparatus (MEIBE-I). The process under study may be represented as follows:

$$e + \mathrm{C}^+(^2P, 1s^22s^22p) \rightleftharpoons C^{**}(1s^22s2p^2nl) \rightarrow C^*(1s^22s^22pnl) + h\nu.$$

Neglecting spin-orbit splitting in our considerations, the radiation that is emitted is very close but not quite equal in wavelength to that emitted by the C^+ resonance transition

$$\mathrm{C}^+(^2D) \rightarrow \mathrm{C}^+(^2P) + h\nu.$$

As a result one observes spectroscopically the $\mathrm{C}^+(^2D\text{-}^2P)$ resonance line plus satellite lines which lie close to but lower in energy than resonance transition.[4]

Until this paper no direct experimental measurement of cross sections for dielectronic recombination has been published although Aleksakhin, Zapesochnyi, and Imre[5] claim to have observed it in $e + \mathrm{K}^+$ collisions and several groups[6-9] have deduced experimental rate coefficients for a variety of ions from plasma modeling techniques. The rich theoretical literature has been reviewed by Seaton and Storey[10] and Dubau and Volonte[4] while Hahn and co-workers[11-14] have recently published cross-section estimates for Si^{11+}, C^{3+}, Cl^{7+}, and Mg^+ and will soon publish a calculation for C^+.[15]

The MEIBE-I apparatus has been described in detail elsewhere.[16,17] Briefly, a beam of C^+ ions is formed from carbon monoxide in an rf ion source mounted in the terminal of a 450-keV Van de Graaff accelerator. The C^+ ions are mass analyzed, electrostatically deflected to remove neutrals, and passed through a differentially pumped interaction region located inside of an ultrahigh vacuum (2×10^{-10} Torr) vessel.

As spectroscopically observed and theoretically predicted, the cross section for dielectronic recombination consists of a Rydberg series of very narrow resonances which converge toward the $\mathrm{C}^+(^2D)$ ionization limit at 9.29 eV. Unless the experiment has very high energy resolution (ours is intermediate), measurements will yield an effective cross section which represents a convolution of the series of resonances with the center-of-mass electron energy resolution. This, and the fact that the neutral which results from

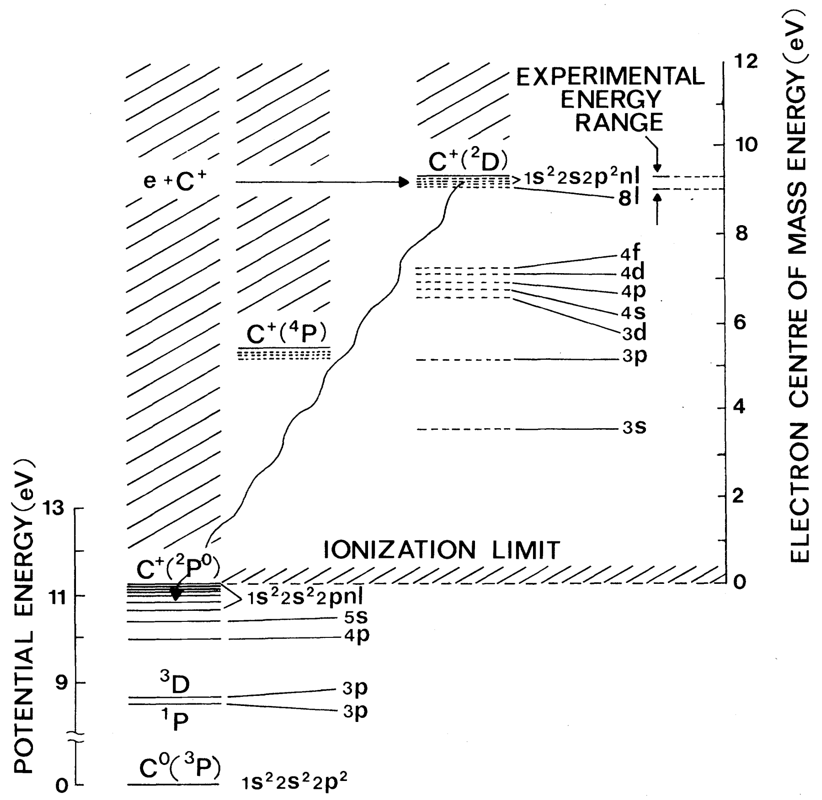

FIG. 1. Energy-level diagram for C^0 and C^+ showing the dielectronic recombination resonances and the interval over which our experiment has been carried out.

the recombination is often left in a high Rydberg state which may be easily field ionized, must be considered when making comparison with theory.

The electron beam is formed with use of an indirectly heated barium oxide cathode. It is initially moving parallel to the ion beam and passes through a trochoidal analyzer where crossed magnetic and electric fields cause the electrons to be shifted laterally so that they take up a new path superimposed on the ion beam. The two beams interact over a distance of 8.6 cm before they are separated by a second trochoidal analyzer. After separation, the electrons are collected in a Faraday cup while the ion beam is analyzed electrostatically to remove the primary ions from the product C atoms formed in the interaction region.

The neutrals are detected with a silicon surface-barrier detector which approaches 100% detection efficiency for carbon atoms at these energies[18] while the ions are collected in a Faraday cup. Unfortunately the field of 3.6 kV cm^{-1} in the electrostatic analyzer used to separate the product neutrals from the parent ions field ionizes those neutrals which have been formed in levels higher than $n=20$. As a result the cross section reported here, near the $C^+(^2D)$ limit where high Rydberg states dominate, is markedly decreased due to the field ionization of high-lying resonance states corresponding to $n \geqslant 20$.

The neutral atoms formed due to background collisions are separated from those due to electron-ion recombination by using electron beam modulation with gated counting to register the signal plus background and background counts separately in different quadrants of the ND600 multichannel analyzer. Even with a pressure of 2×10^{-10} Torr, the background is large because of the large C^+ charge-transfer cross section ($\sim 3\times10^{-16}$ cm^2) with H_2 the principal residual gas. As a result, running times greater than 30 h per point were necessary to acquire meaningful statistics for the 16 points measured through a 0.3-eV band below the $C^+(^2D)$ limit.

Signal to background ratios encountered during the measurements reached a maximum of 4×10^{-4}. Merged and other intersecting beam experiments are prone to extraneous noise effects resulting from pressure modulation and space-charge modulation.[19] However, we did not detect any significant evidence of these as witnessed by the very low (4×10^{-20} cm^2) cross section measured at 9.04 eV compared with the much larger cross section at 9.08 eV. In practice the electron energy was systematically varied by a minicomputer which also was used to carry out a running analysis of the results as a function of time. The complete counting arrangement has been described in detail elsewhere.[20]

The center-of-mass collision energy, for small θ, is

$$E_{\text{c.m.}} \cong [(E_+)^{1/2} - (E_e)^{1/2}] + (E_+E_e)^{1/2}\theta^2, \tag{1}$$

where $E_+ = (m_e/m_i)E_i$, m_e, v_e, E_e, m_i, v_i, and E_i are the electron and ion masses, velocities, and energies. θ is the angle of intersection of the two beams and is kept small, less than 1°.

The experimental cross section is

$$\sigma(E_{\text{c.m.}}) = \frac{C_n e^2 F}{I_e I_i L}\left|\frac{v_i v_e}{v_i - v_e}\right|, \tag{2}$$

where I_e and I_i are the electron and ion beam currents, C_n is the measured count rate of product neutrals, e is the electronic charge, and L is the length of the interaction region. F is the effective overlap of the beams which was repeatedly measured at three places along the interaction length.[17]

Since an rf source is used to produce the ions it may be expected that some fraction of the beam will be excited. While some workers[21-23] have produced C^+ ion beams with measured metastable (^4P) fractions of 30%–40%, Rutherford[24] has been able to quench these metastables by using elevated pressures in a subsequent collision chamber. In our case the rf source was operated at high pressure (~100 mTorr), so it may be inferred that the excited-state population is well below 30%.

The presence of metastable $C^+(^4P)$ states in the $C^+(^2P)$ ion beam also tends to give a lower limit to the absolute dielectronic recombination cross section. However, the presence of the metastable ion is unlikely to otherwise affect our measurements. From private communication with LaGuttuta and Hahn,[15] resonances associated with dielectronic recombination of the metastable are unlikely to lie in the band of energies studied by us even though the dielectronic recombination cross section associated with the ^4P state is estimated by them to be large.

The center-of-mass electron energy was calibrated by examining the cusp shape of the signal for the dissociative recombination of both CO^+ and H_3^+ in the vicinity of zero center-of-mass energy. $E_{\text{c.m.}} = 0$ corresponds to the maximum in the signal.[25] The energy of the ion beam was accurately calibrated by measuring the x-ray yield from the $F(p,\gamma)Ne$ resonance at 340.5 keV. The energy resolution in the center of mass for a merged beam experiment is estimated to be 0.04 eV.[26] This figure is consistent with the poorly defined structure observed just below 9.1 eV and predicted by LaGuttuta and Hahn.[15]

Figure 2 summarizes our results which are a lower limit to the cross section for dielectronic recombination of $C^+(^2P)$ with electrons in the center of mass energy range 9.04–9.32 eV. It is important to realize the reasons why they must be considered a lower limit: (1) there is a contribution of $C^+(^4P)$ metastables in the beam which

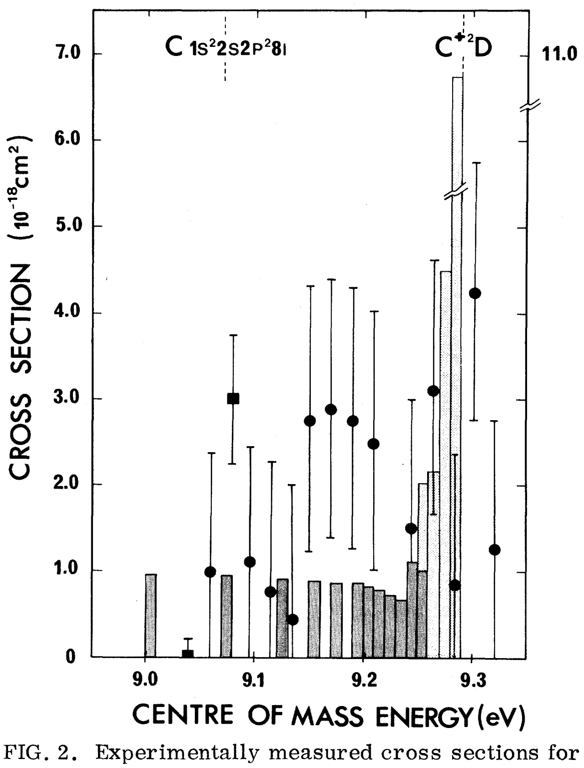

FIG. 2. Experimentally measured cross sections for the dielectronic recombination of C^+ ions with electrons. Circles, results taken by repeated scans over 16 energy points. Squares, points where repeated measurements have been taken. The bar graph is the theoretical estimate of the cross section calculated by LaGattuta and Hahn with 0.01-eV resolution folded in. The heavily shaded bars correspond to upper limit of the cross section when all states above $n = 20$ are field ionized while those with the lighter shading correspond to the calculated cross section when states $21 \leq n \leq 41$ are included.

effectively dilute the primary beam, and (2) the highly excited neutral carbon atoms formed with $n \geqslant 20$ are predicted to be field ionized in the 3.6 kV cm^{-1} electric field of the ion-beam analyzer. The theoretical estimates of LaGuttuta and Hahn[16] are reproduced in Fig. 2. In this case they have folded in a resolution of 0.01 eV, almost 20% of our estimated experimental resolution. Above 9.26 eV all product neutrals are expected to be field ionized. However, we still observe signal.

Our results were accumulated over a total running time approaching 700 h. The error bars shown represent one standard deviation and are due to statistical variations in the count rate. An absolute uncertainty of 20% must be added due mainly to uncertainties in the measured beam currents. The first and third points at 9.04 and 9.08 eV, respectively, were measured for longer times 135 and 105 h, respectively, yielding values of the cross section $4 \pm 40\times10^{-20}$ cm^2 and $2.6 \pm 0.8\times10^{-18}$ cm^2.

The energy scale shown is accurate to ± 0.04 eV. Also shown in Fig. 2 are the position of the ^2D excited state of C$^+$, to which the series of doubly excited resonance states converges, and the calculated position of the $(1s^22s2p^28l)$ states as estimated from a term-averaged single-configuration Hartree-Fock approximation.[15] It would appear that the structure at 9.08 eV is real and is due to capture into one or more of the $8l$ states. As n increases, the resonances overlap each other leading to the broad structure observed between 9.14 and 9.22 eV. LaGuttuta and Hahn have estimated that as n becomes very large, at 9.2 eV, the cross section for C$^+$ recombination should reach a value of $\sim 1\times10^{-17}$ cm^2. Note, that because of the large number of resonances in this region the results of their calculations will be essentially the same for resolutions of 0.01 and 0.045 eV. This estimate is at least a factor of 3 below what we observe as our lower limit. In reality the discrepancy is even greater.

It should be noted that when a 0.045-eV resolution for our experiment is folded into the theory at 9.08 eV, the cross section we attribute to the $n = 8$ state is larger than that predicted theoretically by at least a factor of 8. These discrepancies thus necessitate further theoretical and experimental studies of this important process.

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