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ELECTRIC FIELD EFFECTS ON DIELECTRONIC RECOMBINATION IN A COLLISIONAL-RADIATIVE MODEL

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ABSTRACT

We have carried out quantal calculations for the dielectronic recombination of C^{3+} in an electric field. We have used these results in a collisional-radiative model for a carbon seeded hydrogen plasma. We find that the plasma microfield increases the effective dielectronic recombination rate coefficient for C^{3+} by only 40% at $n_H = 10^9$ cm^{-3}, for example, compared to the near factor of 3 enhancement predicted by Reisenfeld et al. in 1992. The large effects predicted by Reisenfeld et al. over a wide range of densities are the result of an overestimation of the electric field enhancement of dielectronic recombination by their approximate calculations.

Subject headings: atomic data — atomic processes — Sun: transition region

1. INTRODUCTION

Ever since its importance was recognized by Burgess (1964), the process of dielectronic recombination has been an essential component of non-local thermodynamic equilibrium (non-LTE) plasma models (see Burgess & Summers 1969; Summers 1974). Such models require large amounts of atomic data and have made use of a variety of simplifications to supply those needs. Theoretical and computational advances now mean that it is possible to carry out quantal calculations of fully LS-resolved configuration-mixing dielectronic recombination data for complete isonuclear sequences of light ions and large parts (H-like through Mg-like) of heavier sequences. In parallel with this, collisional-radiative population rate equation models have been generalized to take full account of the detailed atomic data now available (Summers et al. 1993) and the more sophisticated applications (e.g., in dynamic plasmas). An important validation of the detailed theoretical data has been made possible by advances in experimental techniques for the study of dielectronic recombination. These have enabled high energy resolution measurements to be made for many ions and the agreement with theory is very good in general. Of particular relevance to this letter are the studies on carbon ions: for C^{2+} see Badnell et al. (1991), for C^{3+} see Andersen, Bolko, & Kvistgaard (1990) and Griffin, Pindzola, & Krylstedt (1989), for C^{4+} see Andersen et al. (1990), Wolf et al. (1991) and Badnell, Pindzola, & Griffin (1990), and for C^{5+}, see Wolf et al. (1991) and Pindzola et al. (1990). These solenoidal merged-beams experiments create electric fields in the interaction region, similar to those in the first experiments of Dittner et al. (1983), which are orders of magnitude greater than the plasma microfield for the densities involved. Quantal calculations by Griffin et al. (1989), which involved diagonalization of the Hamiltonian including the dipole coupling to the electric field, generated field-dependent dielectronic recombination cross sections that were able to reproduce the experimental results for C^{3+} by Andersen et al. (1990) to within the uncertainties of the fields involved. However, the experimental uncertainties are large (Dittner et al. 1983; Andersen et al. 1990), and so it is possible that even these sophisticated quantal calculations may underestimate the field-enhanced dielectronic recombination rate coefficients by as much as a factor of 2. Electric field enhancements of the dielectronic recombination process were originally predicted by Jacobs, Davis, & Kepple (1976) for a plasma microfield. However, field enhancements (due to the plasma microfield or external fields) are generally not included in collisional-radiative models. The line of argument is that collisional effects dominate over field-induced effects, at least as far as the plasma microfield is concerned, i.e., LTE has been established for those high n-states which would be field-enhanced at zero density. For example, compare the continuum lowering due to the plasma microfield (Holtzmark 1919) with that due to collisions (Wilson 1962). Recently, Reisenfeld (1992) carried out approximate calculations for the electric field enhancement of dielectronic recombination rate coefficients for C^{+}, C^{2+}, and C^{3+} ions (rates for C^{4+} and C^{5+} are not field enhanced). When Reisenfeld et al. (1992) incorporated these results into a collisional-radiative model, they obtained substantial differences from the zero-field results. For example, at a density of $n_H = 10^9$ cm^{-3} their results indicated that the plasma microfield increased the effective dielectronic recombination rate coefficient for C^{3+} by nearly a factor of 3. C^{+} and C^{2+} were little affected as collisions dominate over the field effects for these two ions. Apart from the immediate impact of these results on interpreting solar C^{3+} line emission, these results call into question the validity of using zero-field die-

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lectronic recombination rate coefficients in non-LTE plasma models, which is the general practice. Although low-charge Li-like ions like C^{3+} are most susceptible to electric field effects, the size of the effect predicted by Reisenfeld et al. (1992) would mean that results, and interpretations based on them, for many low-charge ions would need to be reassessed. We show that this is not the case in general. In fact, the approximate approach taken by Reisenfeld (1992) greatly overestimates the field enhancement of partial dielectronic recombination rate coefficients, compared to our ab initio quantal results, for precisely those principal quantum numbers where collisional effects are weakest ($n \lesssim 100$ at $n_H = 10^9$). At higher n-shells ($n \gtrsim 100$) where their field enhancements agree with our results, collisional equilibrium has been established.

2. THEORETICAL APPROACH

Zero-field configuration-mixing LS-coupling dielectronic recombination data for $\Delta n = 0$ and $\Delta n = 1$ core excitations in C^{q+} (q = 1–5) ions were generated according to the prescription of Badnell (1986) and Badnell & Pindzola (1989). Following Reisenfeld (1992), we need only consider the electric field enhancement of C^{3+} $\Delta n = 0$ dielectronic recombinations. This was done for each n by explicitly diagonalizing a Hamiltonian containing the Stark matrix element (see Griffin, Pindzola, & Bottcher 1986). Thus, l-mixing is taken into account, but not n-mixing. This is adequate for the present problem. Although much of the carbon data had been calculated before (see the studies referenced in the introduction) it was necessary to generate the complete set afresh so as to manipulate it into a form suitable for the collisional-radiative population rate equation model. The lowest terms (those with principal quantum number $n \leq 6$) were fully resolved, while the higher n-states were bundled to $S_c L_c nS$. Thus, the $L_c S_c$-parents were resolved as were the total-spin systems, all other quantum numbers being summed over. The breakdown of the total spin as a good quantum number is taken into account in the present collisional-radiative model only by the inclusion of spin-forbidden autoionization rates. Since we are principally interested in the effects of field-dependent dielectronic recombination data compared to zero field, the reader is referred to previous work for details of the other types of atomic data that was used; see Summers & Hooper (1983), Spence & Summers (1986), and Behringer et al. (1989). Such data are automatically accessed from the JET atomic data base. We solved the quasi–steady-state generalized collisional-radiative population rate equations as discussed in detail by Summers (1977), Summers & Hooper (1983), and by Summers et al. (1993). This approach is quite general. Briefly: the level populations fall into three groups; the LS-resolved ground plus metastables whose time evolution in a plasma environment matters, other LS-resolved nonmetastables whose spectral emission is of interest, and high-lying bundled $S_c L_c nS$ states. The latter two groups are assumed to be in quasi-static equilibrium with the metastables. The high-lying states were treated using matrix condensation techniques (Burgess & Summers 1976) and their influence projected down onto the low-lying states (Summers & Hooper 1983).

3. RESULTS

In Figure 1, we present our results for the field enhancement factor (the ratio of field-dependent to zero-field results) for the dielectronic recombination rate coefficient of C^{3+} as a function

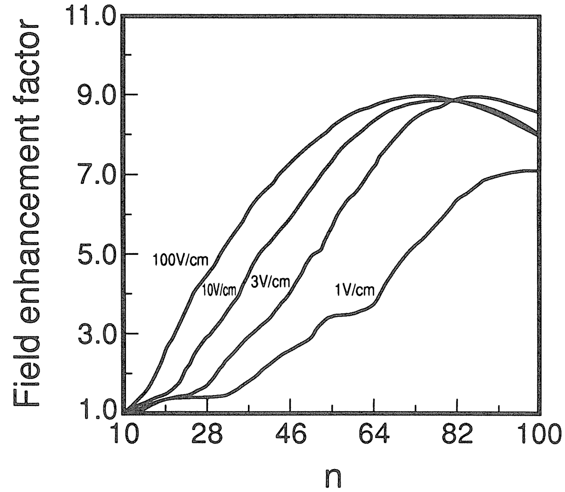

FIG. 1.—Dielectronic recombination field-enhancement factors for C^{3+} as a function of principal quantum number for electric field strengths of 1 V cm^{-1}, 3 V cm^{-1}, 10 V cm^{-1}, and 100 V cm^{-1}.

of principal quantum number n for various electric field strengths. In particular, 1 V cm^{-1} corresponds to the plasma microfield found at a density of about $n_H = 10^9$ cm^{-3}. We see that there is no enhancement for $n \lesssim 10$ but for higher n the enhancement increases steadily up to a maximum factor of 9 at $n \sim 80$ for $F \gtrsim 3$ V cm^{-1}. The reason that electric fields enhance dielectronic recombination via a $\Delta n = 0$ core excitation in low-charged ions in this way is as follows. In the zero-field case, the autoionization rates A_a and radiative rates A_r satisfy $A_r \ll A_a$ for a wide range of n-values and $l = 0 - l_0$, where l_0 ranges between 5 and 10 depending on the particular ion. The autoionization rates decrease rapidly for $l > l_0$ and so the dielectronic recombination rate coefficient α_d is proportional to $(2l_0 + 1)A_r$. Electric fields can Stark-mix the low angular momentum states ($l < l_0$) with the higher angular momentum states ($l > l_0$) for a given n-value, allowing them to contribute to the recombination. For low-lying n-shells the level splittings are too large for Stark-mixing to have any effect. As n increases the level-splitting decreases while the Stark-splitting remains constant. Eventually, electric fields Stark-mix the whole complex. If the fields are large enough to enable the whole complex to satisfy $A_r \ll A_a$ then $\alpha_d \propto (2n - 1)A_r$ and the maximum enhancement over the zero-field case is $(n/n_0)^2$. Since $A_a \sim n^{-3}$, as n increases the enhancement starts to decrease and eventually $A_a < A_r$ for all l and there is no enhancement. This is the basis of Reisenfeld's (1992) field-dependent calculations for dielectronic recombination. Zero-field results are used until the Stark splitting reaches half of the level splitting for $l = l_0$, at $n = n_0$ say. For $n > n_0$, the autoionization rates for $l = 0 - l_0$ are redistributed over the whole complex. For C^{3+}, $n_0 = 40$ and $l_0 = 6$ and an order of magnitude enhancement is possible. In Figure 2, we compare our quantal results for 1 V cm^{-1} for C^{3+} with the approximate results of Reisenfeld (1992), our zero-field results were normalized to those of Reisenfeld (1992) to facilitate the comparison. We see that only for $n \gtrsim 100$ do the results of Reisenfeld (1992) approach our results. The overestimate by Reisenfeld (1992) of the plasma microfield enhancement of dielectronic recombination in turn causes an over estimation of the effective dielectronic recombination rate coefficient for C^{3+} by Reisenfeld et al. (1992) over a wide range of densities, in Figure 3 we present and compare

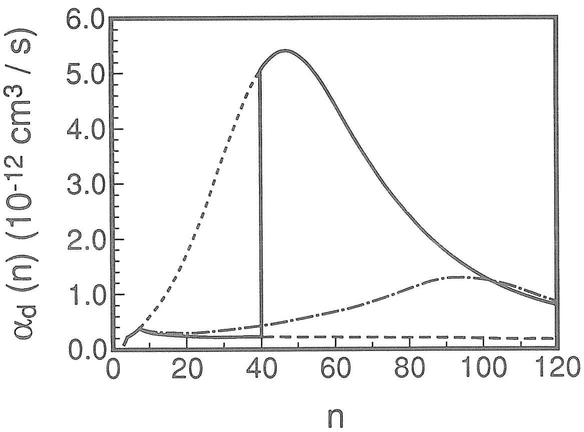

FIG. 2.—Dielectronic recombination rate coefficients for C^{3+} as a function of principal quantum number. (*Long-dashed line*) zero-field (this work and Reisenfeld 1992); (*short-dashed line*) maximum field enhancement of Reisenfeld (1992); (*solid line*) approximate 1 V cm^{-1} results of Reisenfeld (1992); (*dot-dashed line*) quantal 1 V cm^{-1} results of this work.

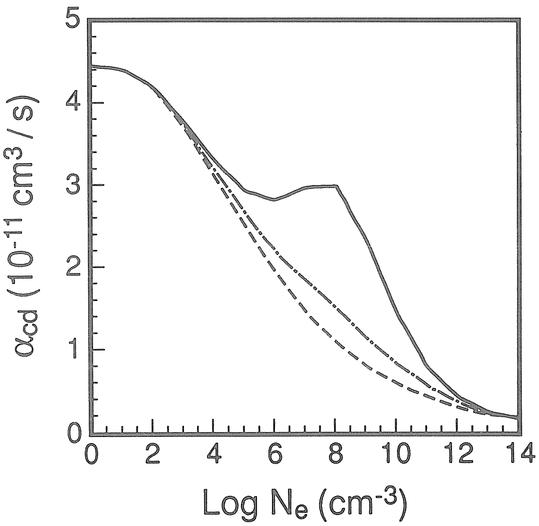

FIG. 3.—Effective dielectronic recombination rate coefficients for C^{3+}. (*Long-dashed line*) zero-field (this work and Reisenfeld et al. 1992); (*dot-dashed line*) quantal field-enhanced results (this work); (*solid line*) approximate field-enhanced results (Reisenfeld et al. 1992).

such results. We find that our effective dielectronic recombination rate coefficient is field-enhanced by at most 40%, at $n_H = 10^9$ cm^{-3}, compared to the near factor of 3 enhancement obtained by Reisenfeld et al. (1992), at $n_H = 10^9$ cm^{-3}.

The electric field enhancement of dielectronic recombination in complex ions is substantially smaller than for ions with one electron outside of a closed shell, typically a factor of 2 at zero density—see also the results of Reisenfeld et al. (1992) for C^+ and C^{2+}. Thus, in general, the error in neglecting the plasma microfield enhancement of dielectronic recombination can be expected to be no greater than that due to uncertainties in the basic atomic structure or approximations inherent in the kinetic plasma modeling. For the special case of low-charge Li-like and Na-like ions, which are most sensitive to field enhancement of dielectronic recombination, the results presented here for C^{3+} provide an indication as to whether or not field effects are likely to be important in a given environment. If applied external electric fields in excess of the plasma microfield are present then it may no longer be valid to neglect their effect on dielectronic recombination, in general. However, unless the field is large enough so as to fully Stark-mix many of the non-LTE states, an approximate approach of the type given by Reisenfeld (1992) is likely to result in an overestimate of the effect. Indeed, the current practice of neglecting field effects altogether is likely to be more acceptable although the accuracy may be low. The quantal treatment described in this *Letter* is the preferable approach. However, such calculations are computationally intensive and the computer codes used have only been developed for one electron outside of a closed-shell in the target state. Further development in this area is desirable, particularly if large external electric fields turn out to be of common occurrence in the plasma environment.

Finally, it should be noted that Stark-mixing of Rydberg autoionizing states is not the only way of accessing the high angular momentum reservoir in dielectronic recombination. Collisional redistribution of the Rydberg complex before stabilization can have the same effect (see Burgess & Summers 1969). Again, Li-like and Na-like ions can be expected to be most affected. However, most studies to date have focused on low-lying states at high densities (greater than 10^{15} cm^{-3}). It would be interesting to see, for example, in the C^{3+} problem whether microfields or collisions dominate the redistribution of the Rydberg autoionizing states at $n_H = 10^9$ cm^{-3} say.

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