On Dielectronic Recombination in Some Coronal Ions

H. P. Mital

Astrophysics Research Group, Physics Department, Meerut College, Meerut 250001, India

and U. Narain *

Lehrstuhl für Theoretische Astrophysik der Universität, Auf der Morgenstelle C-10, 7400 Tübingen, Federal Republic of Germany.

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Dielectronic recombination rate coefficients for some ions found in the solar corona have been investigated in the temperature range 20–1000 eV using two different expressions. A comparison has also been made with the corresponding radiative recombination rate coefficients.

1. Introduction

It was pointed out by Burgess [1] that the process of dielectronic recombination in plasmas appears to be of much greater possible importance at high temperatures than had been previously realized by Massey and Bates [2], Pery-Thorne and Garton [3], Bates and Dalgarno [4] and Seaton [5]. The process has significant influence on several astrophysical phenomena like ionization equilibrium of coronal ions and thereby determines the temperature distribution in the solar corona (Burgess and Seaton [6], Tucker and Gould [7], Jordan [8, 9], Ansari et al. [10], Landini and Monsignori Fossi [11], Summers [12, 13], Narain and Chandra [14, 15] and Mital and Narain [16]. The fact that the dielectronic recombination dominates over the radiative recombination (Burgess and Seaton [6]) reduces the appreciable discrepancy between the coronal temperatures as determined from the observation line broadening method and that deduced on the basis of the theory of ionization balance (Mital and Narain [16]). The radio recombination lines are also influenced by the dielectronic recombination (Gayet et al. [17]). The process also plays an important role in planetary nabulae (Goldberg and Dupree [18]) and in the interstellar space (Ansari et al. [10]).

The need of detailed calculations of the dielectronic recombination rate coefficients for many elements in various stages of ionization was suggested by Burgess [1] in order to revise the then existing calculations on the physical state of ionized gases and he presented an expression for their calculations. Since then, various investigators have included this process in their computations and have also tried to modify it in order to obtain simpler expressions. Burgess [19] himself presented a general formula for the recombination rate coefficients by introducing some slowly varying coefficients. Allen [20], Tucker and Gould [7], Van Rensbergen [21] and Beigman et al. [22] also developed approximate expressions for the rate coefficients. Later, Landini and Monsignori Fossi [11] developed two approximate expressions corresponding to two different groups of isoelectronic sequences.

Here we have used the general formula of Burgess [19] for computing the dielectronic rate coefficients and compared them with those obtained using the expressions of Landini and Monsignori Fossi [11]. A comparison has also been made with the corresponding radiative recombination rate coefficients.

2. Theoretical Details and Calculations

The process of dielectronic recombination can be represented as follows (Bates and Dalgarno [4], Burgess [1] and Trefftz [23]):

$$X^{+Z}(i) + e(E_e, l_e) \rightarrow X^{+(Z-1)}(i', i''), \qquad (1)$$

$$X^{+(Z-1)}(i', i'') \qquad \rightarrow X^{+(Z-1)}(i_s, i'') + h\nu, \qquad (2)$$

where $X^{+(Z-1)}(i', i'')$ is a $(Z-1)$-times-ionized atom in a doubly excited state (i', i''). E_e, l_e are the energy and angular momentum quantum number of the incident electron, respectively, ν is the frequency of the emitted photon. It has been shown

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* On leave of absence from Physics Department, Meerut College, Meerut 250001, India.

Reprint requests to Herrn H. P. Mital, Physics Department, Meerut College, Meerut 250001/Indien.

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(Ansari et al. [10]) that the most efficient recombination is obtained, if the state i_s of the inner electron of $X^{+(Z-1)}$ is configurationally the same as the state i of the recombinition ion X^{+Z}, the transition $i \rightarrow i'$ being an optical one.

Burgess [1] derived the expression for the dielectronic recombination rate coefficients and, later on, he himself gave a general and simplified expression (Burgess [19]), Gabriel and Jordan [24])

$$\alpha_{\mathrm{di}} = 8.2 \times 10^{-4}\, T^{-3/2}\, B(Z) \times \sum_j f_{ij}\, A(X)\, E_j^{1/2} \exp(-E_j/kT) \qquad (3)$$

with

$$B(Z) = Z^{1/2}(Z+1)^2(Z^2+13.4)^{-1/2},$$

and

$$A(X) = (1 + 0.105\,X + 0.015\,X^2)^{-1}$$

and

$$X = 0.0735\,E_j/(Z+1),$$

where E_j is in eV, T is in °K. E_j in eV is the energy and f_{ij} is the oscillator strength for the resonance transition $i \rightarrow j$ in the recombining ion, Z is the charge on the recombining ion. The expression is summed over the strong resonance levels j to obtain a total recombination rate. As suggested by Burgess [1] only those transitions are used for which the initial state is the ground state. As an example, the transitions chosen for Fe X are given in Table A (taken from Fawcett et al. [25]).

Landini and Monsignori Fossi's Expressions

Landini and Monsignori Fossi [11] developed two approximated formulae for the total rate coefficients corresponding to two different cases:

Table A

Ion	Transition	J	λ(Å)	f_{ij}
Fe X	$3p^5\ ^2P - 3p^4(^3p)\ 3d''\ ^2D$	$\frac{3}{2}-\frac{5}{2}$	174.58	1.6275
$z=9$		$\frac{3}{2}-\frac{3}{2}$	170.58	0.0670
	$3p^5\ ^2P - 3p^4(^3p)\ 3d'\ ^2P$	$\frac{3}{2}-\frac{3}{2}$	177.24	0.8025
		$\frac{3}{2}-\frac{1}{2}$	175.48	0.1253
	$3p^5\ ^2P - 3p^4(^1D)\ 3d\ ^2S$	$\frac{3}{2}-\frac{1}{2}$	184.53	0.1730
	$3p^5\ ^2P - 3p^4(^3P)\ 4d\ ^2D$	$\frac{3}{2}-\frac{5}{2}$	77.83	0.2140
	$3p^5\ ^2P - 3p^4(^1D)\ 4d\ ^2D$	$\frac{3}{2}-\frac{5}{2}$	75.8	0.1025
	$3p^5\ ^2P - 3p^4(^1D)\ 4d\ ^2P$	$\frac{3}{2}-\frac{3}{2}$	76.1	0.1128
	$3p^5\ ^2P - 3p^4(^1D)\ 4s\ ^2D$	$\frac{3}{2}-\frac{5}{2}$	94.07	0.0935
	$3p^5\ ^2P - 3p^4(^3P)\ 4s\ ^2P$	$\frac{3}{2}-\frac{3}{2}$	96.12	0.1183
		$\frac{3}{2}-\frac{1}{2}$	95.34	0.0403
	$3p^5\ ^2P - 3p^4(^3P)\ 4s\ ^4P$	$\frac{3}{2}-\frac{5}{2}$	97.83	0.0035
		$\frac{3}{2}-\frac{3}{2}$	97.12	0.0503

Table B

Ion	Z	W_1(eV)	F
Ni XI	10	56.54	40
Ni XII	11	41.71	40
Ni XIII	12	41.49	40
Ni XIV	13	38.63	28
Fe IX	8	47.50	40
Fe X	9	35.80	40
Fe XI	10	37.00	40
Fe XII	11	33.50	28
Fe XIII	12	35.80	30
Fe XIV	13	37.30	20

Case 1. If the recombining ion pertains to the isoelectronic sequences of H, He, Ne and K to Ni, the rate coefficient can be obtained from the expressions

$$\alpha_{\mathrm{di}} = 2 \times 10^{-4}\, T^{-3/2}(Z+1)^2 f_{1,0}\, W_1^{1/2} \cdot \exp(-10.6 \times 10^3\, W_1/T), \qquad (4)$$

where $f_{1,0} = n$, n being the number of electrons in the outer shell of the recombining ion X^{+Z} and W_1 is the excitation potential in eV of the first allowed transition.

Case 2. If the recombining ion pertains to the isoelectronic sequences not included in Case 1 then

$$\alpha_{\mathrm{di}} = 2 \times 10^{-4}\, T^{-3/2}(Z+1)^2 F \cdot \exp(-10.6 \times 10^3\, C\, W_1/T), \qquad (5)$$

where

$$C = (Z + 2.3)/3.3$$

and F is a constant for each isoelectronic sequence. The parameters used are improvements over those published by Landini and Monsignori Fossi [11] (cf. Table B).

3. Results and Discussion

The dielectronic rate coefficients (α_B) for some Fe and Ni ions (Fe IX to XIV and Ni XI to XIV) have been computed using expression (3) in the temperature range 20–1000 eV and are displayed in Tables 1–3. The required oscillator strengths have been taken from Fawcett et al. [25]. To represent their behaviour with temperature they have also been plotted in Figs. 1 and 2. It is found that the rate coefficients have smaller values at lower temperatures, increase at coronal temperatures and then decrease with further increase in temperature. The behaviour with temperature for all the ions is almost similar. Rate coefficients (α_{LM})

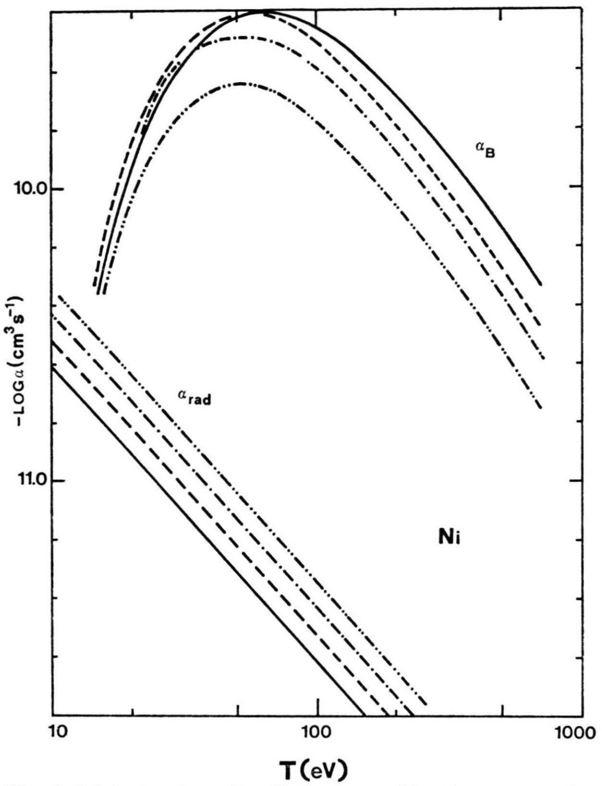

Fig. 1. Dielectronic and radiative recombination rate coefficients for ——, Ni XI; ----, Ni XII; -·-·-·-, Ni XIII; -··-··-··-, Ni XIV.

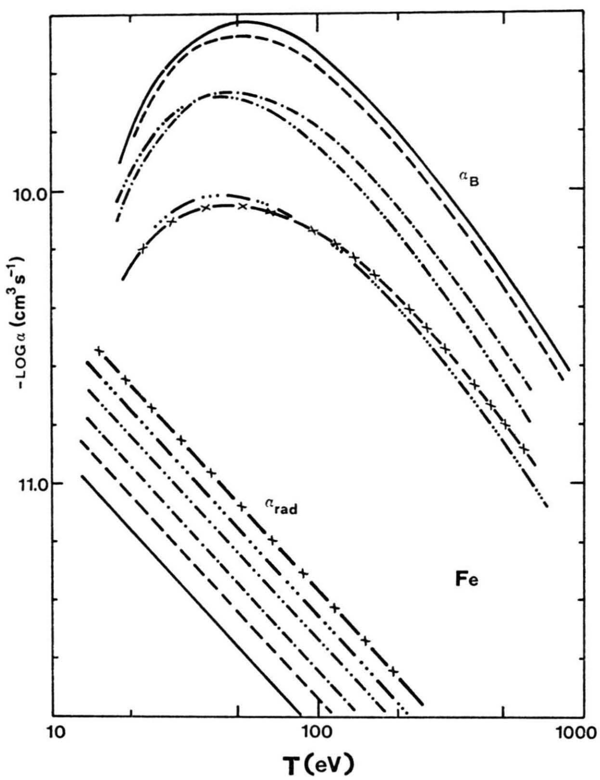

Fig. 2. Dielectronic and radiative recombination rate coefficients for ——, Fe IX; ----, Fe X; -·-·-·-, Fe XI; -··-··-··-, Fe XII; -···-···-···-, Fe XIII; -×-×-×-, Fe XIV.

Table I. Dielectronic recombination rate coefficients (in $cm^3 s^{-1}$)

Temperature (eV)	Ni XI		Ni XII		Ni XIII		Ni XIV	
	α_B [a]	α_{LM} [b]	α_B	α_{LM}	α_B	α_{LM}	α_B	α_{LM}
20	0.113^{-9} [c]	—	0.135^{-9}	0.477^{-11}	0.122^{-9}	—	0.914^{-10}	—
30	0.253^{-9}	0.770^{-11}	0.284^{-9}	0.336^{-10}	0.247^{-9}	0.276^{-10}	0.175^{-9}	0.229^{-10}
40	0.337^{-9}	0.249^{-10}	0.363^{-9}	0.784^{-10}	0.309^{-9}	0.705^{-9}	0.214^{-9}	0.581^{-10}
50	0.377^{-9}	0.466^{-10}	0.390^{-9}	0.121^{-9}	0.327^{-9}	0.115^{-9}	0.223^{-9}	0.942^{-10}
70	0.386^{-9}	0.845^{-10}	0.374^{-9}	0.176^{-9}	0.310^{-9}	0.177^{-9}	0.207^{-9}	0.145^{-9}
100	0.344^{-9}	0.113^{-9}	0.310^{-9}	0.199^{-9}	0.254^{-9}	0.209^{-9}	0.168^{-9}	0.171^{-9}
150	0.264^{-9}	0.117^{-9}	0.221^{-9}	0.181^{-9}	0.180^{-9}	0.197^{-9}	0.117^{-9}	0.161^{-9}
200	0.205^{-9}	0.105^{-9}	0.164^{-9}	0.151^{-9}	0.133^{-9}	0.168^{-9}	0.865^{-10}	0.137^{-9}
300	0.135^{-9}	0.784^{-10}	0.102^{-9}	0.106^{-9}	0.825^{-9}	0.120^{-9}	0.534^{-10}	0.979^{-10}
400	0.961^{-10}	0.598^{-10}	0.712^{-10}	0.785^{-10}	0.572^{-10}	0.897^{-10}	0.370^{-10}	0.729^{-10}
500	0.729^{-10}	0.471^{-10}	0.531^{-10}	0.606^{-10}	0.426^{-10}	0.697^{-10}	0.275^{-10}	0.566^{-10}
700	0.470^{-10}	0.318^{-10}	0.336^{-10}	0.400^{-10}	0.269^{-10}	0.462^{-10}	0.173^{-10}	0.375^{-10}

[a] α_B = Dielectronic rate coefficients using the Burgess formula.
[b] α_{LM} = Dielectronic rate coefficients using expressions of Landini and Monsignori Fossi.
[c] The superscript denotes the power of ten by which the number is to be multiplied.

Table II. Dielectronic recombination rate coefficients (in $cm^3\ s^{-1}$).

Temperature	Fe IX		Fe X		Fe XI	
(eV)	α_B	α_{LM}	α_B	α_{LM}	α_B	α_{LM}
20	0.154^{-9} [a]	—	0.149^{-9}	—	0.102^{-9}	—
30	0.288^{-9}	0.346^{-10}	0.269^{-9}	0.932^{-10}	0.177^{-9}	0.708^{-10}
40	0.352^{-9}	0.694^{-10}	0.321^{-9}	0.154^{-9}	0.208^{-9}	0.131^{-9}
50	0.371^{-9}	0.977^{-10}	0.334^{-9}	0.193^{-9}	0.214^{-9}	0.176^{-9}
70	0.353^{-9}	0.128^{-9}	0.313^{-9}	0.221^{-9}	0.199^{-9}	0.219^{-9}
100	0.294^{-9}	0.134^{-9}	0.258^{-9}	0.209^{-9}	0.163^{-9}	0.220^{-9}
150	0.212^{-9}	0.114^{-9}	0.185^{-9}	0.165^{-9}	0.116^{-9}	0.182^{-9}
200	0.159^{-9}	0.931^{-10}	0.139^{-9}	0.129^{-9}	0.870^{-10}	0.146^{-9}
300	0.998^{-10}	0.635^{-10}	0.871^{-10}	0.848^{-10}	0.546^{-10}	0.979^{-10}
400	0.698^{-10}	0.462^{-10}	0.608^{-10}	0.605^{-10}	0.382^{-10}	0.706^{-10}
500	0.522^{-10}	0.354^{-10}	0.455^{-10}	0.458^{-10}	0.286^{-10}	0.538^{-10}
700	0.332^{-10}	0.231^{-10}	0.289^{-10}	0.294^{-10}	0.182^{-10}	0.349^{-10}

[a] The superscript denotes the power of ten by which the number is to be multiplied.

Table III. Dielectronic recombination rate coefficients (in $cm^3\ s^{-1}$).

Temperature	Fe XII		Fe XIII		Fe XIV	
(eV)	α_B	α_{LM}	α_B	α_{LM}	α_B	α_{LM}
20	0.117^{-9} [a]	—	0.576^{-10}	0.760^{-11}	0.552^{-10}	—
30	0.185^{-9}	0.644^{-10}	0.874^{-10}	0.439^{-10}	0.808^{-10}	0.197^{-10}
40	0.206^{-9}	0.117^{-9}	0.963^{-10}	0.930^{-10}	0.881^{-10}	0.478^{-10}
50	0.204^{-9}	0.155^{-9}	0.960^{-10}	0.135^{-9}	0.882^{-10}	0.753^{-10}
70	0.180^{-9}	0.189^{-9}	0.869^{-10}	0.183^{-9}	0.821^{-10}	0.112^{-9}
100	0.140^{-9}	0.188^{-9}	0.713^{-10}	0.197^{-9}	0.706^{-10}	0.129^{-9}
150	0.960^{-10}	0.154^{-9}	0.518^{-10}	0.171^{-9}	0.546^{-10}	0.119^{-9}
200	0.700^{-10}	0.123^{-9}	0.393^{-10}	0.141^{-9}	0.431^{-10}	0.101^{-9}
300	0.429^{-10}	0.823^{-10}	0.253^{-10}	0.973^{-10}	0.290^{-10}	0.713^{-10}
400	0.295^{-10}	0.592^{-10}	0.179^{-10}	0.711^{-10}	0.210^{-10}	0.528^{-10}
500	0.219^{-10}	0.451^{-10}	0.135^{-10}	0.546^{-10}	0.161^{-10}	0.409^{-10}
700	0.138^{-10}	0.292^{-10}	0.867^{-11}	0.358^{-10}	0.105^{-10}	0.270^{-10}

[a] The superscript denotes the power of ten by which the number is to be multiplied.

have also been computed by the expressions of Landini and Monsignori Fossi [11] and have been displayed in Tables 1–3. It is found here that the values of the rate coefficients obtained from the expressions of Landini and Monsignori Fossi [11] are not very close to those obtained from the Burgess [19] formula. Hence the approximation of Landini and Monsignori Fossi [11] cannot be taken as very accurate and therefore their expressions may be used only where good accuracy is not required.

Radiative recombination rate coefficients have also been computed for the said ions using the expressions of Elwert [26] and Burgess and Seaton [6]. They have been plotted in Figs. 1 and 2 to compare them with the corresponding dielectronic rate coefficients. Burgess and Seaton [6] pointed out that the dielectronic recombination is ~ 20 times the radiative recombination at coronal temperatures. But it has been found here that this ratio is much more than that pointed out by them.

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