CONF-8706176--1

Dielectronic Recombination Measurements of Multicharged Ions

Peter F. Dittner

Physics Division, Oak Ridge National Laboratory
Oak Ridge, Tennessee 37831-6377, USA

"The submitted manuscript has been authored by a contractor of the U.S. Government under contract No. DE-AC05-84OR21400. Accordingly, the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for U.S. Government purposes."

CONF-8706176--1

DE87 011671

Abstract

Dielectronic recombination rates have been measured for several charge states of isoelectronic Li-like, Be-like, B-like, and Na-like ions. We observed the amount of electron capture attending the passage of MeV/nucleon ion beams through a collinear, magnetically confined space-charge-limited electron beam as a function of relative energy. The experimental rates are consistent in magnitude and shape with rates determined from distorted-wave calculations of the dielectronic-recombination cross sections.

1. Introduction

Dielectronic recombination begins with the capture of a free electron by an ion with the simultaneous excitation of one of the electrons already bound to the ion, viz.

$$X^{q+}(i) + e \rightarrow \{X^{(q-1)+}(j, w)\}^{**} \quad (1)$$

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

where i and j represent the initial and final quantum numbers of the electron initially bound to the ion, respectively and w represents the quantum numbers of the captured electron. The doubly excited ion, thus created may decay in two different ways, either by autoionization, with the emission of an electron into the continuum, viz.

$$\{X^{(q-1)+}(j,w)\}^{**} \rightarrow \{X^{q+}(m)\}^* + e \quad (2)$$

or by radiative decay to a bound state, which lies below the ionization limit, (see Fig. 1), viz.

$$\{X^{(q-1)+}(j,w)\}^{**} \rightarrow \{X^{(q-1)+}(k,w')\}^* + h\nu \quad (3)$$

where k and w' are the final quantum numbers of the electrons. Unless the free electron is captured into a very low n state, the dominant radiative decay is a transition by the inner electron back to its initial state ($k=1$ and $w'=w$ on the right-hand side of Eq. 3). The process consisting of Eqs. 1 and 3 is called dielectronic recombination (DR) and occurs in environments containing ions and free electrons. DR, along with radiative recombination and charge exchange with ions, atoms, or molecules, is an important mechanism for decreasing the charge state of ions in a plasma. Therefore, a knowledge of DR cross sections is of importance in the modelling of astrophysical conditions in stellar coronae and/or in the detailed balancing of the densities of ions in specific charge states of fusion devices.

The theoretical treatments of DR date back to 1964 when Burgess [1] showed that the inclusion of DR could explain the long-standing discrepancy in temperature measurements of the solar corona. Most plasma models used the Burgess formulation as modified by Merts [2]. In the last decade a flurry of activity in the calculation of DR cross sections and DR rates has appeared in the literature [3-36] including the effects of fields [37-50] on DR cross sections. This paper shall not discuss the theory of DR although results of calculations will be included.

The first direct experimental measurements [51-53] of DR did not appear until 1983. These had been preceded by the observation of DR satellite lines in spectra emitted from laboratory plasmas [54-60] and the observation of a process closely related to DR, resonant transfer excitation [61-64]. The effect of fields on the measured DR cross section [65] has also been explored and compared to theory. To date, the only direct measurements of DR using multicharged ions have been reported [53,66-68] by the group from the Oak Ridge National Laboratory (ORNL). A summary of the ORNL results, comparison with theory and possible future DR experiments will be presented.

2. Experimental Method

The apparatus used for these experiments (see Fig. 2) has been described in detail previously [66] and only a brief description follows. Ion beams, having energies of 1 to 2 MeV/nucleon produced in our EN-tandem facility are merged with a high-density electron beam,

having an energy of 1 to 2 keV, and interact over a distance of about 1 meter. In the interaction region, the electron beam is kept from expanding radially due to its space charge by the imposition of a solenoidal magnetic field. Following the interaction region, the electrons strike the walls of the chamber and the ions undergo charge separation via electrostatic deflection. The initial beam is steered into a Faraday cup and the ions that have acquired an electron via DR (signal) or charge exchange (background) strike a position-sensitive solid state detector. The background arises from slit edge scattering and residual gas (typical pressure in the system $<1 \cdot 10^{-9}$ Torr). In order to scan over a DR resonance, the ion beam energy is varied in steps corresponding to 1 eV in relative energy while the electron energy is fixed. The application of a modulated square wave voltage to the tube surrounding the electron beam modulates the electron energy between regions in relative energy where a DR signal plus background is expected to one where there should be no DR and only background. Subtraction of the two separately stored counts at every ion energy facilitates background elimination. The electron density, ρ_e , and the length of the interaction region, L , are determined beforehand. At each ion energy and hence at each relative energy, E_r , the ion velocity, v_i , is known, and the ratio, R , of the number of ions with charge state $(q-1)^+$ to the number of ions in the incoming beam of charge state q^+ is measured. We then calculate a quantity, having the dimensions of a rate coefficient cm^3/s , at every E_r , which is the product of the relative velocity, v_r , and the cross section, σ ,

convoluted with the relative velocity distribution of the two merged beams. This quantity, $\langle v_{r\sigma} \rangle$, is given in terms of the measured quantities by the expression,

$$\langle v_{r\sigma} \rangle = R \cdot v_i / \rho_e \cdot L \quad . \quad (6)$$

This rate coefficient can be compared with that calculated from theoretical predictions for the DR cross section.

3. Comparison of Experiment and Theory

In order to make a meaningful comparison of the experimental results and the theoretical predictions, we must consider the field ionization of Rydberg states caused by the charge state analyzer, the enhancement of the DR cross section due to fields in the interaction region and the relative velocity distribution of the merged beams. The first effect is accounted for by assuming that ions, that have undergone DR, rapidly ionize for all values of $n > n_m$ (here n is the same as w of Eq. 3). The cutoff n_m is given by the semiclassical formula [69],

$$n_m = (6.2 \cdot 10^8 q^3/E)^{1/4} \quad (7)$$

where E is the electric field strength in V/cm, and q is the initial charge of the ion before recombination. The field in the interaction region is not known precisely, but it is of the order of 20 - 60 V/cm depending on ρ_e and the alignment of the two beams. Calculations for the Li-like and Na-like ions [44] have been done at various fields in the interaction region, and for the Be-like ions [68] only for the no field case and complete λ -mixing. The relative velocity distribution,

$f(v_r)$, is composed of a transverse component (with respect to the ion beam), f_t , and a parallel component, f_p , given by,

$$f_t = 2\beta v_t \exp(-\beta^2 v_t^2)$$

and

$$f_p = \alpha \pi^{-1/2} \exp(-\alpha^2 (v_p - v_0)^2)$$

where v_t and v_p are the electron velocity components transverse and parallel to the ion beam, respectively, v_0 is given by,

$$v_0 = (2E_r/m)^{1/2},$$

$\alpha = 6.897 \cdot 10^{-8}$ s/cm and $\beta = 7.557 \cdot 10^{-9}$ s/cm. The values of α and β and the functional form of f_t and f_p were deduced from our experiments with Na-like ions [66]. The same relative velocity distribution was used when comparing theory with experiment for all the other ions investigated. The calculated cross section (for a particular value of the field), properly truncated at n_m , at a relative energy E_r was multiplied by v_r and convoluted with the relative velocity distribution to yield the theoretical value of $\langle v_r \sigma \rangle$ for the E_r 's of interest.

The Oak Ridge National Laboratory Accelerator-Based Atomic Physics Group has measured DR using the following multicharged ions: 4 Li-like ions [67] (B^{2+} , C^{3+} , N^{4+} , O^{5+}); 4 Be-like ions [68] (C^{2+} , N^{3+} , O^{4+} , F^{5+}); 3 B-like ion [70] (N^{2+} , O^{3+} , F^{4+}); 3 Na-like ions [66] (P^{4+} , S^{5+} , Cl^{6+}). The results for one typical example from each group are shown in Figs. 3-6. The error bars indicated are the relative

uncertainties, which include counting statistics and background subtraction. The absolute uncertainty is about $\pm 35\%$ and is dominated by the imprecise ($\pm 30\%$) knowledge of the electron density. Two separate sets of data and the results of calculations are shown in Fig. 3 for Li-like C^{3+} . In the first data set the electron velocity is greater than the ion velocity (open circles) and in the second data set the electron velocity is smaller than the ion velocity (solid circles). The agreement between the two sets of data is within statistical error and provides assurance that the signals seen depend only on the relative velocity, as they should. A typical result for a Be-like ion, O^{4+} , is shown in Fig. 4. The ions issuing from the EN tandem contain $\sim 70\%$ in the metastable $1s^2 2s 2p \ ^3P$ state and 30% in the $1s^2 2s^2 \ ^1S$ ground state. The calculated DR cross section from the 3P state is $\sim 1/10$ the cross section from the 1S state. The dashed curve corresponds to no field in the interaction region and the solid curve is for complete ℓ -mixing. The small bump in the solid curve at an E_r of 8 eV is the effect of the 3P state. Figure 5 illustrates the results of our DR measurements on B-like F^{4+} . No calculations have been done on this system. Since the core of the intermediate state of this system, $1s^2 2s 2p^2$, couples to three states, 2D , 2S and 2P , and since the dominant feature of a $\Delta n=0$ transition is a peak at the transition energy, we placed a peak of arbitrary height at the locations of the three transition energies and varied the heights until the composite (solid curve) gave the best linear least squares fit to the data. The results for Na-like ions are demonstrated in Fig. 6 where the two curves have the same meaning as in Fig. 4.

4. Discussion

The overall agreement between the measurements and the calculations is quite good. The Z dependence within any group of isoelectronic ions is correctly predicted. In the case of the Li-like ions, the measurements for all the ions exceed the calculated value (including the field enhancement) by about 50% and no explanation has been found for this discrepancy. The data for the Na-like ions agree very well with a calculation [44] for a field of 25 V/cm. The data for the Be-like ions fall between the two extreme predictions for no field and complete λ -mixing, as they should. There is a slight indication that the contribution to the DR rate from the metastable state has been underestimated by theory but with the present resolution it is difficult to quantify this discrepancy. Theorists [71] are attacking the complex problem of the B-like ions and a comparison with experiment will then be possible.

Future experimental tests of theoretical methods should concentrate on $\Delta n=1$ transitions where DR leads to low n states having large cross sections which are unaffected by fields. This would eliminate the need to accurately know the field and simplify the calculations. Further, it should be possible to carry out experiments with much higher energy resolution to measure isolated transitions to specific states. An experiment [72] on hydrogen-like oxygen satisfying these criteria should be possible as soon as O^{7+} ions are injected into LEAR at CERN. The electron cooler already installed in LEAR would supply the low energy spread electron beam. The heavy ion

storage rings under construction (Astrid at Aarhus, TSR at Heidelberg, CRYRING at AFI, Stockholm, ESR at GSI, Darmstadt and HISTRAP at ORNL) will be ideal devices for DR measurements. They all include high energy resolution electron beams, extremely low vacua, highly charged ions, and highly charged atomic physicists.

Acknowledgements

The author would like to thank his coworkers: S. Datz, H. F. Krause, P. D. Miller, and P. L. Pepmiller of Oak Ridge National Laboratory; C. M. Fou of the University of Delaware; and H. Poth of the University of Karlsruhe and CERN. This research was sponsored by the U.S. Department of Energy, Division of Chemical Sciences under Contract No. DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

References

1. Burgess, A., *Astrophys. J.* 139, 776 (1964).
2. Merts, A.L., Cowan, R.D. and Magee, Jr., N.H., Los Alamos Scientific Laboratory Report No. LA 6220-MS (unpublished).
3. Beigman, I.L., Vainshtain, L.A., and Sunyaev, R., *Sov. Phys.-Usp.* 11, 411 (1968).
4. Trefftz, E., Physics of One- and Two-Electron Atoms, (ed. Bopp, F. and Kleinpoppen, H.), North-Holland, Amsterdam, 1969.
5. Gau, J. and Hahn, Y., *Phys. Lett.* 68A, 197 (1978).
6. Bely-Dubau, F., Gabriel, A.H., and Volonte, S., *Mon. Not. R. Astron. Soc.* 189, 239 (1979).
7. Hahn, Y., *Phys. Rev. A* 22, 2896 (1980).
8. Dubau, J. and Volonte, S., *Rep. Prog. Phys.* 43, 199 (1980).
9. Gau, J. and Hahn, Y., *J. Quant. Spectrosc. Radiat. Transfer.* 23, 121 (1980).
10. Vainshtain, L.A., *Proc. P.N. Lebedev Inst.* 119, 3 (1980).
11. LaGattuta, K. and Hahn, Y., *Phys. Lett.* 84A, 468 (1981).
12. Dubau, J., Gabriel, A.H., Loulergue, M., Steenman-Clark, L., and Volonte, S., *Mon. Not. R. Astron. Soc.* 195, 705 (1981).
13. Pradhan, A.K., *Phys. Rev. Lett.* 47, 79, (1981).
14. LaGattuta, K. and Hahn, Y., *J. Phys. B* 15, 2101 (1982).
15. McLaughlin, D.J. and Hahn, Y., *Phys. Lett.* 88A, 394 (1982).
16. Roszman, L.J., Physics of Electronic and Atomic Collisions (ed. Datz, S.) North-Holland, Amsterdam, 1982.
17. LaGattuta, K. and Hahn, Y., *Phys. Rev. A* 26, 1125 (1982).

18. Bely-Dubau, F., Dubau, J., Faucher, P., and Gabriel, A.H.,
Mon. Not. R. Astron. Soc. 198, 239 (1982).
19. McLaughlin, D.J. and Hahn, Y., Phys. Rev. A 27, 1389 (1983).
20. McLaughlin, D.J. and Hahn, Y., Phys. Rev. A 28, 493 (1983).
21. Nasser, I. and Hahn, Y., J. Quant. Spectrosc. Radiat. Transfer.
29, 1 (1983).
22. Younger, S.M., J. Quant. Spectrosc. Radiat. Transfer. 29, 67
(1983).
23. LaGattuta, K. and Hahn, Y., Phys. Rev. A 27, 1675 (1983).
24. LaGattuta, K. and Hahn, Y., Phys. Rev. Lett. 50, 668 (1983).
25. McLaughlin, D.J. and Hahn, Y., Phys. Rev. A 29, 712 (1984).
26. LaGattuta, K. and Hahn, Y., Phys. Rev. A 30, 316 (1984).
27. Nasser, I. and Hahn, Y., Phys. Rev. A 30, 1558 (1984).
28. Pradhan, A.K., Phys. Rev. A 30, 2141 (1984).
29. McLaughlin, D.J. and Hahn, Y., Phys. Lett. 122A, 389 (1985).
30. Griffin, D.C., Pindzola, M.S., and Bottcher, C., Phys. Rev. A 31,
568 (1985).
31. Dalhed, S., Nilsen, J., and Hagelstein, P., Phys. Rev. A 33, 264
(1986).
32. Nilsen, J., Phys. Lett. B 19, 2401 (1986).
33. Roszman, L.J., Phys. Rev. A 35, 2122 (1987).
34. Roszman, L.J., Phys. Rev. A 35, 2138 (1987).
35. Griffin, D.C. and Pindzola, M.S., Phys. Rev. A 35, 2821 (1987).
36. Roszman, L.J., Phys. Rev. A 35, 3368 (1987).
37. Burgess, A. and Summers, H.P., Astrophys. J. 157, 1007 (1969).

38. Jacobs, V.L., Davis, J., and Kepple, P.C., Phys. Rev. Lett. 37, 1390 (1976).
39. Huber, W.A. and Bottcher, C., J. Phys. B 13, L399 (1980).
40. LaGattuta, K. and Hahn, Y., Phys. Rev. Lett. 51, 558 (1983).
41. Griffin, D.C., Pindzola, M.S., and Bottcher, C., Atomic Excitation and Recombination in External Fields (ed. Nayfeh, M.H., and Clark, C.W.) Harwood Academic, New York, 1985.
42. LaGattuta, K.J., J. Phys. B 18, L467, (1985).
43. LaGattuta, K. and Hahn, Y., Phys. Rev. A 33, 2782 (1986).
44. Griffin, D.C., Pindzola, M.S., and Bottcher, C., Phys. Rev. A 33, 3124 (1986).
45. Bottcher, C., Griffin, D.C., and Pindzola, M.S., Phys. Rev. A 34, 860 (1986).
46. Harmin, D.A., Phys. Rev. Lett. 57, 1570 (1986).
47. Sakimoto, K., J. Phys. B 19, 3011 (1986).
48. Sakimoto, K., J. Phys. B 20, 807 (1987).
49. LaGattuta, K., Nasser, I., and Hahn, Y., J. Phys. B 20, 1565 (1987).
50. LaGattuta, K., Nasser, I., and Hahn, Y., J. Phys. B 20, 1577 (1987).
51. Mitchell, J.B.A., Ng, C.T., Foraud, J.L., Levac, D.P., Mitchell, R.E., Sen, A., Miko, D.B., and McGowan, J.Wm., Phys. Rev. Lett. 50, 335 (1983).
52. Belic, D.S., Dunn, G.H., Morgan, T.J., Mueller, D.W., and Timmer, C., Phys. Rev. Lett. 50, 339 (1983).

53. Dittner, P.F., Datz, S., Miller, P.D., Moak, C.D., Stelson, P.H., Bottcher, C., Dress, W.B., Alton, G.D., and Neskovic, N., Phys. Rev. Lett. 51, 31 (1983).
54. Brooks, R.L., Datta, R.U., and Griem, H.R., Phys. Rev. Lett. 41, 107 (1978).
55. Breton, C., De Michelis, C., Finkenthal, M., and Mattioli, M., Phys. Rev. Lett. 41, 110 (1978).
56. Brooks, R.L., Datta, R.U., Krumbein, A.D., and Griem, H.R., Phys. Rev. A 21, 1387 (1980).
57. Chichkov, B.N., Mazing, M.A., Shevelko, A.P., and Urnov, A.M., Phys. Lett. 83A, 412 (1981).
58. Isler, R.C., Crume, E.C., and Arnurius, D.E., Phys. Rev. A 26, 2105 (1982).
59. Bely-Dubau, F., Bitter, M., Dubau, J., Faucher, P., Gabriel, A.H., Hill, K.W., von Goeler, S., Sauthoff, N., and Volonte, S., Phys. Lett. 93A, 189 (1983).
60. Meng, H.C., Greve, P., Kunze, H.-J., and Schmidt, T., Phys. Rev. A 31, 3276 (1985).
61. Tanis, J.A., Bernstein, E.M., Graham, W.G., Clark, M., Shafroth, S.M., Johnson, B.M., Jones, K.W., and Meron, M., Phys. Rev. Lett. 49, 1325 (1982).
62. Tanis, J.A., Bernstein, E.M., Graham, W.G., Stockli, M.P., Clark, M., McFarland, R.H., Morgan, T.J., Berkner, K.H., Schlacter, A.S., and Stearns, J.W., Phys. Rev. Lett. 53, 2551 (1984).

63. Schönfeldt, W.A., Mokler, P.H., Hoffmann, D.H.H., and Warczek, Z. für Phys. A 321, 693 (1985).
64. Tanis, J.A., Bernstein, E.M., Clark, M., Graham, W.G., McFarland, R.H., Morgan, T.J., Mowat, J.R., Mueller, D.W., Müller, A., Stockli, M.P., Berkner, K.H., Gohil, P., McDonald, R.J., Schlacter, A.S., and Stearns, J.W., Phys. Rev. A 34, 2543 (1986).
65. Müller, A., Belic, D.S., DePaola, B.D., Djuric, N., Dunn, G.H., Mueller, D.W., and Timmer, C., Phys. Rev. Lett. 56, 127 (1986).
66. Dittner, P.F., Datz, S., Miller, P.D., Pepmiller, P.L., and Fou, C.M., Phys. Rev. A 33, 124 (1986).
67. Dittner, P.F., Datz, S., Miller, P.D., Pepmiller, P.L., and Fou, C.M., Phys. Rev. A 35, 3668 (1987).
68. Dittner, P.F., Datz, S., Krause, H.F., Miller, P.D., Pepmiller, P.L., Bottcher, C., Fou, C.M., Griffin, D.C., and Pindzola, M.S., Phys. Rev. A 35, (1987).
69. Broulliard, F., Atomic and Molecular Processes in Controlled Thermonuclear Fusion, (ed. Joachain, C.J. and Post, D.E.) Plenum, New York, 1983.
70. Dittner, P.F., Datz, S., Krause, H.F., Miller, P.D., Pepmiller, P.L., and Fou, C.M., to be published.
71. Hahn, Y., private communication.
72. Dittner, P.F., and Poth, H., "Considerations for a Dielectronic Recombination Experiment with Oxygen Ions in LEAR", CERN PS/LI/Note 86-2, April, 1986 (unpublished).

Figure Captions

- Fig. 1. Generic energy level diagram showing the ion X^{q+} ($q=Z-N$) capturing an electron having energy E_i to the state j of the ion $X^{(q-1)+}$.
- Fig. 2. Schematic view of the merged beams apparatus used in the dielectronic recombination measurements.
- Fig. 3. The DR rate $\langle v_r \sigma \rangle$ versus E_r for C^{3+} . Open circles are the data for $v_e > v_i$, solid circles for $v_e < v_i$, the curves are calculated from the σ of Ref. 44 for a field (in V/cm) in the interaction region of 0 (.....), 5 (----), 25 (-----), 125 (-----), and 625 (—).
- Fig. 4. The DR rate $\langle v_r \sigma \rangle$ versus E_r for O^{4+} . The dashed curve is the calculated rate for no field mixing and the solid curve is that for complete field mixing.
- Fig. 5. The DR rate $\langle v_r \sigma \rangle$ versus E_r for F^{4+} . The transition energies of the $2D$, $2S$, and $2P$ levels are indicated on the abscissa. The curves are the $2D$ (----), $2S$ (....), and $2P$ (-----) contributions to the sum (—).
- Fig. 6. The DR rate $\langle v_r \sigma \rangle$ versus E_r for S^{5+} . The lower curve is the calculated rate for no field mixing and the upper curve is that for complete field mixing.

FIG. 1

ORNL-DWG 84-10367

Fig. 2

Fig. 3

Fig. 5

Fig. 6