International Atomic Energy Agency

INDC(NDS)-160/GA

INDC INTERNATIONAL NUCLEAR DATA COMMITTEE

ATOMIC COLLISION DATA

FOR DIAGNOSTICS OF MAGNETIC FUSION PLASMAS

Summary Report of the third and final Research Coordination Meeting
of the Coordinated Research Programme on Atomic Collision Data
for Diagnostics of Magnetically confined Fusion Plasmas,
held at IAEA Headquarters, 19-20 June 1984

Edited by K. Katsonis
Nuclear Data Section
International Atomic Energy Agency

October 1984

IAEA NUCLEAR DATA SECTION, WAGRAMERSTRASSE 5, A-1400 VIENNA

INDC(NDS)-160/GA

ATOMIC COLLISION DATA

FOR DIAGNOSTICS OF MAGNETIC FUSION PLASMAS

Summary Report of the third and final Research Coordination Meeting
of the Coordinated Research Programme on Atomic Collision Data
for Diagnostics of Magnetically confined Fusion Plasmas,
held at IAEA Headquarters, 19-20 June 1984

Edited by K. Katsonis
Nuclear Data Section
International Atomic Energy Agency

October 1984

Reproduced by the IAEA in Austria

October 1984

84-05547

Table of Contents

ABSTRACT

This report constitutes a comprehensive review of the developments in the domain of the atomic collision data for diagnostics of magnetic fusion plasmas during the last year. Data produced up to June 1984 are discussed and recommended data sets are presented. This report was written by three working groups convened on 19-20 June 1984 at the IAEA Headquarters in Vienna on the occasion of the third Research Coordination Meeting connected with the IAEA Coordinated Research Programme on atomic collision data for diagnostics of magnetically confined fusion plasmas. The members of these groups reviewed the work in progress and the current status of data on electron impact excitation and ionization, on dielectronic recombination, and on charge exchange and related processes for selected fusion relevant elements, made specific recommendations on the use of these data, and identified those data which needed to be measured or calculated.

I. INTRODUCTION

This review is the result of the work performed by three working groups formed during the third meeting of the Coordinated Research Programme (CRP) of the IAEA on Atomic Collision Data for Diagnostics of Magnetic Fusion Plasmas. This Research Coordination Meeting (RCM), convened by the IAEA Nuclear Data Section on 18-20 June 1984 at the IAEA Headquarters in Vienna was run by the Scientific Secretary K. Katsonis with the assistance of three co-chairmen, G. Dunn, H. B. Gilbody and Y. Itikawa.

In addition to the members of the CRP attending the meeting, eleven scientists working in Austria in the field of atomic data were invited to participate as observers. Also, seven specialists from various countries attended as observers. The participants in the second RCM are listed in Appendix 1, and the Adopted Agenda is given in Appendix 2. Each participant presented a short review on the work in progress at his laboratory. The abstracts of these presentations will be published in forthcoming issues of the International Bulletin on Atomic and Molecular Data for Fusion.

II. REVIEW OF THE DATA STATUS AND OF THE DATA REQUIREMENTS

WORKING GROUP REPORT ON ELECTRON IMPACT EXCITATION OF IONS

Y. Itikawa (Chairman), K. Katsonis and M. R. C. McDowell

1. General Considerations

The present report is based mostly on the following bibliographic sources: the second supplement [1] to previous bibliographic work on electron-ion collision presented in the IPPJ-AM report series [2, 3], and the recent issues of the IAEA bulletin [4]. The bibliographic data contained in [2, 3] and their supplement have been rearranged and they will be published shortly [5].

Since the last research coordination meeting in September 1983 [6], a large number of calculations have been made on the excitation cross sections. They have been, however, motivated mainly by astrophysical interest. There are still very few measurements of excitation cross sections of ions.

At the IPP/Nagoya the task of compilation and evaluation of data on excitation cross sections is continuing. Former work is now being extended to C-like ions.

Although this working group is not concerned with data on excitation of neutral atoms, the fusion relevant among them are occasionally mentioned. An assessment of the available experimental and theoretical data has been made on the excitation of He [7]. Based on the assessed data, rate coefficients were calculated for the temperature range below 3 x 10^6 ^oK.

2. Experimental Data

Differential cross sections for Cd^+ excitation [8] were obtained with the same technique as for Zn^+. Those data are not of immediate interest to fusion, but serve as a test of the theoretical methods used for the production of data for other ions.

There are several measurements of the excitations rate coefficients (for Ne^{6+} [9], Ne^{7+} [10], Fe^{7+}, Fe^{8+}, Fe^{10+} [11], Fe^{10+} [12]) with the use of theta-pinch devices. Those measurements are usually made at a few points of temperatures and constitute a test of the theoretical data for which beam-type experiment is very difficult to be done.

3. Calculations

Data reported after completion of [6] are listed in Table I. Three theoretical methods were used to obtain those data: R-matrix (RM) method, close-coupling (CC) approximation, and distorted-wave (DW) approximation. There are several other calculations based on the Born or Coulomb-Born approximations. Though they give rough estimates of missing data, these calculations do not have sufficient accuracy for plasma diagnostics and are not mentioned here.

For lighter elements, a number of very elaborate calculations have been done (C^{4+}, O^{2+}, O^{3+}, O^{6+}, Ne^{4+}, Mg^{10+}, Si^{8+}, S^{11+}, Ca^{14+}, Ca^{16+}). Most of them show a considerable resonance enhancement of the excitation cross section. Radiative decay of the intermediate resonant states could have a large effect on this enhancement. The role of resonances including radiative decay in electron impact excitation of highly charged ions was studied in detail for He-like ions [20]; autoionization and dielectronic recombination effects were also considered for high Z He-like ions [28]. Particularly, the modification of collision rates due to resonances was calculated for O^{6+} [20] Fe^{24+} [20, 28] and Mo^{40+} [28] ions. Although the effect was found important, quantitative results for Fe^{24+} from [20] and [28] are in disagreement.

For heavier elements, extensive calculations have been reported for Fe^{q+} (q = 9, 14-25) [26]. Those data and previous ones on Be, Mg, Cu and Zn isoelectronic sequences resonance transition cross sections obtained by DW-type calculations [30, 31] are useful for fusion research and may be reliable except for the threshold region of the electron energy.

A project is being organized by Seaton to calculate collision strengths for any ions of astrophysical interest with use of the R-matrix code. The results, when available, could also be used to fusion research.

Other work in progress initiated from astrophysical interest includes calculation of the collision strengths for various S ions. Electron impact excitation of S^+ have been calculated by use of a two-state [32] and six-state [33] CC approximation.

Collision strengths for transitions from the ground state of neon-like Ar have been calculated recently in DW approximation for energies from threshold to 2.5 keV [34]. The obtained cross sections show similarities to those obtained earlier for neon-like Kr.

Finally it should be mentioned that Whitten et al [35] have improved their previous study of high-density effects on collisions of electrons with H-like ions. This work is primarily of interest for inertial fusion.

4. Data Requirements

In the last report of this working group [6] a rather detailed description was made on data needs. Many of them, especially for heavier elements, have not yet been answered. It is estimated that one hundred of excitation measurements covering many charge states and $\Delta n = 0,1$ transitions are needed to confirm the theory, whereas no experimental data for $\Delta n = 1$ are yet available. New techniques will be necessary for the experimental determination of these cross sections [36].

Also with the current emphasis to the scrape-off plasma region (e.g. study of divertors), data on low charge states in a lower collision energy region will become more important.

Some new requirements have been raised with the development of fusion research. Highly ionised Ar was used for probing hot plasmas in Alcator C [37]. The measured x-ray spectra of Ar^{14+} to Ar^{17+} show strong recombination effects and non-corona line ratios. In relation to the neutral beam diagnostics at JET, electron-impact excitation cross sections are needed for Ni ions, especially for Ni^{27+} and Ni^{26+} [38].

Table I

Theoretical data on electron impact excitation of ions

ION	Ref. No.	Method	Energy Range of Cross Section [Collision Rate]
He^{+}	[13]	DW(C-E)*	Thr* - 16 Ry
	[14]	DW(PO)*	41-218 eV
C^{4+}	[15]	DW	(1-1000)xThr
	[16]	RM	$(0.1-100)\times10^{5}$ °K
O^{2+}	[17]	RM	0.5-5.16 Ry [$(0.25-6)\times10^{4}$ °K]
O^{3+}	[18]	CC	$10^{2}-4\times10^{4}$ °K
O^{6+}	[19]	RM	45-210 Ry [$(0.1-100)\times10^{5}$ °K]
	[20]	DW	(0.3-80) 10^{6} °K
	[21]	RM	Thr - 75 Ry [$(0.1-60)\times10^{5}$ °K]
Ne^{4+}	[23]	RM	Thr - 40 Ry [up to 10^{6} °K]
Mg^{10+}	[20]	DW	$(0.3-80)\times10^{6}$ °K
	[16]	RM	$(0.1-100)\times10^{5}$ °K
Al^{10+}	[15]	DW	0.01-10 KeV
Al^{11+}	[15]	DW	0.01-10 KeV
Si^{8+}	[23]	RM	Thr - 90 Ry [up to 2.5×10^{6} °K]
S^{11+}	[25]	CC	$10^{6.1-6.5}$ °K
Ar^{16+}	[15]	DW	(1-1000)xThr
Ca^{14+}	[24]	RM	1-28 Ry [$(0.5-50)\times10^{4}$ °K]
Ca^{16+}	[22]	RM	10-150 Ry [$10^{6.4-7.2}$ °K]
Ca^{18+}	[20]	DW	$(0.3-80)\times10^{6}$ °K
Fe^{9+}, $Fe^{(14-25)+}$	[26]	DW(X)*	
Fe^{24+}	[27]	CC and DW	E/Z^{2}=0.8-9 Ry
	[28]	CC and DW	-
	[20]	DW	$(0.3-80)\times10^{6}$ °K
Se^{32+}	[27]	CC and DW	E/Z^{2} = 0.8-9 Ry
Kr^{26+}	[29]	DW	140 Ry
Mo^{40+}	[27]	CC and DW	E/Z^{2} = 0.8-9 Ry
	[28]	CC and DW	-

*Thr: Threshold, C-E: Coulomb-Exchange, PO: Polarized Orbital
X: Electron Exchange

References

1. Y. Itikawa, Bibliography on electron collisions with atomic positive ions, 1983-1984, preprint.
2. K. Takayanagi and T. Iwai, Bibliography on Electron Collision with Atomic Positive Ions 1940-1977, Report IPPJ-AM-7, Institute of Plasma Physics, Nagoya University, Nagoya (1978).
3. Y. Itikawa, Bibliography on Electron Collision with Atomic Positive Ions 1978-1982, Report IPPJ-AM-24, Institute of Plasma Physics, Nagoya University, Nagoya (1982).
4. K. Katsonis, Editor, International Bulletin on Atomic and Molecular Data for Fusion, IAEA, Vienna.
5. Y. Itikawa, K. Takayanagi and T. Iwai, Atomic Data Nuclear Data Tables (1984), in press.
6. "Working Group Report on Electron Impact Excitation of Ions", in International Bulletin on Atomic and Molecular Data for Fusion No. 24, (Editor K. Katsonis), IAEA, Vienna (1984).
7. K.M. Aggarwal, A.E. Kingston and M.R.C. McDowell, Astrophys. J. 278, 874 (1984).
8. A. Chutjian, Phys. Rev. A 29, 64 (1984).
9. J. Lang, J. Phys. B 16, 3907 (1983).
10. C.C. Chang, P. Greve, K.-H. Kolk and H.-J. Kunze, Phys. Scr. 29, 132 (1984).
11. J.-S. Wang, R.U. Datla and H.R. Griem, Phys. Rev. A 29, 1558 (1984).
12. J.-S. Wang, A. Marotta and R.U. Datla, Astrophys. J. 279, 460 (1984).
13. N.R. Badnell, J. Phys. B 16, 3263 (1983).
14. M. Basu, P.S. Mazumder and A.S. Ghosh, Can. J. Phys. 61 1297 (1983).
15. D. Duston, J.E. Rogerson, J. Davis and M. Blaha, Phys. Rev. A 28, 2968 (1983).
16. S.S. Tayal and A.E. Kingston, J. Phys. B 17, L145 (1984).
17. K.M. Aggarwal, Astrophys. J. Suppl. 52, 387 (1983).
18. M.A. Hayes and H. Nussbaumer, Astron. Astrophys. 124, 279 (1983).
19. A.E. Kingston and S.S. Tayal, J. Phys. B 16, 3465 (1983).
20. L. Steenman-Clark and P. Faucher, J. Phys. B 17 73 (1984).
21. S.S. Tayal and A.E. Kingston, J. Phys. B 17, 1383 (1984).
22. P.L. Dufton, A.E. Kingston and N.S. Scott, J. Phys. B 16, 3053 (1983).

23. K.M. Aggarwal, Astrophys. J. Suppl. 54, 1 (1984).
24. K.M. Aggarwal, J. Phys. B 16, 2231 (1983).
25. H.P. Saha and E. Trefftz, Sol. Phys. 87, 233 (1983).
26. J.B. Mann, Atomic Data Nucl. Data Tables 29, 407 (1983).
27. A.K. Pradhan, Phys. Rev. A 28, 2113 (1983).
28. A.K. Pradhan, Phys. Rev. A 28, 2128 (1983).
29. U. Feldman, A.K. Bhatia and S. Suckewer, J. Appl. Phys. 54, 2188 (1983).
30. S.M. Younger, J. Quant. Spectrosc. Rad. Transf. 22, 155 (1979).
31. S.M. Younger, J. Quant. Spectrosc. Rad. Transf. 23, 489 (1980).
32. Y.K. Ho and R.J.W. Henry, 'Collision strengths for intercombination lines of S^+ ions', Preprint.
33. S. Nakazaki and R.J.W. Henry, 'Collision strengths for transitions among the ground configuration of S^+', Preprint.
34. K. Reed, 'Electron Collision Strengths for Ne-like Ar', Preprint.
35. B.L. Whitten, N.F. Lane and J.C. Weisheit, Phys. Rev. A 29, 945 (1984).
36. C.F. Barnett, Nucl. Instr. Methods 214, 1 (1983).
37. J.E. Rice, E.S. Marmar, E. Kaellne, J. Kaellne and A.K. Pradhan, 'Highly Ionised Argon for Probing Hot Plasmas', Preprint.
38. R.P.W. McWhirter, Editor, Note on the RAL/JET workshop on the Application of Atomic Physics to Fusion Research, 24-25 May (1984).

WORKING GROUP REPORT ON ELECTRON IMPACT IONIZATION OF IONS

V.A. Abramov, G.H. Dunn (Chairman), S. Hayakawa, J.G. Hughes,
C.J. Joachain, M.S. Pindzola, E. Salzborn, W. Wiese

1. General Progress in 1983

There has been substantial activity in the field of electron-impact ionization of atomic ions during the past year [1]. New crossed-beams experimental data is reported below from groups at Culham (U.K.), Giessen (W. Germany), JILA (USA), Louvain-la-Neuve (Belgium), IPP (Japan) and ORNL (USA). New theoretical calculations in support of the experimental effort are reported below from groups at Belfast (UK), LSU (USA) and ORNL (USA). The greatest needs for further study can be identified as:

(1) Further measurements and theory determining the magnitudes and trends of cross sections for direct ionization, excitation-autoionization and resonant-recombination double-autoionization.
(2) Further measurements and theory for multiple ionization.
(3) Measurements and theory for ionization from excited states.
(4) Further measurements and theory along isonuclear sequences of transition metal ions; for example titanium (except +1, +2 and +3), iron (except +1 and +2), nickel (except +3) and copper (except +2 and +3).
(5) Measurements and theory for other species of specific fusion interest: aluminum (except +1 and +2); chromium; chlorine (except +2); fluorine (except +2); tungsten (except +1); molybdenum; including data for very highly ionized species where relativistic effects play a role.

2. *Single Ionization Cross Sections for Ions*

2.1. Light Ions

New experiments on the measurement of total cross sections for electron impact ionization of helium-like, lithium-like and beryllium-like ions are presently being performed at Louvain-la-Neuve (Belgium) by Defrance et al [2], using a high-intensity multiply-charged ion source. Also in the last year a crossed-beams measurement of B^{2+} ionization was performed at ORNL (USA) [3], in a continuing investigation of excitation-autoionization along the lithium isoelectronic sequence. In many of the lighter ions, measurements of the direct ionization cross section compare favorably with the extensive distorted-wave calculations of Younger [4-6] the Coulomb-Born calculations of Jakubowitz and Moores [7] and the scaled hydrogenic calculations of Golden and Sampson [8]. A compilation of recommended data on the electron-impact ionization of light atoms and their ions was also published in the last year [9].

In nearly all theoretical calculations performed thus far, the exchange amplitude $g(\vec{k}_A, \vec{k}_B)$ - where $\vec{k}_A$ and $\vec{k}_B$ are the momenta of the two outgoing electrons has been calculated via the relation

$$g(\vec{k}_A, \vec{k}_B) = \exp[i\ T(\vec{k}_A, \vec{k}_B)] x f(\vec{k}_B, \vec{k}_A)$$

where $f(\vec{k}_A, \vec{k}_B)$ is the direct amplitude for the same process. The phase $T(\vec{k}_A, \vec{k}_B)$ which appears in the above equation is determined in such a way that the total cross section is minimized. Attention is drawn to the fact that this procedure cannot be justified on theoretical grounds and that further investigation of this problem is highly desirable.

2.2 Medium to Heavy Ions

In the previous report [1] many new crossed beam measurements were reported to be in progress. Most of these cross sections have since been published or submitted to be published in the literature, namely:

F^{2+}, Ti^{2+}, Fe^{2+}, Cl^{2+}	Ref. [10]
Ne^{2+}, Ar^{2+}, Kr^{2+}, Xe^{2+}	Ref. [11]
Fe^{+}	Ref. [12]
Xe^{+}, Xe^{2+}, Xe^{3+}, Xe^{4+}	Ref. [13]

New measurements for the xenon isonuclear sequence (Xe^{2+} - Xe^{6+}) have been carried out [14], and measurements for the ions Cu^{2+}, Cu^{3+} and Ni^{3+} are reported to be available [15]. Other measurements recently completed include those at Giessen for the ions Ar^{+}, Kr^{+}, Kr^{2+}, Kr^{3+}, Bi^{+}, Bi^{2+}, Sb^{+}, Sb^{2+} [16]. At ORNL [15] work has also been completed on Kr^{2+} and Sb^{3+}.

Recent combined theoretical and experimental efforts at ORNL have gained some insight into the relative contributions of direct and indirect processes contributing to single ionization [14, 17-20]. However, quantitative agreement between theory and experiment is still unsatisfactory in certain specific cases. Recent calculations on Ca^{+} [21, 22] highlight the continuing discrepancies between different theories and between theory and experiment. Further measurements and more detailed theoretical calculations are required to reach a comprehensive understanding of electron impact ionization. In this light, new theoretical calculations are reported to be in progress at Belfast (Ti^{3+}, Ni^{2+}, Ni^{3+}), Oak Ridge (Ni^{3+}, Cu^{2+}, Cu^{3+}, Fe^{2+}, Ti^{2+}), and LSU/Louisiana (Ti^{3+}).

2.3 Need for K-shell ionization data

The cross section for ionizing K-electrons has been separately given for neutral targets in many literatures. Data of K-shell ionization for ions are useful in identifying abundant ions, since K X-rays can be easily measured. The data needed are (1) the energies of K_{α}, K_{β},..... lines and K-edges, and (2) the K-fluorescence yields. The autoionization cross sections following K-ionization may contribute to multiple ionization cross sections. The cross sections for K-shell ionization are expected to be near those for neutral atoms.

3. Multiple Ionization Cross Sections for Ions

The availability of cross sections for multiple ionization of ions, $\sigma_{q,\ q+k}$ with $k > 1$, is still limited. The only element which has been studied so far in detail is xenon [Refs. 27, 29, 30, 31].

Data for multiple ionization published so far are given in Table I. Further measurements which will be published soon include the references shown in Table II.

Table I: Published data

σ_{13}	σ_{14}	σ_{15}	σ_{24}	σ_{25}	σ_{26}	σ_{35}	σ_{36}	σ_{46}	σ_{68}	σ_{69}	Ref.
Li											[23]
Na											[24]
Ar	Ar	Ar	Ar	Ar		Ar		Ar[30]			[25,30]
								Kr			[30]
Rb	Rb	Rb	Rb								[26]
I											[27]
Xe [27]	Xe [29]	Xe [29]	Xe [27,29]	Xe [29]	Xe [29]	Xe [27]	Xe [29]	Xe [27,29,30]	Xe [31]	Xe [31]	[27,29,30,31]
Cs	Cs	Cs									[28]

Table II: Unpublished data

σ_{13}	σ_{14}	σ_{24}	σ_{25}	σ_{35}	σ_{46}	Ref.
Kr	Kr	Kr	Kr	Kr	Kr	[32]
Sb						[32]
Bi	Bi	Bi	Bi	Bi		[32]

The data for heavy elements, e.g. Xe [29], show that multiple ionization cross sections may be quite large and therefore should be taken into account in plasma modelling codes.

Experiments and calculations show [30] that the main contributions to multiple ionization cross sections may result from two step processes like innershell ionization followed by autoionization rather than simultaneous ejection of outermost shell electrons.

In view of the small data base available, these is a strong need for further measurements. The agreement between theory and experiment is within a factor of two in the cases studied. However, there is a strong need for improved theoretical models to describe the contributions to the cross sections resulting from direct multiple ionization.

References

1. "Working Group Report on Electron Impact Ionization of Ions", in International Bulletin on Atomic and Molecular Data for Fusion, No. 24 (Ed. K. Katsonis), IAEA, Vienna (1984).
2. Louvain-la-Neuve group (private communication).
3. D.H. Crandall, R.A. Phaneuf, D.C. Gregory, D.W. Mueller, T.J. Morgan and G.H. Dunn, Phys. Rev. A (submitted).
4. S.M. Younger, Phys. Rev. A 22, 111 (1980).
5. S.M. Younger, Phys. Rev. A 22, 1425 (1980).
6. S.M. Younger, Phys. Rev. A 24, 1272 and 1278 (1981).
7. H. Jakubowitz and D.L. Moores, J. Phys. B 14, 3733 (1981).
8. L.B. Golden and D.H. Sampson, J. Phys. B 10, 2229 (1977).
9. K.L. Bell, H.B. Gilbody, J.G. Hughes, A.E. Kingston and F.J. Smith, J. Phys. and Chem. Ref. Data 12, 891 (1983).
10. D.W. Mueller, T.J. Morgan, G.H. Dunn, D.C. Gregory and D.H. Crandall, Phys. Rev. A (submitted).
11. A. Matsumoto, S. Ohtani, A. Danjo, S. Harashiro, T. Hino, Y. Kondo, H. Suzuki, H. Tawara, K. Wakiya and M. Yohsino, J. Phys. Soc. Japan (submitted).
12. R.G. Montague, N.J. Diosrens, M.F.A. Harrison and A.C.H. Smith, J. Phys. B (submitted).
13. C. Achenbach, A. Mueller, E. Salzborn and R. Becker, J. Phys. B. 17, 1405 (1984).
14. D.C. Griffin, C. Bottcher, M.S. Pindzola, S.M. Younger, D.C. Gregory and D.H. Crandall, Phys. Rev. A 29, 1729 (1984).
15. A. Howaldand, D.C. Gregory, Phys. Rev. A (submitted).
16. E. Salzborn (private communication).
17. C. Bottcher, D.C. Griffin and M.S. Pindzola, J. Phys. B 16, L65 (1983).
18. D.C. Gregory, P.F. Dittner and D.H. Crandall, Phys. Rev. A 27, 724 (1983).
19. R.A. Falk, G.H. Dunn, D.C. Gregory and D.H. Crandall, Phys. Rev. A 27, 762 (1983).
20. M.S. Pindzola, D.C. Griffin and C. Bottcher, Phys. Rev. A 27, 2331 (1983).
21. P.G. Burke, A.E. Kingston and A. Thompson, J. Phys. B 16, L385 (1983).
22. D.C. Griffin, M.S. Pindzola and C. Bottcher, J. Phys. B (in press).

23. B. Peart and K.T. Dolder, J. Phys. B 2, 1169 (1969).
24. W.E. Sayle and R.K. Feeney, in 'Physics of Electronic and Atomic Collisions', X ICPEAC, Abstracts of contributed papers, p. 1084, N. Holland, Amsterdam (1977).
25. A. Mueller and R. Frodl, Phys. Rev. Lett. 44, 29 (1980).
26. D.W. Hughes and R.K. Feeney, Phys. Rev. A 23, 2241 (1981).
27. C. Achenbach, A. Mueller, E. Salzborn and R. Becker, Phys. Rev. Lett. 50, 2070 (1983).
28. D.R. Hertlin R.K. Feeney, D.W. Hughes and W.E. Sayle II, J. Appl. Phys. 53, 5427 (1982).
29. A. Mueller, C. Achenbach, E. Salzborn and R. Becker, J. Phys. B 17, 1427 (1984).
30. M.S. Pindzola, D.C. Griffin, C. Bottcher, D.H. Crandall, R.A. Phaneuf and D.C. Gregory, Phys. Rev. A 29 1749 (1984).
31. Oak Ridge group, (private communication).
32. E. Salzborn (private communication).

WORKING GROUP REPORT ON CHARGE EXCHANGE AND RELATED TOPICS

C.F. Barnett, S. Bliman, B.H. Bransden, H.B. Gilbody (Chairman),
P. Hvelplund, W. Lindinger, M.R.C. McDowell, S. C. Mukherjee,
Y. Nakai, H. Tawara, H. Winter

This group confirms the report and recommendations made in September 1983 [1] but draws attention to the following areas where significant progress has occurred:

1. Collisions Involving Hydrogen Atoms

A drift tube technique developed jointly by the Universities of Innsbruck and Trento [2] has been used to obtain charge transfer rate coefficients for O^+, CO^+ and CH^+ in H [3] at c.m. energies ranging from thermal to a few tenths of an eV. The method is capable of extension to multiply charged ions in known initial excited states.

In Grenoble, total cross sections for electron capture by fully stripped N, O, F and Ne ions in H have been determined at keV energies [4].

A review of state selective capture by multiply charged ions in H and other targets is now available [5]. Cross sections for state-selective capture by C^{2+} and C^{3+} in H in the range 0.6-18 keV have been determined in Belfast using energy gain spectroscopy [6]. Results for C^{3+} in H are in generally good accord with full quantal calculations [7].

Measurements of state selective capture based on photon emission spectroscopy have been carried out for C^{6+} - H and He^{2+} - H collisions by the FOM Amsterdam/KVI Groningen (see [5]) and Leningrad/Dubna groups [8]. Theoretical results are also available [9,10] for comparison (see [5]). Experimental data for state selective capture in C^{4+}, N^{5+} and O^{6+} collisions with H have been determined in the range 1-6 keV/amu by the FOM Amsterdam/KVI Groningen group and for C^{4+} impact compared with theory [29] (see [5]). Theoretical estimates for state selective capture by slow O^{8+} and C^{6+} in H have also been obtained by Presnyakov and Uskov [11].

McDowell and Janev [12] have employed the classical trajectory Monte Carlo (CTMC) method utilising a non Coulomb potential to take into account the structure of the projectile ion and obtained cross sections for state selective capture by highly ionized Au, Fe and Al ions in H and He within the range 20-200 keV amu^{-1}; scaling laws are also considered. Larsen and Taulbjerg [13] have given a simple description of electron capture by slow highly charged ions in H.

Cross sections for ionization of H by ions on N^{q+} and O^{q+} (q=3,4,5), and by Li^{3+} and C^{3+} have been calculated [11] for velocities $v \gtrsim Z^{-1/2}$. Theoretical values are also available for fully stripped ion impact [15] in the range 20-1000 keV amu^{-1}.

Parameterised empirical formulae for the calculation of charge transfer cross sections in H and He for fully stripped ions (Z < 14) have been obtained by Janev and Katsonis [40].

2. Collisions Involving Multi-Electron Targets

New experimental measurements of state selective capture by multiply charged ions in He are available. These show that, for sufficiently high initial charge states and irrespective of species, single capture populates mainly the n=3 states for N^{6+} and O^{6+} impact [17], and n=4 for O^{8+} and Ne^{8+} impact [18]. Measurements are also available for S^{11+}, S^{13+} and $Kr^{(7-25)+}$ impact at energies of 1xq keV [41] and for $I^{(10-41)+}$ ions in He [42]. In the range of applicability of molecular orbital models, cross sections are only weakly energy dependent. Double capture is observed either by autoionizing electron spectroscopy [19, 20] or by ion translational spectroscopy [21, 41, 42]. Photon emission spectroscopy provides information on the component of double capture which stabilises radiatively [18].

For the H_2 target similar results are observed. Single capture populates the higher n levels [17, 18], for q=6, n=4 and for q=8, n=5. In measurements with Al^{8+} ions [18] a full analysis of the state selective capture process is precluded by lack of detailed knowledge of the energy levels of Al^{7+}.

State-selective electron capture from H_2 by a number of multiply charged ions has been investigated by the FOM Amsterdam/KVI Groningen group. Data are available for impact of He^{2+} (5-40 keV) [36], He-like C, N and O ions (1-7 keV/amu) [17, 37], N^{6+} [17] and Ar^{6+} [38].

Translational spectrocopy for impact of Xe^{2+} and Ar^{3+} below 1 keV [39] has shown that final state population, apart from the reaction energy defect, also depends on the Franck-Condon factors for transitions between vibrational states of H_2 and H_2^+ respectively.

Collisions of protons and multiply charged ions with Li atoms are of interest for plasma diagnostics with active Li beams (investigation of α-particle energy loss and α-particle velocity distribution). Cross sections for the two-electron capture by He^{2+} in Li are now available over a wide energy range [22, 23, 24].

Total one-electron capture cross sections in Li have been measured for Ne^{q+} (q=2-6), Ar^{q+} (q=2-9) and Kr^{q+}, Xe^{q+} (q=2-10) for projectile energies between 100xq and 1000xq eV [25]. Generally these cross sections depend only weakly on impact energy and increase almost linearly with q for $q \geq 3$, with the ion species being of minor influence for given q.

Cross sections for one-electron capture into particular subshells have been measured both for He^{2+} [26] and C^{4+} [27] in Li. For He^{2+} impact, data compare well with a number of recent calculations [28], while for C^{4+} impact, only one calculation is available [29] which, however, reproduces the main experimental findings reasonably well. With a view to application to plasma diagnostics, prominent emission cross sections have been measured for C^{q+} (q=3-6) and O^{q+} (q=4-7) in Li [30].

Measurements and calculations have recently been carried out for electron capture and Li excitation in H^+-Li collisions. Such data are of interest in view to Li beam attenuation and measurement of proton densities and temperatures in plasma edge regions. These are recent accurate data on total electron capture for impact energies between 0.25 and 4 keV [24] and between 2 and 20 keV [31], respectively. State-selective electron capture has been investigated into H(2p) and H(n=3) subshells, for impact energies between 2 and 20 keV [32]. In the same energy range, excitation of Li(2p) has been studied [32]. Calculations are also available for the H^+ - Li system [33].

Finally, it has been shown that electron capture from Li by multiply charged ions leaves the electronic configuration of the latter practically unchanged ("core conservation"). This remarkable feature could be utilized to determine metastable ion beam fractions for some Be-like and B-like ion species [34].

Cross sections for ionization (total electron and ion production) have been determined by Rudd et al [14] for 5-4000 keV protons in He, Ne, Ar, Kr, H_2, N_2, CO, O_2, CH_4 and CO_2 using the condenser plate technique. These appear to be the most accurate measurements of their type.

Cross sections for Balmer alpha and beta emission in collisions of H with H_2 and He have been determined in the range 50 eV - 2.5 keV by Van Zyl et al [16].

3. Collisions Between Positive Ions

Cross sections for the combined processes of charge transfer and ionization in collisions of H^+ with Tl^+, Ga^+ and Al^+ have been measured in Belfast for c.m. energies in the range 50-600 keV [35]. Experimental studies of charge transfer in ion-ion collisions have now commenced in the University of Giessen (Salzborn).

REFERENCES

[1] Second IAEA Research Coordination Meeting on Atomic Collision Data for Diagnostics of Magnetic Fusion Plasmas, Nagoya, 1983, - Reports of the Working Groups, Report INDC(NDS)-150, March (1984); Also 'International Bulletin on Atomic and Molecular Data for Fusion', No. 24, pp. 72-80 (1984).

[2] P. Tosi, S. Iannotta, D. Bassi, H. Villinger, W. Doble and W. Lindinger, J. Chem. Phys. 80, 1905 (1984).

[3] W. Federer, H. Villinger, F. Howorka, W. Lindinger, P. Tosi, D. Bassi and E. Ferguson, Phys. Rev. Lett., 52, 2084 (1984).

[4] M. Bendahman, S. Bliman, S. Dousson, D. Hitz, C. Harel, R. Gayet and A. Salin, Jour. de Phys. (Paris) - in course of publication.

[5] R.K. Janev and H. Winter, Physics Reports - in course of publication.

[6] R.W. McCullough, F.G. Wilkie and H.B. Gilbody, J. Phys. B 17, 1373 (1984).

[7] S. Bienstock, F.G. Heil, C. Bottcher and A. Dalgarno, Phys. Rev. A 25, 2850 (1982).

[8] V.V. Afrosimov, E.D. Donets, A.N. Zinov'ev, S.Y. Ovchinnikov and M.N. Panov, Pis'ma Zh. Ehksp. Teor. Fiz. 38, 70 (1983).

[9] T.A. Green, E.D. Shipsey and J.C. Browne, Phys. Rev A 25, 1364 (1982).

[10] W. Fritsch and C.D. Lin, Phys. Rev. A 29, 3039 (1984).

[11] L. Presnyakov and D. Uskov, Zh. Ehksp. Teor. Fiz. 86, 982 (1984).

[12] M.R.C. McDowell and R.K. Janev -

a) J. Phys. B 17, 2295 (1984) [Au^{q+} in He q = 5 - 25]

b) Phys. Lett. A, 1984, in course of publication [Scaling law for ions in He and He]

[13] O.G. Larsen and K. Taulbjerg, J. Phys. B - in course of publication.

[14] M.E. Rudd, R.D. DuBois, L.H. Toburen, C.A. Ratcliffe and T.V. Goffe, Phys. Rev A 28, 3244 (1983).

[15] D.S.F. Crothers and J.F. McCann, J. Phys. B 16, 3229 (1983).

[16] B. Van Zyl, M.W. Gealy and H. Neumann, Phys. Rev. A 28, 176 (1983).

[17] Yu S. Gordeev, D. Dijkkamp, A.C. Drentje and F.J. de Heer, Phys. Rev. Lett. 150, 1842 (1983).

[18] S. Bliman, J.J. Bonnet, A. Bordenave-Montesquieu, J. Desesquelles, M. Druetta, D. Hitz and M. Mayo, "Radiative decay following charge exchange at the AGRIPPA facility". Invited paper, Int. Conf. on the Physics of Highly Ionised Atoms, Oxford 2 July (1984).

[19] A. Bordenave-Montesquieu, P. Benoit-Cattin, A. Gleizes, A.I. Marrakchi, S. Dousson and D. Hitz, J. Phys. B 17, L127 (1984).

[20] A. Bordenave-Montesquieu, P. Benoit-Cattin, A. Gleizes, A.I. Marrakchi, S. Dousson and D. Hitz, J. Phys. B 17, L223 (1984).

[21[P. Roncin, M. Barat, H. Laurent, J. Pommier, S. Dousson and D. Hitz, J. Phys. B 17, L521 (1984).

[22] R.W. McCullough, T.V. Goffe, M.B. Shah, M. Lennon and H.B. Gilbody, J. Phys. B 15, 111 (1982).

[23] G.A. Murray, J. Stone, M. Mayo and T.J. Morgan, Phys. Rev. A 25, 1805 (1982).

[24] S.L. Varghese, W. Waggoner and C.L. Cocke, Phys. Rev. A 29, 2453 (1984).

[25] W. Waggoner, C.L. Cocke, S.L. Varghese and M. Stöckli, Phys. Rev. A 29, 2457 (1984).

[26] K. Kadota, D. Dijkkamp, R. Van der Woude, Pan Guang Yan and F.J. de Heer, Phys. Letts. 88A, 135 (1982).

[27] D. Dijkkamp, A. Brazuk, A.G. Drentje, F.J. de Heer and H. Winter, J. Phys. B 16, L343 (1983).

[28] A.M. Ermolaev and B.H. Bransden, J. Phys. B 17, 1083 (1984).

[29] W. Fritsch and C.D. Lin, J. Phys. B 17 (1984) in course of publication.

[30] A. Brazuk, H. Winter, D. Dijkkamp, A. Boellaard, F.J. de Heer and A.G. Drentje, Phys. Letters 101, 139 (1984).

[31] F. Aumayr and H. Winter, to be published.

[32] F. Aumayr, H.M. Fehringer and H. Winter, J. Phys. B 17 (1984) in print.

[33] A.M. Ermolaev, J. Phys. B 17, 1069 (1984).

[34] A. Brazuk, D. Dijkkamp, A.F. Drentje, F.J. de Heer and H. Winter, J. Phys. B 17, 2489 (1984).

[35] M.F. Watts, K.F. Dunn, G.C. Angel and H.B. Gilbody, to be published J. Phys. B.

[36] D. Ciric et al., to be published.

[37] D. Dijkkamp et al., to be published.

[38] Th.M. El Sherbini, A. Salop, E. Bloemen and F.J. de Heer, J. Phys. B 13, 1433 (1980).

[39] B. Huber et al., to be published.

[40] R.K. Janev and K. Katsonis, to be published in Nuclear Fusion.

[41] T. Iwai, Y. Kaneko, M. Kimura, N. Kobayashi, A. Matsumoto, S. Ohtani, K. Okuno, S. Takagi, H. Tawara and S. Tsurubuchi, J. Phys. B 17, L95 (1984).

[42] H. Tawara, T. Iwai, Y. Kaneko, M. Kimura, N. Kobayashi, A. Matsumoto, S. Ohtani, K. Okuno, S. Takagi and S. Tsurubuchi, J. Phys. B, in course of publication.

WORKING GROUP REPORT ON DIELECTRONIC RECOMBINATION (DR)

V.A. Abramov, G.H. Dunn (Chairman), S. Hayakawa, J.G. Hughes,
C.J. Joachain, M.S. Pindzola, E. Salzborn, W. Wiese

Both experimental and theoretical activity has been high in the last part of 1983 and first part of 1984. There remain questions about the completeness of our understanding of this process, and hence about the accuracy of data normally used for modelling. One may look for substantial progress in the next year or two, however, since the level of effort is high throughout the world, and since the synergism of experiment and theory is leading to new insights.

On the theoretical side, DR has been calculated in different ways. Griffin et al [1] have made distorted wave calculations for Li-like ions C^{3+}, B^{2+}, O^{5+} to test the effects of intermediate coupling; and they found an increase of about 50% compared to LS coupling. Geltman [2] made calculations based on a unified collision process and obtained results for B^{2+}, C^{3+}, Mg^{+} and Ca^{+} very close to the earlier LS coupled distorted wave calculations of Hahn [3-6] for these species. Hickman [7] has made a model calculation using quantum defect theory to study the effects of overlapping resonances in DR. Pradhan [8] has used a procedure based on quantum defect theory extrapolation of close-coupling calculation of excitation cross sections to make predictions of DR in C^{3+} and Mg^{+}, and again finds results within 50% of the other calculations.

Roszman [9] has continued his distorted wave calculations of total rate coefficients for ions of the lithium isoelectronic sequence. He computed rates numerically for selected ions (Ne^{+7}, Ar^{+15}, Fe^{+23}, Kr^{+33}) over a wide temperature range and developed interpolation formulae to produce data for other Li-sequence ions. Roszman and Weiss [10] have examined the effects of configuration mixing and found these to introduce significant changes in partial rates, but much less on the total rate. Roszman [9] has also studied plasma density effects and finds 20-30% changes for densities typical of Tokamak conditions. Density effects have been considered previously by Zhdanov [11] and by Jacobs et al [12].

Experimentaly, since the 1983 report [13], Dittner et al [14] have measured the cross section for Cl^{6+}. The data seem to indicate-much as the Ca^{+} data of Williams [15] - the need to understand better the DR process involving low quantum numbers n. Their work in progress to measure DR cross sections for Cl^{7+} should yield the first direct measurements for $\Delta n \neq 0$ for the core transition. Briand et al [16] observed dielectronic recombination resonances for $Ar^{12+, 13+, 14+, 15+}$ in an EBIS ion source. Though absolute rate cross section measurements were not obtained, the method may be promising for highly charged species if calibration methods can be worked out. Dunn et al [17] have begun measurements of cross section versus n, the principal quantum number of the product Rydberg state. Preliminary measurements indicate a variation with n much like that predicted by LaGattuta and Hahn [18] for an extrinsic field of 24 V/cm (the field in the experimental collision volume). Whether the effect is caused by fields remains to be seen.

From a user point of view, there seems to be little choice but to use the direct results of theory - which are becoming more readily available, but to do so recognizing substantial uncertainties which are being actively explored. In view of the activity in the field, this does not seem to be a good time to recommend specific data nor to have a comprehensive review of the area.

References

1. D.C. Griffin, M.S. Pindzola, C. Bottcher, Phys. Rev. A (submitted, 1984).
2. S. Geltman, submitted to J. Phys. B (1984).
3. K. LaGattuta and Y. Hahn, Phys. Rev. Lett. 50, 668 (1983).
4. K. LaGattuta and Y. Hahn, J. Phys. B 15, 2101 (1982).
5. D.J. McLaughlin and Y. Hahn, Phys. Rev. A 28, 493 (1983).
6. D.J. McLaughlin and Y. Hahn, Phys. Rev. A 27, 1389 (1983).
7. A.P. Hickman, J. Phys. B 17, L101 (1984).
8. A. Pradhan, private communication (1984).
9. L. Roszman, private communication (1984).
10. L. Roszman and A. Weiss, Jour. Quant. Spect. Rad. Transf. (1983).
11. V. Zhdanov, Fiz. Plazmy 9, 887 (1983); Fiz. Plazmy 5, 572 (1979).
12. A. Jacobs et al.
13. Second IAEA Research Coordination Meeting on Atomic Collision Data for Diagnostics of Magnetic Fusion Plasmas, Nagoya, 1983, - Reports of the Working Groups, Report INDC(NDS)-150, March (1984); Also 'International Bulletin on Atomic and Molecular Data for Fusion', No. 24, p. 81 (1984).
14. P.F. Dittner, Private communication (1984).
15. J.F. Williams, Phys. Rev. A 29, 2936 (1984).
16. J.P. Briand, P. Charles, J. Arianer, H. Laurent, C. Goldstein, J. Dubau, M. Loulergue and F. Bely-Dubau, Phys. Rev. Lett. 52, 617 (1984).
17. G.H. Dunn, D. Mueller, N. Djuric, C. Timmer, D. Belic, Private communication (1984).
18. K. LaGattuta and Y. Hahn, Phys. Rev. Lett. 51, 558 (1983).

III. APPENDICES

Appendix 1

Coordinated Research Programme (CRP) on Atomic Collision Data for Diagnostics of Magnetic Fusion Plasmas

Third Research Coordination Meeting
Vienna, 18 - 20 June 1984

LIST OF PARTICIPANTS

V. A. Abramov*	Institut Atomnoi Energii, I.V. Kurchatova, Ploshchad I.V. Kurchatova, Moscow D-182, 123182, USSR
F. Aumayr*	Institut fuer Allgemeine Physik, Technische Universitaet Wien, Karlsplatz 13, A-1040 Wien, Austria
C. F. Barnett*	Building 6003, Oak Ridge National Laboratory, P.O. Box X, Oak Ridge, Tennessee 37830, U.S.A.
O. Benka*	Institut fuer Experimentalphysik, Universitaet Linz, Austria
G. Betz*	Institut fuer Allgemeine Physik, Technische Universitaet Wien, Karlsplatz 13, A-1040 Wien, Austria
S. L. Bliman	Centre d'Etudes Nucléaires de Grenoble, 53 Avenue des Martyrs, B.P. No. 85, Centre de Tri, F-38041 Grenoble Cedex, France
B. H. Bransden	Professor of Theoretical Physics, Department of Physics, University of Durham, Science Laboratories, South Road, Durham DH1 3LE, U.K.
A. Brazuk*	Institut fuer Allgemeine Physik, Technische Universitaet Wien, Karlsplatz 13, A-1040 Wien, Austria
H. -W. Drawin*	Departement de Physique des Plasmas et de la Fusion Controlée, Association Euratom-CEA sur la Fusion Controlée, Centre d'Etudes Nucléaires, B.P. No. 6, F-92260 Fontenay-aux-Roses, France
G. H. Dunn	University of Colorado, J.I.L.A., Campus Box 440 Boulder, Colorado 80303, U.S.A.

M. Fehringer*	Institut fuer Allgemeine Physik, Technische Universitaet Wien, Karlsplatz 13, A-1040 Wien, Austria
H. B. Gilbody	The Queen's University of Belfast, Pure & Applied Physics, Belfast BT7 1NN, Northern Ireland, U.K.
S. Hayakawa*	Department of Astrophysics, Nagoya University, Chikusa-Ku, Nagoya 464, Japan
J. G. Hughes	Department of Computer Science, Queen's University of Belfast, Belfast BT7 1NN, Northern Ireland, U.K.
W. Husinsky*	Institut fuer Allgemeine Physik, Technische Universitaet Wien, Karlsplatz 13, A-1040 Wien, Austria
P. Hvelplund	University of Aarhus, Institute of Physics, DK-8000 Aarhus, Denmark
Y. Itikawa	Institute of Space and Astronautical Science, 4-6-1 Komaba, Meguro-ku, Tokyo 153, Japan
C. J. Joachain	Physique Theorique, Université Libre de Bruxelles, Code Postal 227, Boulevard du Triomphe, B-1050 Bruxelles, Belgium
K. Katsonis	(Scientific Secretary) Atomic & Molecular Data Unit, International Atomic Energy Agency, P.O.Box 100, A-1400, Vienna
W. Lindinger*	Institut fuer Experimentalphysik, Universitaet Innsbruck, Karl-Schoenherr-Strasse 3, A-6020 Innsbruck, Austria
A. Lorenz	Head, Atomic & Molecular Data Unit, International Atomic Energy Agency, P.O.Box 100, A-1400, Vienna
M. R. C. McDowell	Department of Applied Mathematics, Royal Holloway College, Egham Hill, Egham, Surrey TW20 OEX, U.K.
S. C. Mukherjee	Indian Association for the Cultivation of Science, Jadavpur, Calcutta 700032, India
Y. Nakai*	Nuclear Data Center, Japan Atomic Energy Research Institute (JAERI), Tokai-Mura, Naka-Gun, Ibaraki-Ken 319-11, Japan
M. S. Pindzola	Department of Physics, Auburn University, Auburn, Alabama 36849, U.S.A.
E. Salzborn	Institut fuer Kernphysik, Justus Liebig-Universitaet, Leihgesterner Weg 217, D-6300 Giessen, Germany
J. J. Schmidt	Head, Nuclear Data Section, International Atomic Energy Agency, Wagramerstrasse 5, P.O. Box 100, A-1400, Vienna

H. Stoeri*	Institut fuer Allgemeine Physik, Technische Universitaet Wien, Karlsplatz 13, A-1040 Wien, Austria
H. Tawara*	Research Information Centre, Institute for Plasma Physics, Nagoya University, Nagoya 464, Japan
W. Vanek*	Institut fuer Allgemeine Physik, Technische Universitaet Wien, Karlsplatz 13, A-1040 Wien, Austria
P. Varga*	Institut fuer Allgemeine Physik, Technische Universitaet Wien, Karlsplatz 13, A-1040 Wien, Austria
W. L. Wiese*	Institute of Basic Standards, National Bureau of Standards, US Department of Commerce, Washington, D.C. 20234, U.S.A.
H. Winter	Institut fuer Allgemeine Physik, Technische Universitaet Wien, Karlsplatz 13, A-1040 Wien, Austria
U. Wutte*	Institut fuer Allgemeine Physik, Technische Universitaet Wien, Karlsplatz 13, A-1040 Wien, Austria

N.B. Names of invited observers are marked with an asterisk.

Appendix 2

Coordinated Research Programme (CRP) on Atomic Collision Data for Diagnostics of Magnetic Fusion Plasmas

Third Research Coordination Meeting
Vienna, 18 - 20 June 1984

ADOPTED AGENDA

1. Opening Statements and Announcements

    1.1. Opening of meeting (9:30 hrs)
    1.2. Appointment of chairmen of working groups
    1.3. Adoption of agenda
    1.4. Announcements

2. Progress reports by CRP participants on their work

3. Reports on related work in progress in laboratories not included in CRP

4. Review of the status of the existing required A+M Data, their accuracy and completeness by the following working groups:

    - Electron Impact Excitation
    - Electron Impact Ionisation
    - Charge Exchange and Related Processes
    - Dielectronic Recombination

5. Writing of working group reports

6. Reports of the working groups on the conclusions on the current status and availability of the required data

7. Summary of Conclusions

8. Next Meeting