ATOMIC DATA FOR THE ANALYSIS OF EMISSION LINES[1]

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Abstract

Within the last decade or so new atomic data has become available for most atomic systems of interest in astrophysics. Recent progress in atomic processes relevant to spectral formation is reviewed and the data sources are listed. Recommended transition probabilities and effective collision strengths are presented for a number of nebular emission lines.

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1. Introduction

In a pioneering study on the electron impact excitation of atomic oxygen, Seaton (1953) formulated the now well known close-coupling approximation of atomic collision theory, which he termed the "continuum state Hartree-Fock method", reflecting the physical picture that the new method was an extension of the bound state method to the continuum region that encompassed electron-ion scattering and photoionization phenomena. For nearly three decades, the close coupling approximation has been widely employed to calculate the most accurate low-energy cross sections for excitation and photoionization, and radiative transition probabilities. Large computational packages were developed, mainly at University College London and the Queen's University of Belfast, to carry out the enormous task of fulfilling the needs of astrophysicists and plasma physicists. In particular, the R-matrix method developed by Burke and associates (Burke *et al.* 1971) has proved to be computationally very efficient for large-scale calculations.

A huge amount of radiative atomic data was produced, during last 10 years or so, under the auspices of an international collaboration of atomic physicists and astrophysicists, called the Opacity Project, led by Seaton (Seaton *et al.* 1994). Photoionization cross sections and oscillator strengths were calculated using the R-matrix method (Seaton 1987, Berrington *et al.* 1987) for almost all astrophysically abundant elements in various ionization stages. The calculations were carried out for LS multiplets; fine structure was not considered as it is relatively less important for the calculation of stellar opacities, which was the express aim of the Project. Recently, employing the basic tecniques of the Opacity Project and new developments incorporating relativistic effects into the R-matrix method, a new project called the Iron Project has been initiated (Hummer *et al.* 1993) that aims to compute accurate cross sections for electron impact excitation of most astrophysical ions including fine structure. The main aim of the Iron Project is the calculation of precise atomic data for the Iron group elements that are astrophysically very important but for which little reliable data is presently available. Thus the Opacity Project and the Iron Project are now providing much of the atomic data needed by astronomers.

This report consists of a review of data sources for:

• Electron impact excitaton • Photoionization • Radiative transition probabilities • Electron-ion recombination

For completeness, data sources are also given for line broadening, recombination lines, electron impact ionization, charge exchange, proton impact excitation, isotopic and hyperfine structure, and energy levels and wavelengths. With the exception of energy levels, very little of the data is experimental; we confine ourselves mainly to a discussion of the theoretical data. A general bibliography for most of these atomic processes has been presented by Butler (1993). More up-to-date data and information on the Opacity Project, the Iron Project, and related work may be obtained from the Website: http://www.astronomy.ohio-state.edu/∼pradhan.

The prominent spectral lines in nebular astrophysics are mostly due to forbidden transition among low-lying levels of atomic ions. In an attempt to update and extend the extremely useful compilation by Mendoza (1983) more than a decade ago, recommended data for electron impact excitation and transition probabilities for emission lines in AGN's, nebulae and other sources are tabulated.

2. Theoretical considerations

Electron-ion interactions may be depicted by the following diagram:

Figure 1: Inter-related radiative and collisional atomic processes: EIE - electron impact excitation, AI - autoionization, DR - dielectronic recombination, PI - photoionization, RR - radiative recombination

Quantum mechanically *all* of the atomic processes shown may be treated by a wavefunction expansion that represents the total e+ion system in terms of the coupled eigenfunctions of the "target" or the "core" states of the ion, i.e.

$$\Psi(E) = A \sum_i \chi_i \theta_i + \sum_j c_j \Phi_j, \tag{1}$$

where χ_i is the target ion wave function in a specific state S_i L_i and θ_i is the wave function for the free electron in a channel labeled as $S_i L_i k_i^2 \ell_i (SL\pi)$; k_i^2 being its incident kinetic energy. While the close coupling approximation (e.g. the R-matrix method) includes coupling between the target states of the ion, simpler approximations such as the distorted wave or the central field approximations neglect the coupling effects which may be important at low energies.

One particularly important coupling effect manifests itself as autoionizing resonances, from doubly-excited states of the e+ion system (the center of the Fig. 1), that can substantially enhance the cross sections and rates for excitation, photoionization and recombination. The near threshold region of the cross sections, that dominates the rate of electron excitation and line formation for forbidden and intercombination transitions, may be particularly affected by broad and extensive resonance structures. Dipole allowed transitions are less affected. In general therefore it is necessary to employ the accurate close coupling approximation for the forbidden and the intercombination lines, but for the dipole allowed transitions the distorted wave approximation often suffices to obtain rates to 10-30% uncertainty.

A brief discussion of a few points related to the atomic processes is given below.

2.1. Electron impact excitation

The quantity usually computed for electron impact excitation is denoted as $\Omega(i,j)$, which was introduced by Hebb and Menzel (1940) and later termed the "collision strength" by Seaton, in analogy with the line strength for radiative transitions. The Ω is dimensionless and symmetric with respect to initial and final states. It is related to the cross section as

$$Q(i,j;k_i^2) = \frac{\Omega(i,j)}{k_i^2 g_i}(\pi a_o^2), \tag{2}$$

in units of the area of the H atom.

The usually tabulated quantity is the maxwellian averaged collision strength, also called the effective collision strength,

$$\Upsilon(i,j) = \int_0^\infty \Omega(i,j) exp(\frac{-\epsilon}{kT}) d(\frac{\epsilon}{kT}). \tag{3}$$

The excitation rate coefficient, in cm^{3}sec^{-1}, is defined as

Figure 2: Collision strength for the forbidden transition $^6D_{9/2} - ^6D_{7/2}$ in Fe II (Pradhan and Zhang 1993). The $\Upsilon(T)$, at T = 10,000 K, using the close coupling collision strengths shown in Fig. 2 is approximately a factor of three higher than the one calculated using the distorted wave values (diamonds) calculated by Nussbaumer and Storey (1980).

$$q(i,j) = \frac{8.63 \times 10^{-6}}{g_i T^{1/2}} \Upsilon(i,j) exp(\frac{-\Delta E_{ij}}{kT}), \tag{4}$$

related to the de-excitation rate coefficient ($E_i < E_j$) as

$$q(j,i) = \frac{g_j}{g_i} q(i,j). \tag{5}$$

The influence of autoionizing resonances may be seen in Fig. 2.

A detailed discussion on the analysis of collision strengths and rate coefficients is given by Burgess and Tully (1992), who describe analytic fitting procedures to $\Omega(E)$ and $\Upsilon(T)$ for interpolation and extrapolation in a compact form for the different types of transitions.

2.2. Photoionization cross sections

The availability of a very large number of photoionization cross sections from the Opacity Project is likely to influence considerably the modeling of radiative and collisional plasmas. There are two main features of these data: (i) inclusion of autoionizing resonances in the near-threshold region, (ii) cross sections for many excited states, typically several hundred bound states for each atom or ion. Prior to the Opacity Project, such data was available mainly for the ground states of relatively few ions, and the excited states were treated in either the hydrogenic approximation or with some Coulomb screening (such as in the quantum defect method).

Fig. 3 shows the photoionization cross section of a complex system, Fe II, illustrating the effect of resonances and the covergence of the close coupling wavefunction expansion. A total of 83 states of the core ion Fe III were included in the R-matrix (Nahar and pradhan 1994a). In comparison, the central field calculations of Reilman and Manson (1979) underestimate the cross sections by several factors in the near threshold region, although at higher energy the discrepancy is relatively small. Comparison is also made with previous R-matrix calculations of Sawey and Berrington (1992) whose wavefunction expansion had not converged as it did not include the channels that contribute to the phtoionization of the dominant 3d shell; consequently their values are up to two orders of magnitude lower.

Another important effect in photoionization, first described by Yu and Seaton (1987), is the formation of large resonances due to photoexcitation-of-core (PEC). The PEC resonances appear most strongly in the photoionization of excited bound states along a Rydberg series, characterized by a core ion state and a Rydberg electron, i.e. $(S_cL_c)n\ell$. At incident photon frequencies corresponding to dipole core transitions a doubly excited autoionizing state is formed, resulting in a large resonance. Fig. 4 illustrates the magnitude of PEC resonances in the photoionization of two excited Rydberg states of Fe III (Nahar, private communication).

We have

Figure 3: Photoionization cross section of the ground state $3d^6 4s(^6D)$ of Fe II (Nahar and Pradhan 1994a); filles circles - Reilman and Manson (1979); dashed line - Sawey and Berrington (1992).

Figure 4: Large resonances in photoionization cross sections due to photoexcitation-of-core (PEC). The arrow denotes the peak position of the PEC resonance, at the energy of the dipole transition $3d^5(^6S) \rightarrow 3d^4 4p(^6P^o)$ in the core ion S IV.

$$h\nu + Fe\ III \longrightarrow e^- + Fe\ IV$$

$$h\nu + 3d^5(^6S)ns[^7S] \longrightarrow 3d^4 4p(^6P^o)ns[^7P^o]$$

The dipole transition $^6S \rightarrow ^6P^o$ between the Fe IV core states is responsible for the PEC resonance, while the Rydberg electron essentially remains a "spectator" owing to the weak interaction with the core states (the process is basically the same as in di-electronic recombination). The PEC resonances attenuate the photoionization cross sections by orders of magnitude, and the cross sections for apparently hydrogenic excited states deviate substantially from what may otherwise by a hydrogenic background.

2.3. Electron-ion recombination

Recombination rates are usually calculated for two processes, radiative recombination (RR) and di-electronic recombination (DR), and summed together to obtain the total. It is assumed that the RR values are derived from photoionization cross sections for the "background" cross sections (i.e. without autoionizing resonances), and the DR values correspond to the contribution from resonances as they converge to excited states of the recombining ion, at electron temperatures sufficiently high to affect excitation of the ion states. The rates for RR and DR are calculated separately, the former using "background", resonance-free photoionization cross sections obtained via approximations such as the Central Field (e.g. Reilman and Manson 1979), and the latter using the Burgess (1965) General Formula, or more recent works by Jacobs *et al.* (1977 onwards) and others (references are given later).

However the two processes, RR and DR, are in principle unified. With the availability of the Opacity Project photoionization cross sections, including resonances, it might at first appear that a straightforward integration over the photoionization cross sections, using the Milne relation (Osterbrock 1989), should yield the effective (e+ion) recombination rate coefficients. However, a careful consideration shows that the treatment is rather difficult and laborious. For example, low-lying resonances close to ionization threshold may significantly enhance the recombination rate, i.e. low-temperature DR first discussed by Nussbaumer and Storey (1983). A unified approach to electron-ion recombination has been developed by Nahar and Pradhan (1992,1994b), that subsumes both RR and DR processes in an *ab initio* manner within the framework of the close coupling approximation, thus extending excitation and photoionization calculations to recombination. The method has been applied to a number of ions. Fig. 5 shows the total electron-ion recombination rate

Figure 5: Total electron-ion recombination rate coefficients for C-like ions (Nahar and Pradhan 1994b).

coefficient $\alpha_R(T)$ for recombination to several ions in the carbon isoelectronic sequence. Results in Fig. 5 are illustrative; numerical data – unified recombination rates - for over 40 atoms and ions may be obtained from the first author (references at: http://www.astronomy.ohio-state.edu/~pradhan).

Owing to the paucity of atomic data, ionization balance calculations have heretofore employed radiative and collisional data that is inconsistent in the sense that different physical approximations are used to calculate all the data. With the new Opacity Project data, and ongoing recombination calculations, it is now possible to redress the situation in the case of radiative ionization, using photoionization and recombination rates that are self-consistent.

During the previous decade, experimental measurements of DR cross sections for some ions showed large enhancements due to weak, external electric fields. Theoretical works indicate that while for neutral atoms the enhancement could be several factors, the effect is much smaller for mutiply charged ions due to stronger intrinsic Coulomb field. Badnell *et al.* (1993) discuss the problem and find that the maximum field enhancement for C IV is about 40%. Further work is needed to determine the precise extent of the influence of plasma microfields on DR.

3. General Databases and Centers

Compilation and evaluation of atomic data is carried out at several locations listed below. Apart from astronomy, perhaps the largest user of atomic data is the nuclear fusion community which is served by some of these data centers.

• The Controlled Fusion Atomic Data Center at Oak Ridge National Laboratory; data include electron impact ionization and charge transfer cross sections and rates and analytic fits thereof.

• National Institute of Fusion Science, Nagoya, Japan; data includes fits to excitation, ionization and charge transfer rate coefficients.

• International Atomic Energy Agency, Vienna, Austria; database includes excitation, ionization and charge exchange data. Janev *et al.* (1988,1989) and Janev (1992) describe the atomic and molecular database relevant to fusion, which is obtainable in the ALADDIN database system (Hulse 1990). Limited data is available for electron and neutral H collisions with H and $H, He^{q+}, Li^{q+}, Be^{q+}, B^{q+}, C^{q+}, O^{q+}, Si^{q+}, Ti^{q+}, Fe^{q+}, Cr^{q+}, Ni^{q+}, Mo^{q+}, W^{q+}$ ions, and with $H_2, H_2^+, CH_4, CH_4^+, C_mH_n, C_mH_n^+, O_2, O_2^+, CO, CO^+, H_2O, H_2O^+$ molecules (Phaneuf 1993).

• The wavelengths and energy levels continue to be provided by the National Institute for Standards and Technology, Gaithersburg, Maryland. An electronic database is in preparation and can be accessed on Internet (IP: atm.phy.nist.gov; username: asd).

• TOPBASE: This is the most extensive electronic database containing radiative data, oscillator strengths and photoionization cross sections, from the Opacity Project (Seaton *et al.* 1994; Cunto *et al.* 1993).

The latest version 0.7 of TOPBASE may be accessed from two nodes:

▷ Centre de Donnees Astronomique de Strasbourg (CDS);

IP: 130.79.128.5, login: topbase, pw: Seaton+

The WWW interactive version is now available from NASA Goddard,
http://heasarc.gsfc.nasa.gov/topbase/topbase.html, or from
http://www.astronomy.ohio-state.edu/∼pradhan.

Some of the TOPBASE data is being upgraded through new calculations by the Iron Project, in particular for the important low ionization stages of Iron (Fe I - V). The photoionization cross sections obtained using the low energy close coupling approximation with the R-matrix method, and incorporated in TOPBASE, are of high accuracy in the important near-threshold region containing the extensive autoionizing resonance structures. However, in the high energy region the cross sections are often inaccurate owing to the presence of pseudo resonances. Thus the TOPBASE photoionization cross sections were fitted to a simple ν^{-3} "tail" above all thresholds of ionization included in the close coupling calculations; these are not reliable for applications that need such data (e.g. X-ray opacities that involve inner-shell ionizations). A new effort is under way to improve the high energy "tails" of the photoionization cross sections and will be incorporated into TOPBASE in due course.

Further extensions of TOPBASE are also planned to include collisional data from the Iron Project (TIPBASE), as well as data for electron-ion recombination rate coefficients.

4. Data Sources

This section gives published references with some discussion.

4.1. Electron impact excitation

There are three recent compilations of data sources:

1. A special issue of *Atomic Data and Nuclear Data Tables* entitled "Electron Excitation Data for Analysis of Spectral Line Radiation from Infrared to X-ray Wavelengths: Reviews and Recommendations" (**57**, No.1/2, May/July 1994; Ed: James Lang), contains assessments of data, up to March 1992, along several isoelectronic and isonuclear sequences. The atomic systems (and reviewers) are: H and H-like (Callaway), He and He-like (Dubau), Li and Li-like (McWhirter), Be and Be-like (Berrington), B and B-like (Sampson, Zhang and Fontes), C and C-like (Monsignori Fossi and M. Landini), N and N-like (Kato), O-like (Lang and Summers), F-like (Bhatia), Si II - Si IV and S II - S IV (Dufton and Kingston), Fe II - Fe VIII (Pradhan), Fe IX - Fe XIV (Mason), Fe XV - Fe XVII (Badnell and Moores).

2. While reference 1. concentrates on recently computed data, nearly all of the previously available data sources in literature has been evaluated by Pradhan and Gallagher (At.Data.Nucl.Data.Tables, **52**, 227, 1992). A discussion of the various methods of atomic collision theory, and important atomic effects, is also given (copies are available from AKP).

3. The most recent review of excitation cross sections of Carbon, Oxygen, Iron and rare gas ions is by Tayal, Pradhan and Pindzola (in *Atomic and Molecular Processes in Magnetic Fusion Edge Plasmas*, Ed: R.K. Janev, Plenum 1995). The ions reviewed are: C II - C VI, O II - O VIII, Fe II - Fe VIII, Ar VII-VIII, and Kr VII.

Large-scale calculations, primarily for electron impact excitation, are in progress under the Iron Project. The results are being published in *Astronomy and Astrophysics, Supplement Series* (some in the main A&A journal). An up-to-date list of publications follows.

Atomic data from the IRON Project:

I. Goals and methods. D.G.Hummer, K.A.Berrington, W.Eissner, Anil K. Pradhan, H.E.Saraph, J.A.Tully, A&A 279, 298-309, 1993.
II. Effective collision strengths for infrared transitions in carbon-like ions. D.J.Lennon, V.M.Burke, A&A Suppl. Ser. 103, 273-277, 1994.
III. Rate coefficients for electron impact excitation of Boron-like ions: Ne VI, Mg VIII, Al IX, Si X, S X, Ar XIV, Ca XVI and Fe XXII, Hong Lin Zhang, Mark Graziani and Anil K. Pradhan, A&A 283, 319-330, 1994.
IV. Electron excitation of the ${}^2P^o_{3/2} - {}^2P^o_{1/2}$ fine structure transition in fluorine-like ions. H.E.Saraph, J.A.Tully, A&A Suppl. Ser. (in press).
V. Effective collision strengths for transitions in the ground configuration of oxygen-like ions. K.Butler, C.J.Zeippen, A&A Suppl. Ser. (in press).
VI. Collision strengths and rate coefficients for Fe II. Hong Lin Zhang and Anil K.Pradhan, A&A (in press).
VII. Radiative transition probabilities for Fe II. Sultana N. Nahar, A&A (in press).
VIII. Electron excitation of the $3d^4({}^5D_j)$ ground state fine structure transition in Ti-like ions V II, Cr III, Mn IV, Fe V, Co VI and Ni VII. K.A. Berrington, A&A Suppl. Ser. (submitted).
IX. Electron excitation of the ${}^2P^o_{3/2-1/2}$ fine structure transitions in chlorine-like ions from Ar II to Ni XII. J.C.Pelan and K.A.Berrington, A&A Suppl. Ser. (submitted).
X. Effective collision strengths for infrared transitions in silicon- and sulphur-like ions. M.E.Galavis, C.Mendoza and C.J.Zeippen, A&A Suppl. Ser. (submitted).
XI. The ${}^2P^o_{1/2-3/2}$ fine-structure lines of Ar VI, K VII and Ca VIII. H.E.Saraph and P.J.Storey, A&A Suppl. Ser. (submitted).

In addition to the Iron Project work there are some other recent calculations, also using the R-matrix method, for important astrophysical ions. Two of these are:

O II : McLaughlin and Bell (ApJS 1994, in press) have presented analytical fits to their earlier data for $\Upsilon(T)$ for the transitions between the 11 states $2p^3({}^4S^o, {}^2D^o, {}^2P^o), 2s2p^4({}^4P, {}^2D, {}^2S, {}^2P), 2p^34s({}^4P, {}^2D, {}^2S, {}^2P)$. Work on fine structure transitions is in progress.

S II : Cai and Pradhan (ApJS, **88**, 329, 1993) have presented $\Upsilon(T)$ for all 378 transitions between 28 fine structure levels of the 12 lowest LS terms $3p^3({}^4S^o, {}^2D^o, {}^2P^o), 3s3p^2({}^4P, {}^2D, {}^2S), 3p^23d({}^2P, {}^4F, {}^4D, {}^2F0, 3p^24s({}^4P, {}^2P)$.

These works update previous data for the optical and the UV lines of O II and S II, with some significant changes. For example the rate coefficient for the S II $\lambda1256$ UV multiplet $3p^3({}^4S^o)_{3/2} \rightarrow 3s3p^4({}^4P_{1/2,3/2,5/2})$, observed by the Hopkins Ultraviolet Telescope in the Io torus, is calculated by Cai and Pradhan to be nearly a factor of two lower than the ealier results of Ho and Henry (1990), bringing the observed intensity and abundance in better agreement with observations.

4.2. Radiative transition probabilities

A general bibliography of forbidden transitions was prepared by Biemont and Zeippen, in proceedings of the Meudon Atomic Data Workshop (1989) published in Journal de Physique, Vol.1, Coll.1, Suppl. II, No. 3, 1991 (Ed: C.J. Zeippen and M. LeDourneuf). This volume (hereafter referred to as ZLD) also contains a review by Wiese.

Several evaluated compilations, including the data, are:

1. "Forbidden lines in ns^2np^k ground configuration and nsnp excited configurations of Beryllium through Molybdenum atoms and ions", Victor Kaufman and Jack Sugar , *J. Phys. Chem. Ref. Data*, **15**, 321 (1986). This work is complemented by additional compilations in *J. Phys. Chem. Ref. Data* **16** Suppl. 3, and **17** Suppl. 4, by J.R. Fuhr, W.C. Martin and W.L. Wiese.

2. "Atomic transition probabilities", J. Fuhr and W. Wiese in the *CRC Handbook of Chemistry and Physics, 71st Edition*, 1990. This is a critical compilation including both forbidden and allowed lines.

3. "Atomic data for resonance absorption lines I. wavelengths longward of the Lyman limit", D.C. Morton, ApJSupp, **77**, 119 (1991).

4. TOPBASE contains a large number of oscillator strengths (A-values may also be obtained) for *dipole* transitions between LS multiplets for all isoelectronic sequences up to Si-like ions, with Z $\leq$ 26. The TOPBASE data is with calculated (not observed) wavelengths, and does not include fine structure components within the multiplets. Future revisions of TOPBASE intend to include such data.

Some of the Opacity Project data has been extended to incorporate fine structure through algebraic transformation, from LS multiplet to LSJ components, and using experimentally observed energy levels: Si I, S III, Ar V and Ca VII (Nahar 1993) and Fe II (Nahar 1994); the Fe II data includes 21,587 fine structure transitions. Another calculation using the R-matrix method is by Bell *et al.* (1994, ApJS in press) for 26 dipole fine structure transitions in O II.

An updated version of the old NBS tables is in preparation at the National Institute for Standards and Technology (NIST). This is an evaluated compilation with some data from experiments and other sources, but primarily incorporating the Opacity Project data for some of the light elements (with fine structure included as in Nahar's work). The preliminary reference is: "Atomic Transition Probabilities of Carbon, Nitrogen, and Oxygen - A Critical Data Compilation", W.L. Wiese, J.R. Fuhr, and T.M. Deters, Monograph Series of *J. Phys. Chem. Ref. Data*, 1995.

Experimental measurements are relatively few. Among the recent works are the intersystem A-values measured by the Harvard-Nevada groups for several ions (Smith and Parkinson, paper presented at this meeting); dipole transitions in Si I and Fe II using the laser resonance-fluorescence method (e.g. O'Brian and Lawler 1991), and for dipole allowed transitions in O II, O III and other ions using Beam-Foil spectroscopy (Engström 1993). The experimental techniques employed by these groups are highly accurate, with uncertainties within a few percent for lifetimes and A-values.

4.3. Photoionization cross sections

A comprehensive bibliography has been compiled by LeDourneuf (ZLD, 1991). General data sources are as follows.

1. TOPBASE provides detailed photoionization cross sections for Z = 1-14 isoelectronic sequences up to Iron. As mentioned above, these cross sections may not be accurate in the high energy, non-resonant region where they have been fitted to a simple analytic form that does not correspond to actual photoionization calculations. The photoionization data for some of the heavier elements in low ionization stages (e.g. Fe I - V) is being updated, as the older data is not accurate (users are advised to check the NEWS file).

2. "Subshell photoionization cross sections and ionization energies of atoms and ions from He to Zn", have been computed by Verner *et al.* (1993) using the Hartee-Dirac-Slater method, analogous to the central field calculations but including some relativistic effects. Ground state photoionization cross sections are tabulated in analytic form up to high energies, E $\leq$ 50 kev, including inner-shell ionization edges.

3. “Analytic fits for partial photoionization cross sections”, by Verner and Yakovlev (1994, A&A in press), gives partial cross sections for the ground state shells of all atoms from H to Zn up to 100 kev.

4. “Photoabsorption cross sections for positive atomic ions with Z $\leq$ 30”, by Reilman and Manson (1979) are obtained through Hartree-Slater central-field calculations. These include only the ground state data and do not include autoionizing resonances, or coupling effects, and consequently are not generally accurate in the low energy region of photoionization. However, at high energies and for multiply charged ions these data reproduce well the background cross sections, compared to TOPBASE or other R-matrix calculations.

5. “X-ray interactions: photoionization, scattering, transmission, and reflection at E = 50-30,000 eV, Z = 1-92”, by Henke *et al.* (1993) describes the absorption and scattering of X-rays in terms of atomic scattering factors calculated from photoabsorption cross sections (both of which are tabulated). This work should be useful in applications involving high energy photoabsorption.

For astrophysical applications, a combination of 1. and 2. is recommended, for low and high energies respectively, until more accurate calculations are completed in the high energy range and incorporated into TOPBASE.

6. H-ions: A computer program for analytic calculations for H-like ions has been written by Storey and Hummer (1991).

7. Photoionization of heavy atomic systems is discussed by Kelly (1990).

4.4. Electron-ion recombination

General reviews are:

1. “Electron-ion recombination”, Flannery (1993).

2. “Di-electronic recombination and related resonance processes”, Hahn and Lagattuta (1988).

Scaling laws for DR are discussed by McLauglin and Hahn (1991). References to works on RR and DR are given in the following recent papers.

3. Analytic fits to RR rates: Pequignot *et al.* (1991).

4. Ionization balance calculations with references to previous collisional ionization and RR and DR rates: Arnaud and Rothenflug (1985) and Arnaud and Raymond (1992).

5. More recent works on DR rates are: C IV (Badnell *et al.* 1993), C V (Kilgus *et al.* 1993), O II (Badnell 1992), $S^{q+}(q = 1 - 5)$ (Badnell 1991). The influence of external electric fields on DR is discussed in the work on C IV.

6. Unified, total rate coefficients are being calculated by Nahar and Pradhan, and are available for carbon-sequence ions: C I, N II, O III, F IV, Ne V, Mg VII, Si IX, S XI, and for C II, S I, S II, S III and Si I, SI II, SI III. These recombination rate coefficients incorporate both the RR and the DR processes in a unified manner and are consistent with the Opacity Project photoionization cross sections.

4.5. Recombination Lines

The Hydrogen recombination lines are covered thoroughly by Hummer and Storey (1987) and Storey and Hummer (1988), including dust opacity (Hummer and Storey 1992).

The Helium lines have recently been computed by Smits (1991), with references to previous work by Brocklehurst and others (see also, Osterbrock 1989).

Recent work on recombination lines of O II by Storey (1994) and Liu *et al.* (1994) extends the treatment to complex ions, based on new Opacity Project data.

4.6. Electron impact ionization

The availabilility of ion accelerators and storage rings have vastly increased the ability to measure ionization cross sections (e.g. Mueller *et al.* 1985, Müller *et al.* 1991). But although there have been a much larger number of experiments for ionization than for electron impact excitation, most of the atomic systems, and their ions, have not yet been measured. Much of the experimental work has been carried out at Oak Ridge National Laboratory and the measured cross sections have been compiled in a recent work "Electron-Impact Ionization of Multicharged Ions at ORNL: 1985-1992" by D.C.Gregory and M.E.Bannister (1994, ORNL/TM-12729). The experimental data have clearly established the importance of excitation-autoionization (E-A) resonances that can enhance the cross section by orders of magnitude above the background. Theoretical calculations are now carried out for both the direct ionization and the E-A processes. Recent work includes the important iron isonuclear sequence (Pindzola *et al.* 1987), used by Arnaud and Raymond (1992) in their ionization balance calculations for Iron. Following are general references to available data (see also references in Arnaud and Rothenflug 1985).

1. Critical reviews are by Lennon *et al.* (1988), Itikawa (1992), Tawara and Kato (1987).
2. Limited data for excited state ionization is given by Golden and Sampson (1980).
3. Hydrogen and Helium ionization is considered by Jones *et al.* (1991).

4.7. Line broadening

The most recent compilation is the "Bibliography on Atomic Line Shapes and Shifts" by J.R.Fuhr and A.Lesage (NIST Special Publication 366, Supplement 4, 1993), including extensive literature references.

As part of the Opacity Project, Seaton (1987, 1988, 1989, 1990) has developed widely applicable approximations to hydrogenic and non-hydrogenic systems, the former including Stark plus electron impact broadening, and the latter with electon impact.

A general disucssion is given by Dimitrijević and Konjević (1987).

4.8. Charge Exchange

1. A recent, exhaustive compilation, "Bibliography on electron transfer processes in Ion-Ion/Atom-Molecule collisions" by H. Tawara (1993), is available from the Research Information Center, National Institute for Fusion Science, Nagoya 464-01, Japan.

While the above reference includes charge exchange data sources for a variety of atomic and molecular species as reactants, most of the following references are for charge exchange between H and positive ions.

2. General references are: Dalgarno (1985), Butler and Dalgarno (1980).
3. A computer program LZRATE has been published by Bienstock (1983).

4. Butler, Heil and Dalgarno (1980) have presented data for C II, C III, C IV, N III, N IV, O III, O IV, Ne III, Ne IV.
5. H I and He II data is given by Jackson *et al.* (1992), H I data by Jouin and Harel (1991), Errea *et al.* (1992), and He I data by Slim *et al.* (1991) .
6. Other works are: O VI (Andersson *et al.* 1991), Al III (Gargaud *et al.* 1990), Si II (Gargaud *et al.* 1982), Si III (McCaroll *et al.* 1976), Si V (Opradolce *et al.* 1985), Ar VII (Opradolce *et al.* 1983).
Detailed quantum mechanical calculations, as in these papers, are difficult to carry out. Approximate Landau-Zener rate coefficients may be obtained relatively simply and are given for some Al and Ca ions by Kingdon *et al.* (1995).

4.9. Proton Impact Excitation

In another pioneering paper, Seaton (1955) pointed out the importance of proton impact excitation for transitions at temperarures where $\Delta E/kT << 1$, e.g. the 2s-2p transition in H (and other Rydberg transitions) at nebular temperatures. Even for highly charged ions, fine structure transitions may be driven to a considerable extent by proton scattering at high temperatures, such as the excitation of coronal lines $Fe^{+13}3p_{1/2-3/2}$ (Seaton 1964). A number of studies have since been carried out and it has been demonstrated by semi-classical and quantum mechanical calculations that proton impact excitation may contribute significantly to the formation of spectral lines due to transitions between closely spaced levels (Dalgarno 1983). A review by Walling and Weisheit (1988) given many references to the relevant data on ion-ion excitation.

4.10. Hyperfine Structure and Isotopic Data

Kurucz (1993) has reviewed isotopic data for nearly all naturally occuring elements. Asymmetries in emission line profiles due to hyperfine components and consequent errors in the determination of velocity fields and abundances are discussed.

Other effects, such as Doppler shifts, and scaling laws are discussed by Hühnermann (1993).

5. Effective collision strengths and A-values

In addition to the up-to-date data sources described above, it is of some interest to have the basic collisional and radiative data available for a limited number of atomic transitions that give rise to nebular lines formed at low temperatures in optically thin plasmas. A widely used compilation of such data was provided by Mendoza (1983) over a decade ago. New data are now available for most of the transitions. Table 1 presents an updated and extended dataset of maxwellian averaged collision strengths, $\Upsilon(T)$, the Einstein A-values, and experimental wavelengths λ(Å). The Υ are tabulated at four temperatures: 5000, 10000, 15000 and 20000 K. In some instances the temperature dependent values are unavailable. The LS collision strengths may be subdivided into fine structure components in a straightforward manner according to the statistical weights if either S = 0 or L = 0 for one of the terms. This procedure is employed for available data where applicable. In Table 1 all data pertain to fine structure transitions; however, in cases where the fine structure collision strengths are not available the total LS multiplet value is listed under the FIRST fine structure transition within the multiplet, followed by blanks for the other transitions in the multiplet. Original references are marked as superscripts and should be quoted by users in literature.

The available atomic data for these and other ions far exceeds the data presented herein. Users should consult these when additional data is required. For instance, the $\Upsilon(T)$ for Fe II given in Table 1 is a very small subset of the data for 10,012 transitions for the IR, O, and UV transitions calculated by Zhang and Pradhan (1994). An even larger dataset is available for Fe III. We have concentrated only on low temperatures but the original references often contain additional data at higher temperatures and at a finer temperature mesh.

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