COMMITTEE 3: COLLISION CROSS SECTIONS AND LINE BROADENING

1. LINE BROADENING

Recent review articles have been published in four books dealing with atomic processes in astrophysical plasmas (**1**, **2**, **3**, **4**). A complete compilation of references will be available very soon (**5**). Information on the bibliography of papers on line broadening, relaxation processes and interaction potentials is provided by the Oak Ridge information centre (**6**).

1.1. *Collision broadening by neutral atoms.* There is now much experimental and theoretical evidence that the broadening due to collisions with light atoms like H and He does not arise from the Van der Waals interaction but from a shorter ranger interaction. This is true at low thermal temperature for experiments with He (**7**, **8**, **9**, **10**, **11**, **12**) and is *a fortiori* true at stellar temperatures for the broadening by H (**13**, **14**). This has been confirmed by recent detailed calculations (**15**, **16**). It is then necessary to know the interatomic potentials. Detailed calculations have been carried out for a few cases (**15**, **17**, **18**). In the case of the broadening of Na by He the agreement between recent calculations (**8**, **11**) and experiments – not yet published – is very good at low temperature. There is still an important disagreement with one experiment at high temperature (**22**). Emphasis is now put on the connection between the broadening mechanisms and other relaxation processes (see below 2.2) like fine structure transfer of excitation or depolarisation. Sensitivity of the results with respect to the interatomic potential and to the exact collisional processes is now under study (**11**, **16**). Non-adiabatic effects in the Van der Waals broadening have been studied (**21**). Calculations of the broadening of Lyman alpha in collisions with H atoms have been carried out in the quasi-static approximation using the accurate interaction potential (**19**). Measurements of line broadening in the extreme wings of spectral lines have been carried out (**20**).

1.2. *Line broadening by charged particles.* For non-hydrogenic lines the impact approximation is valid (**3**, **23**). Most of the calculations have been done using a semi-classical approach. Comparison between semi-classical calculations (**24**, **25**) in the case of Mg^+ and Ca^+ resonance lines with quantum calculations (**28**, **29**, **30**) and with experiments (**24**, **25**, **26**) shows that the semi-classical impact approximation gives good results. Quantum calculations have been done for hydrogenic neutral and ionized systems (**27**).

Many semi-classical calculations have been done recently for isolated lines in neutral and ionized atoms, for N II, C II, C IV, Si II, Si III, Si IV (**31**) for the singly charged ions Li through Ca (**32**), for N II and Ar II (**33**), for Si II and Si III (**34**), for Na (**35**), O I (**36**). Theoretical aspects of collision broadening of ionic lines have been studied (**37**, **39**, **23**). Experiments have been carried out for many non-hydrogenic lines: C II and N II (**40**), N II (**41**), Be II and Ba II (**42**), Si II (**43**), C IV (**44**). The He 4471 Å and its forbidden component have been subjected to further experimental and theoretical studies (**45**, **46**, **47**, **48**). Improvement in the agreement with experimental data is obtained when ion dynamic corrections are included (**44**, **50**, **51**, **52**).

1.3. *The broadening of hydrogenic lines.* In this case the usual impact approximation is not always valid for electrons. Good results can be obtained in many cases (H_β H_γ H_δ, H_6–H_{12}) when the impact approximation is corrected in an empirical way (using the Lewis cutoff instead of a Debye cutoff for large impact parameters) (**3**, **4**, **53**). For the Lyman lines and for H_α the agreement given by this improved impact approximation is not so good and for all lines there are serious discrepancies between theory and experiment near the line centre. This explains the need for a more complete theory, a 'unified' theory valid for the whole profile. More theoretical approaches have been developed (**54**, **55**, **56**, **57**, **58**, **59**, **60**). Many more articles discussing the validity of the 'unified' theories cannot be cited here.

Many experimental works and comparisons with accurate calculations have been carried out for Balmer lines broadened by electrons and protons, in particular for H_α, H_β, H_δ (**61**, **63**) and for high

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Balmer lines (H_6–H_{12}) (**62**) More accurate calculations are going to be published very soon (**3**). Additional references can be found in a recent very detailed study (**61**). New calculations using more refined data on the inelastic cross sections have been made for the radio frequency transitions in hydrogen (**64, 65, 66, 67, 68, 69**) and new measurements of n_α lines of ionized helium have been compared to theoretical calculations (**70**). Many more He II lines in the visible and ultraviolet region have been measured and provide a good test for theory (**71, 72, 73**). More theoretical work has been done on the coupling effects between the Doppler and the impact broadening (**74, 75, 76**).

2. COLLISION CROSS SECTIONS

In addition to the importance references given in the last IAU report (**77**) new general reviews have been published recently. Progress reports on many topics given to a recent international conference on atomic collisions (**78**) are available as well as complete abstracts of recent works (**79**).

Two volumes on case studies in atomic collision physics include many good review articles (**80, 81**), in particular one on interpretation of spectral intensities from laboratory and astrophysical plasmas and one on atomic processes in astrophysical plasma. A recent book on Molecules and Atoms in Astrophysics includes lectures on collision physics given at a summer school (**82**). A general course on atomic collision theory (**83**) and a book devoted to calculation methods of atomic collision processes (**84**) have been recently published.

Further bibliographies are also available (**6, 85, 86, 87**).

2.1. *Heavy particle collision at high energies.* A recent book (**88**) deals with excitation in heavy particle collisions. Impact parameter calculations have been made for excitation in the collision of two ground state H atoms (**89**) and have been extended to the problem of excitation and ionization of an excited H atom by H (**90, 91**). The Born approximation has been used for H+H collisions (**92**). Accurate calculations using the close coupling method have been used for excitation of the $n=2$, 3 levels of H by proton impact (**93**). The same processes have been studied using the Glauber approximation (**94, 95, 96**) and a distortion method (**97**).

Results have been obtained for excitation of the same H levels by α impact using the second Born approximation (**98**).

Quantum mechanical and classical methods commonly used to calculate cross sections for electron capture from atoms by charged nuclei are reviewed in a recent book (**99**) which gives many comparisons between experiments and available calculations at high and low impact energies. The close coupling method has been used for charge exchange in $H^+ + H$ (1*s*) collisions (**93**). The cross section for charge exchange in $H^- + H^+$ has been measured (**100**) and calculated (**101**).

Many more papers have been published on excitation and charge transfer in $H^+ + H$ collisions (**102, 103, 104, 105**), in $H^+ + He$ (**104**), in $He^+ + He$ (**106, 107, 108**). More references on proton and He^+ collisions with different atoms are given in (**99**) and (**6**).

Data and references on inner shell ionization and X-ray production by proton impact can be found in (**109**). The subject of X-ray production in heavy ion atom collisions has been reviewed recently (**110**).

2.2. *Heavy particle collision at low energies.* Recent progress have been made in the study of atom-atom and atom-ion collisions involving excitation transfer, spin exchange or depolarization at low energies (**111, 112**).

A recent review gives many references on the problem of transfer of excitation between fine structure levels by collision with rare gases (**113**). Further work has been done on excited alkali + He (**114, 115**).

Fine structure transitions by H collisions have been studied with semi-classical methods (**116, 117**), and by quantum mechanical methods (**118, 119**), for transition within the ground state level of C II. Collisions between C, N, O atoms and H are now under study (**118, 120, 121**). The cross section for fine structure transitions are calculated for collisions with protons (**122, 123**).

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Many recent papers deal with different processes of collisional relaxation of atomic levels, mainly with depolarization cross section of resonance radiation by atomic collisions (**124, 125, 126, 127, 128, 129, 132, 133**). Effects of collisional relaxation in connection with the interaction of atoms with polarized light have been reviewed (**130**) as well as the problem of spin states of atoms and molecules in the cosmic medium (**131**).

The effects of collisions on the redistribution of resonance radiation has been investigated (**134**).

The question of equilibrium of H^- has been discussed (**135**) in particular the importance of charge exchange $H^- + H^+$ for which the cross section has been measured (**136**) and calculated (**137**). More papers deal with excitation and charge exchange in atom-atom collisions at low energies (**138**). They are reviewed in a recent book (**99**). New theoretical (**139, 140, 141**) and experimental work (**143**) have been made on Penning ionization of H by metastable He.

Rotational excitation cross sections in H_2 by impact with H atoms (**142**) and with H_2 molecules (**144**) have been calculated.

Estimations of rate constants for reactions important for interstellar molecular formation are given in many papers on the physics of interstellar matter (**145, 146**). New works have been done to explain the formation of molecules like CH, CN, OH, rates of formation of CH and CH^+ by radiative association (**147, 148, 149**), of CH and CN (**150**) by inverse predissociation, of excited OH by collisional dissociation of water (**151, 152**). A few quantitative results exist on rotational excitation in molecule-molecule collisions in connection with the problem of eventual collision pumping in the interstellar medium (**153**). A new calculation has been done on excitation of formaldehyde by H_2 molecules (**154**). See also a recent review on excitation processes in H I regions (**155**).

An excellent review, not cited in the last IAU report, deals with the production of rotational and vibrational transitions in encounters between molecules (**156**). More recent references can be found in (**157**) and, in relation with applications in aeronomy and in planetary atmospheres, (**158**).

The problems of ion-molecule reactions in the energy range from thermal to hundred electron volts have been reviewed in a recent book (**159**).

The calculation of molecular wave functions and of potential curves and surfaces, their use in atom-atom collisions are discussed in a recent progress repprt (**160**).

2.3. *Electron collisions with molecules.* Three recent reviews have been published on low energy electron molecule scattering with emphasis on rotational excitation (**161, 162**) completed by (**163**). In the reviews, experiments and calculations are compared, the validity of the Born approximation is discussed for rotational excitation for N_2, N_2, O_2, CO_2. Discussions are given in (**161**) on problems relating to the resonant state $H_2{}^-$ in electron-H_2 collisions, including the production of H^- by dissociative attachment of H_2.

More details on the application of the adiabatic nuclei theory can be found in (**164, 165, 166**). The close coupling method is now applied to the problem of excitation of H_2 (**167, 168, 169**). The corresponding rotation and vibration cross sections have been measured by swarm technique (**170, 171**) and by electron beam method (**172**). Many more papers have been published on more complex molecules like CN (**173**), N_2 (**174, 175, 176**) CH and OH (**177**), CO and CN (**178**), HCl and CN (**179**). Rotational excitations of polyatomic molecules of astrophysical interest have been studied using the Born approximation in a series of papers (**181, 182, 183**). More recent references are given in (**157, 86**). A recent review (**180**) on dissociative recombination is available.

2.4. *Excitation and ionization of atoms by electron impact.* A general review on excitation and ionization by electron impact is now available (**184**). Emphasis on collisions with positive ions is given in a recent review (**185**) in relation with the interpretation of spectral line intensities in laboratory and astrophysical plasmas. References on experimental papers can be found in (**86, 87**). New review articles on theoretical methods have appeared (**186, 187**) and many recent papers deal with accurate computational methods of calculation (**188, 189, 190**). Two recent books have been published (**83, 84**), Approximate methods and interpolation formulae have been studied for calculating excitation and ionization rates (**191, 192, 193, 194**). More progress has been made for

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obtaining classical cross sections particularly for excitation and ionization of excited states (**195, 196, 197, 198**).

New accurate theoretical results have been obtained for excitation in H (**199, 200**), for Li (**202**), for Na (**203**), for different alkalis (**201, 204**), as well as new measurements of excitation cross sections in H (**205**), and in Li, Na and K (**206, 207, 208, 210**). A detailed paper deals with theoretical methods for excitation of hydrogenic ions (**211**). The Coulomb-Born or the distorted wave approximation is valid in many cases and has been applied for Ca II (**212**), for C III, N IV, O V (**213**) for the Li isoelectronic ions (**215**), for Si XII (**216**), for N V, Si XII, Fe XIII, Fe XV, Fe XVII (**217, 218**) and for C III (**190**). Measurements have been made of different cross sections in N V, O VI, Ne VIII (**219**), in N V (**220**), in N IV, O V, Ne VII, Si IX (**221**) Ar VIII (**222**), Ne VIII (**223**), and Ne VII (**225**). More references can be found in (**224**).

Cross sections for excitation of forbidden lines are available for C III (**190, 312, 226**) N IV and O V (**213**), for neutral O (**227, 228, 229**), for ions with ground configuration p^3 (**230**). References related to the cooling mechanism of interstellar matter can be found in (**155**) and (**231**).

Many recent works concern the recombination lines in H II regions and the methods of obtaining the intensities of these lines using correct atomic data in particular for the cross sections for transition between highly excited states (**232, 233, 234, 235, 236**). The cross sections are calculated using classical methods (**195, 196, 197**) or use of a binary encounter theory (**237, 238**). Results are discussed in three recent papers (**240, 197, 239**).

In addition to reference (**184**) additional information on atom or ion ionization by electron is available in a few progress reports (**241, 242, 243, 244, 245**). Emphasis has been given recently to ionization of positive ions; Li II and Mg II (**246**), Li II, Mg II, Na II, Mg III, K II (**248**), C II, N III, N II, O III, Ne II, Na II, Mg III (**249**), C II, N III, O IV (**251**). Experimental cross sections are available for C II, N III, O III, O II (**250**), N II, N III, Ne III, Ar II, Ar IV (**252**) Ne VIII (**253**). The inner shell ionization process of neutral atoms with outer $2p$, $3s$ and $3p$ electrons by electron and proton impact has been studied (**247**).

More work has been done on electron detachment in H^- (**255, 256, 257**). Useful information on negative ions and electron affinities can be found in a recent review (**254**) on photodetachment. Further work has been done on the theory of dielectronic recombination (**258, 259, 260**).

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HENRI VAN REGEMORTER
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COMMITTEE 4: STRUCTURE OF ATOMIC SPECTRA

An excellent review of the present state of the analysis and of future trends has been prepared by B. Edlén (**10**). He discusses the electronic structure of the ground configurations, "arranged in order of the total number of electrons, *N*, for the first half of the periodic system". "The intervals within the ground-configurations are of particular astrophysical significance. The *Z*-dependence of these intervals can be expressed with remarkable accuracy by quite simple relations." He points out that the electrostatic term intervals, which account for the forbidden nebular lines, have a linear *Z*-dependence, while the spin-orbit intervals, increasing with the fourth power of *Z*, explain some of the forbidden lines in the solar corona.

More work needs to be done on the third and fourth spectra in the iron group to meet the needs of astronomers, but progress is being made with selected spectra in this group.

This review contains a current bibliography and an appraisal of the present state of analysis of individual spectra arranged by sequences. The spectra on which "work is in progress" are also indicated. He is preparing a similar report on spectra of the elements of the second half of the Periodic Table ($Z > 30$).

Current work on atomic spectra has been reported from several laboratories. At the Institute of Physics in Lund, B. Edlén lists the following spectra as being investigated: Be III, O II, F IV, F V, F VI, P III, P IV, P V, S II, K IX, Ca X, Sc II, Sc IV, Sc V, Ti III, Ti IV, Ti XII, V V, V VI, Fe IV.

At the Lund Institute of Technology, L. Minnhagen and his associates have work in progress on O III, Mg III, Mg IV, Ar I, K II, Sr III, Sr IV, Ba III, Ba IV.

R. D. Cowan has noted several references to investigations of highly-ionized spectra of V, Cr, Mn and Ni, and their significance in the interpretation of lines observed in the far ultraviolet solar spectrum and in solar flares (**5, 7, 8**).

W. R. S. Garton and his colleagues have continued their work in the short-wave region. They have observed Rydberg series and autoionization resonances in the adsorption spectra of alkali and alkaline-earth atoms.

An annual report from the Spectroscopy Section of the National Bureau of Standards, prepared by L. B. Hagan is in press (**29**). Encouraging progress is being made on the analysis of rare-earth spectra. A general description of the present status of these spectra is described by W. C. Martin in two papers on the energy-level structures of lanthanide atoms and ions (**46, 47**). From 19 known energy differences of the type $4f^{N-1}\,nl(6s^M) - 4f^N(6s^M)$ (with each configuration represented by its lowest level) he has predicted 23 values. "The resulting data confirm striking regularities among the *f*-shell graphs first used by Racah" to predict unknown system differences.

From absolute measurements in He II E. G. Kessler has determined the Rydberg constant to be $109\,737.3208 \pm 0{\cdot}0085\ \mathrm{cm}^{-1}$ (**41**).