

## REPORT ON TRANSITION PROBABILITIES AND CROSS-SECTIONS

(Committee 2)\*

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A review of the research done in the years 1961–1963 on transition probabilities and cross-sections, shows that there is a real revival and strong development of this chapter of physics. The amount of new data is so considerable and the publications are so numerous, that it becomes impossible to publish complete bibliographies in this report, as was done in the previous volume of the *Transactions*. The aim of this report must, therefore, be: to inform the astronomer about the places where he can find the data which he needs; and to indicate the main progress in the methods and in the results.

This is the more so since recently several very extensive bibliographies have been published by the National Bureau of Standards.

(a) *Bibliography on atomic transition probabilities*, under the direction of W. L. Wiese (59, 177); the publication of this material in 1962 was followed by an addendum, covering the work up to June 1963. All the older Russian work (1920–1960) was translated into English and republished. Bibliographical data on photo-ionization have also been collected at the JILA Data Center. (b) *Bibliography on cross sections for collisions with a free electron*, prepared for publication under the direction of L. J. Kieffer. Reasonable requests for printouts will be honoured without charge; they should be addressed to 'Data Center, JILA, University of Colorado, Boulder, Colo.'. (c) *Bibliography on photo-ionization*.

The National Bureau of Standards is also preparing tables for the first ten elements, giving the best available transition probabilities for all individual lines, derived from experimental as well as from theoretical data. By way of example, the table for OI gives data for 108 lines, belonging to 48 multiplets; for 36 of these lines the accuracy is estimated to be within 25%, for the other lines it remains within 50%.

An excellent survey of the whole field of radiative and collisional processes, involving atoms or molecules, is the book: *Atomic and Molecular Processes*, edited by D. R. Bates (8); it contains the basic methods and also the experimental and theoretical results. The survey paper of W. L. Wiese (177) should, also, be quoted.

A review of the literature shows that the overwhelming majority of available data refers to the visual and near UV part of the spectrum. It seems necessary to extend our knowledge to the far ultra-violet and the X-ray region, which are becoming so important for space research. At the Max-Planck Institute, München, a special group measures oscillator strengths in the region 1100–1800 Å. At the Ohio State University, attention is given to the region 2000–3000 Å.

### 1. Experimental Determinations of Transition Probabilities

(a) *In absorption*. The classical method was applied by Moise to a number of metals, heated in a quartz absorption tube. For elements whose vapour pressures are accurately known, absolute  $f$ -values are determined; conversely, from known  $f$ -values the vapour pressure curves may be found. Lines of Ag, Au, Cd, Cu, Ga, In, Pb, Sn, Tl, Zn were studied.

Ostrovskii, Penkin and their collaborators have extensively applied their method, based on the simultaneous measurement of the anomalous dispersion hooks and of the equivalent width. This method does not require the knowledge of the number of atoms in the light-path. Ag, Al, Au, Ba, Ca, Ga, In, K, Mg, Na, Pb, Sn, Sr, Tl have been studied. Recently the anomalous

\*Reference numbers in parentheses refer to the general bibliography which follows the report of the Commission.

dispersion was also used by Pery-Thorne and Chamberlain for the investigation of Ar, Kr and Ne.

The atomic beam apparatus in King's laboratory at the California Institute of Technology has been modified, so that the sensitivity and accuracy have been improved. This method yields absolute  $f$ -values, while the vapour pressure curve need not be known. For 38 lines in the neutral spectra of Ag, Au, Co, Cr, Ga, In, Pd, Sn, Tl, transition probabilities have been found with a precision of 10–20%, including allowances for possible systematic errors (92, 93). Odintsov applied the method to CaI and increased the sensitivity by recording the absorption line profile photo-electrically.

Khokhlov investigated Be, Ge, Pb, Sn, Si, by means of the absorption method, if lines had to be compared with the same lower level; the emission method was used if the upper levels coincided.

An interesting comparison of the results of various authors may be made in the case of PbI. For the resonance line  $\lambda 2883$  the earlier result of Engler (1956) was corrected by Bell and King, who found 0.23. This agreed with the theoretical result 0.21, obtained by Helliwell. It was, moreover, fully confirmed by Penkin and Slavenas, who used the hook method and found 0.212, this value remaining practically the same though the vapour pressure was varied by a factor of 500! The results of Khokhlov, who had measured only relative values, should consequently be connected to these recent values for the resonance line and not to that of Engler. However Penkin and Slavenas showed, also, that the relative values of Khokhlov were considerably in error just for this resonance line, where self-absorption had spoiled the result; they were able to normalize his relative values by means of other Pb lines. These other lines, thus normalized, show a considerable, unexplained discrepancy with Helliwell's theoretical results.

A very special type of absorption experiment is the method of Branscomb, used for the study of photo-ionization and photo-detachment. By this method, Seman and Branscomb carried out the difficult measurement of the absorption by  $C^-$  ions. The beam, produced by the ion source, passes through a mass analyzer and is then illuminated by a chopped beam of light. The detached electrons and ions are collected and measured. The results are an order of magnitude smaller than theoretically predicted by Breene (1958) from a theory that is insufficiently complete. The same authors, together with Steiner, measured also the absorption by  $I^-$ .

The continuous absorption of He was measured by Baker and his collaborators in the region of 180–600Å.

(b) *In emission.* The impressive material on line intensities, obtained by W. F. Meggers and his collaborators in the course of 28 years, has been published (113). Electrodes were made from copper powder, mixed with a small amount of the element under investigation, and compressed. For 39 000 lines of 70 elements comparable intensities are given; for about one-half of these elements the tables contain the first extensive intensity data ever published. For 25 000 of the classified lines the data have been reduced to absolute  $f$ -values by Corliss and Bozman (31).

Corliss devoted a special paper to the lines of Cu.

In all arc measurements, there is always the danger of temperature and density gradients in the metal vapour. For real precision, the distribution of the emission over the arc should be carefully studied. Such an investigation was made for Ba by Eicke.

Another danger is the effect of self-absorption. Letfus showed how the well-known results, earlier obtained by Mitrofanova (1952) with the Fe arc, are strongly vitiated by this. By constructing the curve of growth for this light-source, he was able to eliminate the self-absorption; the temperature of the arc was then found to be 5200°K (instead of 3800°). After these corrections, the results of Mitrofanova correspond quite satisfactorily to other, now well-

established data. Earlier, Leftus had applied similar corrections to the results of Hefferlin (1959), also for Fe, but these corrections were less important.

A great amount of work has been done with different types of high-current arcs, in which temperatures up to  $30\,000^\circ$  can be obtained. A *solid-wall-stabilized arc* was used at the Kiel Physical Institute. The arc passes through several isolated and cooled copper diaphragms and is perfectly cylindrical; the observations are made in transverse or in longitudinal direction. Absolute measurements were made by Richter and Gericke on multiplets of Ni I and Ar I, the temperature of the arc being determined by means of Ni II and Ar II lines. For Fe (Roder) and Ti (Wobig), the vapour of  $\text{FeCl}_3$  or of  $\text{TiCl}_4$  was diluted by  $\text{N}_2$ , Ar or He and injected into the arc; however it was not possible to keep a homogeneous gas mixture in the arc, so that absolute values had to be derived indirectly. At the same laboratory the wall-stabilized arc was also used for measurements of the continuous emission of Ar (Schlüter) and of the other inert gases. It proved even possible to determine roughly the continuous emission of  $\text{Cl}^-$ , corresponding to the  $4p$  levels (Henning). A similar source was used by Wiese and Shumaker for O I.

A *vortex arc* was used at the London Observatory by Foster for the lines of O I, Cl I, Cl II, Cl III, S. At the same institute Woodgate is experimenting with a *solid-walled rotating arc* for Mn I and Mn II. The technique of the *liquid-stabilized arc* was applied by Tatum to the investigation of Ti I and Ti II, by using an arc burning in  $\text{TiCl}_4$ .

At Indianapolis, Olsen uses a conical tungsten cathode and a copper plate anode; the electrodes and the jacket are water-cooled. This author makes use of the great stability of such an arc (in Ar) in order to study carefully the temperature distribution and to avoid all effects of self-absorption. LTE (Local Thermodynamic Equilibrium) is shown to apply.

A very different source of light was used by Kelm and Schlüter, in order to measure the continuous emission of Ca I. Calcium was heated in a tubular crucible by means of an electric furnace at about  $1400^\circ$ ; suspended in the Ca vapour, there was a discharge tube, through which short discharges of 0.5 m sec were passed. LTE was guaranteed and the temperature reached  $4630^\circ$ .

(c) *The shock tube*. This new device is a highly valuable light source for the determination of  $f$ -values. In the book of Bates (8), already quoted, there is a special chapter on this subject by Kolb and Griem; moreover the book of Ferri (51) and the review paper of McLean (111) should be consulted.

In the reflected shock wave the temperature may reach  $15\,000^\circ$ , the excitation is basically thermal, and mostly equilibrium conditions prevail, except at low pressures. From the initial conditions the number of emitting atoms may be calculated. Compared with the arc, the shock tube has the advantage that the gas is more nearly homogeneous in the line of sight. On the other hand, the photometric standardization is difficult and the continuous background is troublesome. Because of the short observation time, the emission has to be strong and self-absorption may occur. The shock tube is particularly useful for atomic lines involving transitions between highly excited states, and for ionized atoms or molecules, which are not easily studied quantitatively by other methods.

McLean studied relative oscillator strengths for He lines and reached a high precision, better than 10%. Similar accuracies may be attainable for other gases if these are diluted in He or  $\text{H}_2$  and if the lines are compared to suitable reference lines of He or  $\text{H}_2$ .

Mention should be made, also, of the work of Doherty on Ar, Cl, Ni, Ne, O I (the absolute values for Ne are about three times lower than earlier determinations); and the work of Berg *et al.* on O II and O III. Wilkerson studied Cr I and Cr II; Charatis and Wilkerson have corrected their earlier work and have now found that the Cr emission is consistent with LTE.

The continuous emission of the shock tube is often difficult to interpret, since ionization, bremsstrahlung, and radiation of excited molecules play a role. At the Kiel Physical Institute,

the continuous radiation of inert gases was measured both in shock tubes and in the high-current arc, and a fairly good agreement with theory was found. Berry, Reimann and Spokes studied the continuous emission of  $\text{Cl}^-$ ; measurements are underway, of which the results should be compared to those of Henning, mentioned earlier. Recently Berry and Reimann observed, also, the absorption of  $\text{F}^-$ .

(d) *The direct determination of life-times.* This method, applied in different modifications, has the great advantage that a knowledge of the number of effective atoms is not required. By the recent work of Demtröder, it has been shown that a precision of a few percent may be obtained. On the other hand, the method yields only the life-time of a given *level*: in order to find transition probabilities of the individual *lines* emitted by this level, it is necessary to determine their relative intensities.

The classical method, which consists of the measurement of line-broadening, has been applied by Hindmarsh and Thomas to the spectrum of Ar. The broadening of  $\lambda 8264$  gives information on the width of the resonance line at  $1048 \text{ \AA}$ .

Kagan and Koritskii produce an electron beam which collides with gas atoms and creates ions. A constant field is applied: the ions have time to acquire a certain velocity during their life-time, their mean drift velocity is measured by the Doppler effect (He II).

The method of delayed coincidences was improved by Aminian, by using tunnel-diodes, but no *f*-values were published (2).

Agarbichanii and others irradiate the vapour by polarized light and observe the fluorescence in a monochromator at right angles. They then apply a magnetic field and measure the depolarization of the fluorescence as a function of the field; this function depends on the life-time (Hg and Na). Demtröder excites an atomic beam by high-frequency modulated light (2-18 MHz): the fluorescent light shows the same modulation, but with a phase-lag which is a measure of the mean life-time. The method was applied to Al, Ga, Mg, Na, Tl. A comparison with the theory of Bates and Damgaard shows a good agreement for P-D transitions, but considerable discrepancies for P-S transitions.

Several measurements were made by the methods of magnetic resonance. Free atoms, excited to fluorescent radiation, are subjected to a uniform magnetic field. When an oscillating magnetic field of the proper radio-frequency is added, mixing between the Zeeman states occurs, which is detected by the changes in the polarization and in the spatial distribution of the fluorescent light. The depth of the modulation depends on the life-time of the level. Such measurements were made by Barrat and Butaux for  $\text{Cd } 5^3\text{P}_1$ , by Tolans and Allen Lurio for  $\text{Tl } 2^3\text{S}_{1/2}$ . In other experiments the atoms are excited by a beam of slow electrons.

## II. Theoretical Determinations

A clear and short paper of Layzer (100) gives a review of the methods of calculation, including his own, already described in earlier papers: the transition integrals are evaluated in terms of suitable screened hydrogenic radial functions. This has been extensively applied by Varsavsky (172).

Two authors have compared the results of the Coulomb approximation (after Bates and Damgaard) with the well-established values, determined earlier. On the whole, Houziaux and Sadoine (72, 73) find a satisfactory agreement. Kunisz (98) finds this only for transitions between low lying levels, not located close to other levels, able to interact with them. Better results are obtained only when configuration interaction is taken into account.

Much effort is being devoted to solving the Hartree-Fock wave equations or to deriving approximate solutions. Green (60) reached a high precision in establishing variational wave functions for the ground and excited states of 2-electron systems ( $\text{H}^-$ ,  $\text{HeI}$ ,  $\text{HeH}^+$ ,  $\text{Li}^{++}$ ). Naqvi (121)

approximated the wave equations by screened hydrogen orbitals, covering the major part of the periodic table and describing the ground and several excited configurations. The necessary screening parameters are calculated. The energy levels are in good agreement with the experiments and with the self-consistent field (SCF) models, but the dipole matrix elements, calculated for a great number of combinations show considerable discrepancies. In the following, reference is made mainly to work in which the calculations have been carried out by a derivation of the transition probabilities proper, since these are needed by the astronomer.

Of general significance is the paper of Garton (56), who investigated a number of cases where configuration mixing has a marked influence on the transition probabilities.

Vainshtein and Poluektov (171) calculated the relative oscillator strengths of permitted lines and of intercombination lines for divalent elements, by assuming intermediate coupling. Weiss (175) calculated  $f$ -values for the Li sequence and is working now on the He sequence. Salpeter and Zaidi derived  $f$ -values for all transitions of He from the ground state to higher states and to the continuum. Nikitin worked on N III. Eddy, House and Zirin calculated a transition of Al, which was corrected in an erratum.

In the case of the  $2p^2$  ( $^4P$ ) $_3s$ - $2p^3$  ( $^4S$ ) transition in the Ni spectrum, Armstrong computed an oscillator strength of 0.12. Kelly and Armstrong have recomputed the oscillator strength, by using the Hartree-Fock equations, and find 0.10, thus confirming their first calculation.

The case of Pb I was investigated by Helliwell, who showed that the deviations from  $LS$ -coupling play a considerable role. His results have been compared with the experiments in the section on absorption measurements.

Garstang and Douglas investigated several transitions in Ca II and Si IV, by using wavefunctions calculated by Douglas and including polarization effects. Garstang studied, also, several interesting lines with low or very low transition probabilities: faint intercombination lines of C I and Si I, occurring in the solar spectrum and which might be useful for abundance determinations; intercombination lines of Mg I, Zn I, Cd I and Hg I, arising by interaction of nuclear moments with the electrons. Moreover, he calculated transition probabilities for permitted and forbidden lines of Si X, Fe X and Fe XIV, which could be observed in the corona or in the far ultra-violet solar spectrum; in some cases intermediate coupling has a large effect; in other cases configuration interaction is by far predominant.

### III. *The Continuous Absorption Coefficient (photo-ionization)*

Cooper (30) calculated the continuous absorption for a number of atoms, especially for spectral ranges where the bulk of the optical oscillator strength is distributed, but where experimental evidence is scarce: Ar, Ag<sup>+</sup>, Cu<sup>+</sup>, He, Kr, Na, Ne were investigated for transitions of 0-150 eV. Sum-rules were used to analyze the spectral distribution of the absorption and to extrapolate to still higher energies. From the results it seems that there are two types of sub-shells, distinguished by the spectral distribution of the absorption: (1) The sub-shells  $1s$ ,  $2p$ ,  $3d$ ,  $4f$ ; (2) the other ones.

Peach (138) made use of the approximate formulae for the continuous absorption coefficient of each level in order to derive the total continuous absorption of H, He, O, N, Mg, Al as a function of wavelength; this is precisely the function in which the astrophysicist is directly interested. For the hydrogenic levels, Gaunt factors were properly taken into account; for the non-hydrogenic levels, Seaton's theory of quantum defects was applied. Except for Mg, the resulting absorption coefficients show a satisfactory agreement with the observations, where these are available. Remarkably high is the absorption by the  $^2P$  ground state of Al, which might influence the solar continuum near 2085 Å.

The free-free absorption of O was investigated by Breene Jr. and Nardone. They included

the effects of exchange and polarization; the latter was found to improve the results considerably.

The photo-ionization of negative ions, often called photo-detachment, has been studied primarily for the  $H^-$  ion, so interesting astrophysically. Tietz tried to find simple analytical expressions for the absorption coefficient. Geltman used improved wave-functions and reached the best results now available for the bound-free absorption; the 'velocity' curve seems to be the most reliable. Sum-rules were applied as a test. Sum-rules were also applied by Dalgarno and Ewart to the recent values obtained for the  $H^-$  absorption, in order to test their correctness.

Cooper and Martin calculated the absorption by  $C^-$ ,  $O^-$ ,  $F^-$ ,  $Cl^-$ .

An investigation by Kaufman (89) gives a comparison between the semi-empirical computed electron affinities of light atoms and the experimental determinations.

#### iv. *Forbidden Transitions*

A comprehensive review, due to Garstang (55), is found as chapter I in the book of Bates (8), already quoted.

It seems that all investigations of transition probabilities of forbidden transitions have been made by theoretical methods. Since a number of forbidden lines have been observed in the laboratory, one wonders whether suitable methods could not be applied for experimental measurements of  $f$ -values.

Garstang obtained transition probabilities for the most important forbidden lines of 39 ions, thus completing the survey of the transitions which might be of astrophysical interest. Special attention was given by this author to  $[FeII]$ . Transition probabilities for about 100 multiplets are given; an extended list is published in mimeographed form and may be obtained on request. The presence of  $[FeII]$  in the Sun could not be confirmed.

Garstang also performed calculations on  $[SiX]$  and  $[FexIV]$  in connection with work on the solar corona.

Czyzak and Krueger (32) calculated new transition probabilities for various ions in  $3p^n$  configurations by using the self-consistent field method. Their results are rather different from the earlier values, because they took exchange into account. An application of these improved results was made to the investigation of a planetary nebula.

Forbidden transitions in  $BrII$  were studied by Martin and Tech.

#### v. *Special Experimental Papers*

No attempt at completeness has been made. The experimental papers have been arranged according to atoms in order to facilitate the survey. Papers in press are quoted only by the journal and the year, without page number. Quotations from *Optika i Spektroskopija* refer to the original Russian edition; in the American translation the page number is smaller.

Key to letters in parentheses following references:

	A	absorption	S	shock tube
	C	coincidences	V	atomic beam
	D	anomalous dispersion	a	absolute values
	E	emission	r	relative values
AgI		Penkin, N. P., Slavenas, I. Yu. <i>Opt. Spektrosk.</i> , <b>15</b> , 9, 1963 (Da); King, R. B. <i>et al.</i> (92); Moise, N. L. <i>Thesis</i> , Cal. Inst. Tech. 1963 (Aa).		
AlI		Demtröder, W. <i>Z. Phys.</i> , <b>166</b> , 42, 1962 (Ca); Penkin, N. P., Shabanova, L. N. <i>Opt. Spektrosk.</i> , <b>14</b> , 12, 1963 (Da).		
ArI		Gericke, W. E. <i>Z. Astrophys.</i> , <b>53</b> , 68, 1961 (Ea); Doherty, L. R. <i>Thesis</i> , Mich. 1961 (Sa); Hindmarsh, W. R., Thomas, K. A. <i>Proc. phys.</i>		

- Ar I  
Cont. *Soc. Lond.*, **77**, 1193, 1961 (Ca); Schlüter, D. *Z. Astrophys.*, **56**, 43, 1962 (Ea); Olsen, H. N. *J. quant. Spectrosc.*, **3**, 59, 1963 (Ea); Razumovskaya, L. P. *Opt. Spektrosk.*, **14**, 189, 1963 (Aa); Pery-Thorne, A., Chamberlain, J. E. *Proc. phys. Soc. Lond.*, **82**, 133, 1963 (Dr).
- Au I Penkin, N. P., Slavenas, I. Yu. *Opt. Spektrosk.*, **15**, 9, 1963 (Da); King, R. B. *et al.* (92) (Va); Moise, N. L. *Thesis*, Cal. Inst. Tech. 1963 (Aa).
- Ba I Ostrovskii, Yu. I., Penkin, N. P. *Opt. Spektrosk.*, **11**, 565, 1961 (Da); Penkin, N. P., Shabanova, L. N. *Opt. Spektrosk.*, **12**, 3, 1962 (Da); Eicke, H. F. *Z. Phys.*, **168**, 227, 1962 (Ea).
- Be I Khokhlov, R. V. *Izv. Krym. astrofiz. Obs.*, **27**, 44, 1962; **28**, 277, 1962 (Ar).
- Cl Doherty, L. R. *Thesis*, Ann Arbor, 1961 (Sa); Foster, E. W. *Proc. phys. Soc. Lond.*, **79**, 94, 1962; **80**, 882, 1962; *Commun. Obs. London* no. 48 and 56 (Ea); Boldt, G. *Z. Naturforsch.*, 1963 (Ea).
- C<sup>-</sup> Seman, M. L., Branscomb, L. M. *Phys. Rev.*, **125**, 1602, 1961.
- Ca I Ostrovskii, Yu. I., Penkin, N. P. *Opt. Spektrosk.*, **11**, 565, 1961 (Da); Penkin, N. P., Shabanova, L. N. *Opt. Spektrosk.*, **12**, 1, 1962.
- Kel'm, S., Schlüter, D. *Z. Astrophys.*, **56**, 78, 1962 (Aa); Odintsov, V. I. *Opt. Spektrosk.* **14**, 322, 1963 (Va).
- Cd I Barrat, P., Butaux, J. *C. R. Acad. Sci. Paris*, **253**, 2668, 1961 (Ca); Moise, N. L. *Thesis*, Cal. Inst. Tech. 1963 (Aa).
- Cl I, II Foster, E. W. *Proc. phys. Soc. Lond.*, **80**, 882, 1962; *Commun. Obs. London* no. 56 (Ea).
- Cl<sup>-</sup> Berry, R. S., Reimann, C. W., Spokes, G. N. *J. chem. Phys.*, **35**, 2237, 1961 (Sa); Henning, H. *Z. Phys.*, **169**, 467, 1962.
- Co I King, R. B. *et al.* (92), (Va).
- Cr I Charatis, G., Wilkerson, T. D. *Phys. of Fluids*, **5**, 1661, 1962 (S); King, R. B. *et al.* (92), (Va).
- Cr I, II Wilkerson, T. D. *Univ. Michigan, Report, Air Force Off. Sci. Res.*, AFOSR 1151, 282 pp. 1961 (Sa).
- Cu I Corliss, C. H. *J. Res. NBS*, **66A**, 497, 1962 (Er); Moise, N. L. *Thesis*, Cal. Inst. Tech. 1963 (Aa).
- Fe I Letfus, V. *Bull. astr. Inst. Csl.*, **13**, 98, 1962 (Er); **12**, 161, 1961; Roder, O. *Z. Astrophys.*, **55**, 38, 1962 (Ea).
- Fe II Roder, O. *Z. Astrophys.*, **55**, 38, 1962 (Ea); Baschek, B., Kegel, W. H., Traving, G. *Z. Astrophys.*, **56**, 282, 1963 (Ea).
- Ga I Demtröder, W. *Z. Phys.*, **166**, 42, 1962 (Ca); Penkin, N. P., Shabanova, L. N. *Opt. Spektrosk.*, **14**, 12, 1963 (Da); King, R. B. *et al.* (92); Moise, N. L. *Thesis*, Cal. Inst. Tech. 1963 (Aa).
- Ge I Khokhlov, M. Z. *Izv. Krym. astrofiz. Obs.*, **28**, 277, 1962 (Ar); **29**, 131, 1963 (E and Ar).
- Hg I Agarbichanu, I. *et al.* *Opt. Spektrosk.*, **14**, 18, 1963 (Ca).
- He I Baker, D. J. *Phys. Rev.*, **124**, 1471, 1961. McLean (111) (Sa).  
Bötticher, W., Roder, O., Wobig, K. H. *Z. Phys.*, **175**, 480, 1963.
- He II Kagan, Yu. M., Koretskii, Ya P. *Opt. Spektrosk.*, **11**, 308, 1961 (Ca).
- I<sup>-</sup> Steiner, B. W., Seman, M., Branscomb, L. M. *J. chem. Phys.*, **37**, 1200, 1963.
- In I Penkin, N. P., Shabanova, L. N. *Opt. Spektrosk.*, **14**, 12, 1963 (Da); King, R. B. *et al.* (92) (Va); Moise, N. L. *Thesis*, Cal. Inst. Tech. 1963 (Aa).
- K I Ostrovskii, Yu. I., Penkin, N. P. *Opt. Spektrosk.*, **12**, 669, 1962 (Da).
- Kr I Pery-Thorne, A., Chamberlain, J. E. *Proc. phys. Soc. Lond.*, **82**, 133, 1963 (Dr).
- Mg I Penkin, N. P., Shabanova, L. N. *Opt. Spektrosk.*, **12**, 3, 1962 (Dr); Demtröder, W. *Z. Phys.*, **166**, 42, 1962 (Ca).
- Mn I, II Woodgate, E. W. London, not published (E).

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- NaI Ostrovskii, Yu. I., Penkin, N. P. *Opt. Spektrosk.*, **11**, 3, 1961 (Da); Demtröder, W. *Z. Phys.*, **166**, 42, 1962 (Ca); Agarbichanu, I. *Opt. Spektrosk.*, **14**, 18, 1963 (Ca).
- NeI Doherty, L. R. *Thesis*, Ann Arbor, 1961 (Sa); Pery-Thorne, A., Chamberlain, J. E. *Proc. phys. Soc. Lond.*, **82**, 133, 1963 (Dr).
- NiI King, R. B. *et al.* (92) (Va).
- OI Foster, E. W. *Proc. phys. Soc. Lond.*, **79**, 94, 1962 (Ea); *Commun. Obs. London* no. 48; Doherty, L. R. *Thesis*, Ann Arbor, 1961 (Sa); Wiese, W. L., Shumaker, J. B. *J. opt. Soc. Amer.*, **51**, 937, 1961 (Ea).
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- Pd King, R. B. *et al.* (92) (Va); Moise, N. L. *Thesis*, Cal. Inst. Tech. 1963 (Aa).
- SiI Khokhlov, M. Z. *Izv. Krym. astrofiz. Obs.*, **29**, 131, 1963 (Er).
- SnI Khokhlov, M. Z. *Izv. Krym. astrofiz. Obs.*, **25**, 249, 1961 (E); **28**, 277, 1962 (Ar); **29**, 131, 1963 (Ar); Penkin, N. P., Slavenas, I. Yu. *Opt. Spektrosk.*, **15**, 154, 1963 (Da); King, R. B. *et al.* (92) (Va); Moise, N. L. *Thesis*, Cal. Inst. Tech. 1962 (Aa).
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- TlI Demtröder, W. *Z. Phys.*, **166**, 42, 1962 (Ca); Ostrovskii, Yu. I., Penkin, N. P. *Opt. Spektrosk.*, **14**, 167, 1963 (Da); King, R. B. *et al.* (92) (Va); Moise, N. L. *Thesis*, Cal. Inst. Tech. 1963 (Aa); Tolans, E. L., Lurio A. *Bull. Amer. phys. Soc.*, **7**, 75, 1961 (Ca).
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## Lines

## VI. Theoretical Papers

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## REPORT ON ELECTRON COLLISIONS

(Committee 2 continued)\*

M. J. Seaton

Electron collisions are important in the atmospheres of hot stars, in gaseous nebulae and in the solar chromosphere and corona. In cooler stars, other collision processes may be more important; thus Pagel (136) argues that, in the solar atmosphere,  $H^- + H \rightarrow H_2 + e$  is more important than  $H^- + e \rightarrow H + e + e$ . Reviews of all aspects of atomic collision work are given in (8) and (64). Reference (64) includes a review of electron collisions, by Heddle and Seaton, with an extensive bibliography of recent experimental and theoretical work. In the present report we consider aspects of electron collisions of particular importance in astrophysics.

I. *Accurate Calculations*

Most accurate calculations are made by using expansions in terms of unperturbed atomic eigenfunctions. This leads to coupled differential or integro-differential equations. It is only recently that it has been possible to solve such equations exactly when several states are included. Solutions of the  $e$ -H  $1s$ - $2s$ - $2p$  equations (23, 34, 134) give  $1s$ - $2s$  and  $1s$ - $2p$  cross sections in rather poor agreement with those obtained experimentally (53, 74, 101, 165). Further work by Burke (22) shows that this is probably due to slow convergence of the expansions. Other methods should, therefore, be developed; an interesting approach is described by Presnyakov, Sobelman and Vainshtein (64). The expansion method is probably good when one has a group of closely coupled states, as is the case for transitions within ground-configuration terms. New calculations for configurations of  $2p$  electrons are being made at University College, London, and calculations for  $3p$  electrons are being made by Czyak (64).

For neutral atoms, cross sections are zero at threshold but for positive ions they are finite. When proper allowance is made for long-range potentials, calculations for positive ions should be more accurate than calculations for neutral atoms. A number of calculations of astrophysical interest have been made (148):

Mg<sup>+</sup>,  $3s$ - $3p$  and Ca<sup>+</sup>,  $4s$ - $3d$  (149); Fe<sup>13+</sup>,  $3p_{1/2}$ - $3p_{3/2}$  (14);  
 O<sup>5+</sup>,  $2s$ - $2p$  and Fe<sup>13+</sup>,  $3s^2$   $3p$ - $3s^2 3p^2$  (11).  
 Na and Li sequences (11).

II. *Approximate Formulae*

One approach, applicable to optically allowed transitions, is to treat the collisional transition as an induced radiative process. The cross section may be expressed in terms of the oscillator strength  $f$  and an effective Gaunt factor  $\bar{g}$  (20, 8, 150). In many cases, estimates good to within a factor of 2 may be obtained by assuming  $\bar{g}$  to depend only on  $\chi = (\frac{1}{2} mV^2)/\Delta E$ ; Van Regemorter (150) gives  $\bar{g}(\chi)$  for neutral atoms and for positive ions. A more refined theory has

\*Reference numbers in parentheses refer to the general bibliography which follows the report of the Commission.