Collision cross sections for electrons with atmospheric species

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ABSTRACT. — Recent laboratory measurements have yielded much detail concerning cross sections for the elastic and inelastic scattering of electrons by stable atmospheric species. Measurements of the energy and angular distribution of inelastically scattered electrons have yielded cross sections for excitation of the principal levels of N₂, O₂ and He and for the distribution of secondary electron energies resulting from collisional ionization of these gases. Electron beam measurements of cross sections for the production of radiation from N₂, O₂ and N₂ provide data of direct applicability to calculations of auroral intensities, etc. Similar data are also obtained from measurements of electron induced fluorescence. Swarm experiments provide cross section data for vibrational and rotational excitation of O₂ and N₂ at electron energies below about 1 eV. Afterglow and shock tube measurements have yielded the electron energy and temperature dependence of the electron-ion recombinations for a few positive ions. Theoretical calculations of the cross sections for excitation of atomic oxygen and nitrogen are particularly important since laboratory measurements are not generally available.

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INTRODUCTION

The past four years have seen the publication of a large number of laboratory determinations of collision cross sections for electrons in atmospheric gases. The stimulus for this work has been both the experimental and theoretical studies of ionospheric disturbances, such as aurora [ÖHMOLT, 1968; HULTQVIST, 1968; MATHIEUS and CLARK, 1968; REES, 1970]; airglow [DALGARNO, MCÉLROY and STEWART, 1969; DÖRING, FASTIE and Feldman, 1970], and man made disturbances [DowNAHUE, 1965]. These studies of the disturbed ionosphere have shown that in many cases [ÖHMOLT, 1968; DALGARNO, McNELROY and STEWART, 1969] the observed changes in radiation and ionization appear to be the result of electron impact with atmospheric species. However, in nearly every case there is a need for additional or more accurate electron collision cross section data.

This review of recent data is divided into sections on the basis of the type of electron collision considered. Thus, we consider first electron ionization; followed by electronic excitation, vibrational and rotational excitation, total scattering, and electron-positive ion recombination. A very extensive review of ionospheric collision processes and their application has been published recently by Takayanagi and Itikawa [1970].

IONIZATION

Recent studies of the ionization of atmospheric species by electron impact have been primarily concerned with the distribution in energy of the secondary electrons produced by ionization and of the ions produced in the dissociative ionization process. Previously, semi-empirical cross sections for secondary electron production based on the available generalized oscillator strengths [LASSETTE, 1969] ionization cross sections [RAPP and ENGELANDER-GOLDEN, 1965; KIEFFER and DUNN, 1966] have been used for moderate and high energy electrons, such as found in aurora. Various authors [PETERSON, PRASAD and GREEN, 1969; REES, STEWART and WALKER, 1969; KAARE, 1969; GARCIA, 1969; VRIENS, 1969 and 1970; TAKAYANAGI and ITIKAWA, 1970] have proposed such relations in varying degrees of detail. Although experimental secondary electron distributions for high energy proton impact have been published [RUDN, SAUTTER and BAILEY, 1966; TÖRUREN, 1971; CROOKS and RUDN, 1971], accurate measurements of the secondary electron distributions resulting from ionization of atmospheric gases by electrons have only become available in recent months. Thus, Peterson, Opal and Beatty [1971] have measured the energy distribution and angular dependence of secondary electrons up to 200 eV produced by the impact of 500 eV primary electrons on gases such as He, Ne, O₂, NO, H₂O, CO and CO₂. For He, Ne, and O₂ the primary energies range from 50 to 2000 eV. Similar measurements have been made for N₂ by Tison [1971] and for He and Ar by Ehhardt et al. [1971]. When integrated over angle, the cross section for the production of secondary electrons with energies between 1 and 200 eV were found to obey a simple empirical relation [PETERSON and BEATY, 1971]. Thus, the differential cross section σ(E₂, Eₗ) for the production of secondary cross energy Eₗ by primary electrons of energy E₂ is given by

\[ \sigma(E₂, Eₗ) = \sigma₀(E₂)(1 + (E₂/E₀)^{1/2})^{-1}. \]

Here \( \sigma₀(E₀) \) varies approximately as the total ionization cross section [RAPP and ENGELANDER-GOLDEN, 1965; KIEFFER and DUNN, 1966] and \( E \) is within 50 % of the first ionization potential \( I \) and increases slowly with \( E₂ \). Equation (1) is found to be valid to within 10 %, for \( E₂ \) up to about \( E₂ - I / 2 \) or the limit of the analyzer at 200 eV.

Since for an ionization process producing ions with a single state of excitation, the energy distribution of secondary electrons leaving the ion is symmetrical about the energy \( E₂ - I / 2 \), it is possible to obtain an estimate of the distribution in energy of secondaries at high energy by reflecting the distribution given by Eq. (1) \( E₂ - I / 2 \). It is of interest to note that because of the approximately quadratic decrease in \( \sigma(E₀, Eₗ) \) with \( E₂ \) in Eq. (1), the higher energy secondaries make a significant contribution to the mean energy of these electrons and to the mean energy degradation calculations using the continuous-slowing down approximation [STOLARSKI and GREEN, 1967; DALGARNO, MCÉLROY and STEWART, 1969; PETERSON, 1969; STEWART, 1970]. A comparison of the results of these experiments with the secondary energy distributions given by Peterson, Prasad and Green [1969] shows very good agreement for N₂ and, as shown in Figure 1, a difference of about 30 % for O₂ at secondary energies above 20 eV. The agreement with the distributions proposed by Rees, Stewart and Walker [1968] is good at secondary energies near 10 eV, but the experimental values are significantly larger at higher energies.

Note that the measurements discussed above do not yield information as to the state of excitation of the ion. In principle, this information could be obtained by energy analysis of both electrons using coincidence techniques. Thus far, such measurements have been reported only for helium and for a limited range of energies and angles [EHARDT et al., 1969]. In cases where the excited state radiates observable photons, measurements have been made of the cross section for simultaneous excitation and ionization. Most recent measurements of the first negative bands of N₂ [HOLLAND, 1969; AARTS, DE HEER and VROOM, 1968; SRIVASTAVA and MIRZA, 1968; SIMPSON and
McConkey, 1969; Stanton and St. John, 1969; Borst and Zipp, 1970; Koval et al., 1969; Sheridan, Oldenberg and Carlton, 1971) and of the first negative bands of \( \text{O}_2 \) [Nishimura, 1968; McConkey and Woolsey, 1969; Srivastava, 1970] are in reasonable agreement with each other. These data plus studies of dissociative ionization [Rapp, Englander-Golden and Briglia, 1965; Kieffer and Van Brunt, 1967; Kieffer, Lawrence and Slater, 1971] and of relative intensities of auroral lines allowed a division of the total ionization cross section into partial cross sections and secondary energy distributions for various states of the ions [Peterson and Green, 1968; Peterson, Prasad and Green, 1969].

Total ionization cross sections for gases of auroral and airglow interest have not been investigated experimentally since the review of Kieffer and Dunn [1966]. These data are available in the compilation by Kieffer [1969]. A number of comparisons have been made of quantum mechanical, classical and semi-empirical calculations of total ionization cross sections for molecular gases [Rudge, 1968; Khare and Padalia, 1970; Sharma, Tripathi and Rai, 1971]. For \( \text{N}_2 \) and \( \text{O}_2 \) the agreement among the experiments is good and the semi-empirical theory [Peterson, Prasad and Green, 1969] can be used to extrapolate to higher energies. The agreement among experiments for atomic oxygen and nitrogen is not good [Kieffer and Dunn, 1966] although there is good agreement between some experiments and theory [Lotz, 1968; Peach, 1970; McGuire, 1971]. Theoretical and experimental ionization cross sections in helium have been compared recently by Inokuti and Kim [1969] and Bell and Kingston [1970].

**Electronic Excitation**

Laboratory determinations of cross sections for electronic excitation of atmospheric gases have been made using observations of visible and ultraviolet radiation produced in single collisions, measurements of electron energy loss spectra and observation of fluorescence spectra produced as high energy electrons degrade in energy. In the following summary, the results are presented according to the gas being studied.

**Nitrogen**

Recent measurements of apparent excitation cross sections for \( \text{N}_2 \) include studies of emission from the \( a^3\Pi_u \) state [Holland, 1969; Ajello, 1970], the \( B^3\Pi_u \) state [Skubenich and Zapesochny, 1967; Stanton and St. John, 1969; McConkey and Simpson, 1969] and the \( C^3\Pi_u \) state [Jore, Sharpont and St. John, 1967; Skubenich and Zapesochny, 1967; Burns, Simpson and McConkey, 1969; Aarts and de Heer, 1969] of \( \text{N}_2 \) and of the \( A^3\Pi_u \) state [Stanton and St. John, 1969; Srivastava and Mirza, 1969; Simpson and McConkey, 1969] and \( B^3\Sigma_u^+ \) state [Holland, 1967; Aarts, de Heer and Vroom, 1968; Srivastava and Mirza, 1968; Stanton and St. John, 1969; Koval et al., 1969; Borst and Zipp, 1970; Sheridan, Oldenberg and Carlton, 1971].
1971] of N2. Comparisons of results [KIEFFER, 1969 and 1971] show many rather significant discrepancies. Fair agreement has been obtained among the more recent measurements for the B^2Σ_u^+ state as shown in Figure 2 from Kieffer [1971]. An example of the experimental difficulties encountered is seen in the order of magnitude difference in excitation cross sections for the C^3Π_u state at 100 eV attributed by Aarts and de Heer to the effects of secondary electrons. Measurements of the cross sections for the dissociative excitation of N2 to various states of N and N^+ have been reported [STOKE, 1969; AARTS, de HEER and VRETEN, 1969; SREBVSTAVA, 1969; AJELLO, 1970]. The values given by Stoka appear to be much too large since they are much larger than other data. The total dissociation cross section obtained by Winters [1966] is comparable with total excitation cross section [BRINKMAN and TRIMAR, 1970].

Measurements of energy and angular distributions of inelastically scattered electrons are providing a large amount of detailed information regarding cross sections for electronic excitation in N2. In addition to the review by Lassette [1969] data have been presented for inelastically scattered electrons in N2 at small angles [SEURBELE, DELLON and LASSETTE, 1967; LASSETTE et al., 1968; GEIGER and SCHRODER, 1969; SEURBELE and LASSETTE, 1970], at intermediate angles and at 90° [WILLIAMS and DOERING, 1969] and over a wide range of angles [BRINKMANN and TRIMAR, 1970]. The measurements of electron scattering at small angles have been particularly useful for the identification of important electron excitation processes, testing of generalized oscillator strength relations, determining Franck-Condon factors, and deriving oscillator strengths for use in the prediction of total excitation cross sections at high energies. The determination of total excitation cross sections from differential cross section measurements at moderate and low electron energies is difficult because of elastic and instrumental background scattering, uncertainties in the effective product of gas density and path length, the difficulties of measurements at both small and large angles, etc. Determinations of the relative cross sections for various energy losses at a few values of incident energy have been normalized to optical excitation and ionization cross sections to obtain a complete set of energy loss cross sections for N2 [BRINKMANN and TRIMAR, 1970]. In some cases it is possible to identify a particular excitation process and compare the measured cross sections with earlier semi-empirical results [STOLARSKI et al., 1967] and with optical experiments [AARTS and de HEER, 1969]. The set of cross sections given by Brinkmann and Trimar [1970] appear to be the best available for the calculation of excitation rates for the lower triplet and singlet states and of total energy loss rates. For the excitation of ionic states semi-empirical cross sections [PETYSER, PRASAD and GREEN, 1969] are easier to use. The use of recent cross section data in auroral calculations will be presented later in this session [CARTWRIGHT, WILLIAMS and TRIMAR, 1971].

Additional cross section data for electronic states of N2 have been obtained from measurements of the excitation cross sections near threshold [BRONGERSMA, BOERHOM and KSTERMACHER, 1969]. Although recent studies [FEURIG, 1969; MAEGER and HOLLAND, 1970] have increased our understanding of the lifetimes and energies of maximum excitation of metastable states of N2 and N3, these studies have not yielded absolute cross section data.

Cross section measurements have been reported for the dissociative excitation of N2+ [VAN ZYL and DUNN, 1967] and for the excitation of the N2 B^2Σ_u^+ state from the N2^+ X^2Σ_u^+ state [LEE and CARLETON, 1969]. Recent theoretical calculations above such excitation cross sections in N2 include those for singlet states by Rozenhai [1967] and for triplet states by Cartwright [1970].

Measurements of fluorescence efficiency under electron and photon bombardment are intended to give directly the rates of emission of photons and so bypass cross section determinations and electron energy degradation calculations. Recent measurements of the fluorescent yields produced by 0.65 to 1.6 MeV energy electrons [HURMII, POSI and ENDER, 1970] and 1 to 10 keV photons [MITCHELL, 1970] yield efficiencies for conversion of electron and photon energy to 3914 Å radiation from the N2 B^2Σ_u^+ state of about 5%. A somewhat lower value 0.3% was obtained [HARTMAN, 1968] when the primary electron beam was completely stopped in the gas. Some of these experiments [HARTMAN, 1968; MITCHELL, 1970] yielded efficiencies for other auroral features. Except for studies of the 3914 Å band, very little effort appears to have been devoted to the comparison of the fluorescent efficiencies determined from laboratory measurements and from calculations using laboratory or theoretical cross sections. In addition to the cross sections considered above, such a calculation requires a knowledge of the quenching rate for each excited state [MITCHELL, 1970] the effect of cascading [CARTWRIGHT, TRIMAR and WILLIAMS, 1971a], the accuracy of the electron energy distribution [PETYSER, 1969], etc. The comparisons discussed here are a far more sensitive test of the models of electron excitation used for auroral calculations than are the earlier calculations of ionization yields [PETYSER and GREEN, 1968]. Examples of effects to be considered in such a calculation we note the very complicated cascading effects among the triplet states of N2 [CARTWRIGHT, TRIMAR and WILLIAMS, 1971a].

**Molecular Oxygen**

Recent measurements of apparent cross sections for excitation from the O2X^3Σ_g state include studies of emission from the O2B^3Σ_u state [NISHIMURA, 1968;
Atomic Oxygen and Nitrogen.

Most of the available cross sections for the excitation of atomic oxygen and nitrogen from their ground states have been obtained from theoretical calculations for O are reviewed and criticized by Takayanagi and Itikawa [1970]. Thus, the earlier calculations of cross sections for transitions among the fine-structure levels of the 2P state by Brag and Lin [1966] have been shown by Dalgaro and Degges [1968] to make a significant contribution to electron cooling in the upper atmosphere. Cross sections for the excitation of the 3P level of O, i.e., the upper level of the 1302 Å line [Pek, 1970; Hicks and Chubb, 1970], have been made most recently by Takayanagi and Onda [1968]. Cross sections for excitation of the 1D and 1S states of O from the 2P ground state of O and of the 2D and 3P states of N from the 3S ground state of N have been calculated recently by Henry, Burke and Sinfailam [1969]. Very recently, Stone and Zipf [1971] have obtained cross sections for the excitation of the O1P and N2P states which are much larger than predicted by theory at electron energies below 25 eV.

Helium

Large numbers of papers concerned with the electron excitation cross sections for helium have appeared in recent years. We will cite only a few of those appearing since the reviews by Moiseiwitsch and Smith [1968] and Lassettre [1969], the compilation by Kieffer [1969] and the recommended complete set of cross sections by Jusick et al. [1967]. Measurements of polarization and optical excitation cross sections have been reported by Bogdánova and Marusić [1969]. Most recent determinations of helium excitation cross sections using differential electron scattering techniques have been concerned with the n = 2 levels [Vrieze, Simpson and Mielczarek, 1968; Ehrhardt, Langhans and Linder, 1965; Truhlar et al., 1970; Chamberlain, Mielczarek and Kuyatt, 1970; Peressi, Le Nandan and Pochat, 1970]. Excitation cross sections near threshold have also been obtained using the trapped electron technique [Brongersma, Borbroom and Kistemacher, 1969] and the diffusion method of Meir-Leibnitz [Schafer and Schiernekr, 1969]. As indicated by the comparisons of excitation cross sections obtained in various experiments [Jusick et al., 1967; Kieffer, 1969] there is still considerable uncertainty as to the correct values for most of the helium excitation cross sections. An apparent exception is the agreement between cross sections for the 2P level as obtained from optical measurements [Johre and St. John, 1967; Moustafa Moussa, de Heer and Schuttten, 1969; Van Eck and De Jongh, 1970; McConkey, Donaldson and Hender, 1971] and electron scattering measurements [Chamberlain, Mielczarek and Kuyatt, 1970]. Theoretical calculations of cross sections for the excitation of He have been reviewed by Moiseiwitsch and Smith [1968] and, for singlet states, by Flannery [1970] and Truhlar et al. [1970].
Boerboom and Kistermacher, 1969] and for the relative intensities of several allowed and forbidden transitions [Lassetre et al., 1968; Foo, Brian and Hasted, 1971].

In the case of \( \text{H}_2\text{O} \), the cross section has been measured for the dissociative excitation of the \( 2P \) and \( 2S^0 \) states of \( \text{O} \) [Lawrence, 1970], and some information has been obtained as to relative excitation cross sections at a few energies for metastable fragments [Freund, 1971 a] and as to the identification of excited levels with significant excitation cross sections [Lassetre et al., 1968; Trajmar, Williams and Kupperman, 1971 a; Claydon, Segal and Taylor, 1971].

Of possible interest in connection with planetary atmospheres are the recent measurements for CO of cross sections for the production of radiation by various states of \( \text{CO} \) and \( \text{CO}^+ \) [Skeubenich, 1967; Aarts and de Heer, 1970 a, b], of the \( A^1 \Pi \) state of \( \text{CO} \) [Mumma, Stone and Zipf, 1971] and the \( 3P \) and \( 3S^0 \) states of \( \text{O} \) [Lawrence, 1970]; of the cross section for excitation of the \( a^3 \Pi \) state near threshold [Brongesma, Boerboom and Kistermacher, 1969]; and of differential electron scattering cross sections for excitation of the \( A^1 \Pi \) state at high energies [Lassetre and Skeubelle, 1971; Meyer and Lassetre, 1971] and of various levels of \( \text{CO} \) [Trajar . Williams and Cartwright, 1971].

Dissociative excitation cross sections for \( \text{O} \) from \( \text{NO} \) have been measured [Lawrence, 1970] and some electron scattering data are available [Lassetre et al., 1968].

The work on excitation of positive atomic ions has been reviewed by Moisewitsch and Smith [1968] and Burgess, Hummer and Tulley [1970] and compiled by Kieller [1969].

**Vibrational and rotational excitation**

The experimental and theoretical data for vibrational excitation of molecules have been reviewed by Takayanagi [1967], by Phelps [1968] and by Takayanagi and Itikawa [1970]. More recent measurements in \( \text{N}_2 \) have yielded vibrational excitation cross sections in the 10 to 100 eV range [Skeubelle, Dillon and Lassetre, 1968; Trajar . et al., 1971], the energy dependence of the de-excitation cross section for what is probably the \( v = 5 \) level of \( \text{N}_2 \) [Burrow and Davidovits, 1988], and the cross section for excitation of the first vibrational level very near threshold [Burrow and Schulz, 1969]. Measurements of the angular dependence of the scattering cross section in the vicinity of the 2 eV resonance of \( \text{N}_2 \) have been correlated with theories of the resonance [Ehrhardt and Willmann, 1967; Birdesley, Mandle and Wood, 1967; Birdesley, 1968; Krauss and Mies, 1970; Soninikov, 1971; Birtwistle and Herzberg, 1971].

Recent measurements of vibrational excitation in \( \text{O}_2 \) [Spence and Schulz, 1970; Linder and Schmidt, 1971] have demonstrated that the excitation cross sections are a series of very narrow spikes located at the energies of the vibrational states of \( \text{O}_2 \) and that most of the resonant collisions result in excitation of the first vibrational state of \( \text{O}_2 \). Although these observations mean that the set of vibrational cross sections proposed by Hake and Phelps [1967] is no longer valid in detail, one expects reasonable agreement between the rates of electron energy loss calculated using the cross sections of Hake and Phelps [1967] and those of Linder and Schmidt [1971], but not with those of Spence and Schulz [1970].

Of possible interest in planetary atmospheres are recent studies of vibrational excitation in \( \text{CO} \) which have been concerned with the region near threshold [Hake and Phelps, 1967; Itikawa and Takayanagi, 1969; Burrow and Schulz, 1969]; the resonance region [Ehrhardt et al., 1968] and relatively high energies [Skeubelle, Dillon and Lassetre, 1968]. Recent determinations of vibrational excitation cross sections in \( \text{CO} \) include measurements of differential scattering cross sections [Bones and Schulz, 1968; Andrick, Danner and Ehrhardt, 1969] and of total cross sections near threshold [Stamatovic and Schulz, 1969]. These experiments have led to a considerable revision [Phelps, 1970] of the set of vibrational excitation cross sections proposed by Hake and Phelps [1967] but little change in averaged energy exchange or loss rates. These data have also been considered in recent theoretical models of electron scattering by \( \text{CO}_2 \) [Bardesley, 1969; Claydon, Segal and Taylor, 1970; Itikawa, 1971; Andrick and Read, 1971]. Vibrational excitation and de-excitation of ions by electrons have been considered by Boikov and Obedkov [1968] and by Egevag and Obedkov [1969], but their results do not appear to have been applied to atmospheric ions.

An important point to remember when using the measured cross sections for vibrational excitation is that as the population of vibrationally excited states increases, it is necessary to consider the effect of electron excitation and de-excitation of the excited states. At present the only cross sections available for this purpose are the theoretical results for \( \text{N}_2 \) obtained by Chen [1964]. An application of these cross sections by Nigham [1970] shows that for mean electron energies above about 1 eV the net rate of electron energy loss is nearly independent of vibrational temperature for temperatures up to 4000 K.

The excitation of rotational states of molecules has been reviewed by Phelps [1968] and, more recently, by Takayanagi and Itikawa [1970]. In the case of \( \text{N}_2 \), the cross sections given by the Born approximation are in good agreement with distorted wave calculations [Sampson and Mølness, 1965] for energies below the vibrational threshold. From comparisons with experiment [Phelps, 1968] one
expects the rotational excitation cross section at energies above 0.3 eV to increase less rapidly than predicted theoretically [Geltman and Takayanagi, 1966; Oksuk, 1966]. In the case of $O_2$, experimental data [Nelson and Davis, 1971] which will allow determination of rotational excitation cross sections for orientation with theory [Geltman and Takayanagi, 1966] is just becoming available. A preliminary analysis by the author indicates that the rotational excitation cross sections at low energy are very low, as predicted by theory [Takayanagi and Geltman, 1966], but rise less rapidly than calculated.

The rotational excitation of homonuclear ions by electrons has been considered most recently by Boikova and Obedkov [1968]. Theory [Stabler, 1963; Sampson, 1965] indicates that the rate of electron energy loss by this process is equal to or smaller than that for the recoil of the ions in elastic scattering collisions.

**Energy Loss Rates**

The inelastic and ionization cross sections discussed above are often used to calculate energy loss functions or stopping cross sections and the related energy loss rate coefficients. Thus, Peterson and Green [1968], Dalgarro, McElroy and Stewart [1969] and Takayanagi and Itikawa [1970] have given values of these coefficients for electron energies between $4 \times 10^7$ eV and 300 K. At mean electron energies below about 1 eV the energy exchange rate coefficients obtained from electron transport coefficients [Englehardt, Phelps and Risk, 1964; Hake and Phelps, 1967; Phelps, unpublished] can be converted into energy loss coefficients by multiplying by the excess of the corresponding electron energy above the thermal value. This procedure shows that some of the estimates of energy loss rates based on theoretical rotational excitation cross sections are too large [Takayanagi and Itikawa, 1970]. Plots of electron energy exchange frequencies per molecule as calculated from electron transport coefficient data are shown in Figure 3.

Electron energy loss as the result of the recoil of positive ions in elastic collisions has been reviewed by Dalgarro [1969] and Takayanagi and Itikawa [1970]. Electron energy "loss" in collisions with other electrons has been considered recently by Schunk and Hays [1971] and Schunk, Hays and Itikawa [1971]. However, it must be kept in mind that their results include two separate effects, i.e., a true energy loss due to the generation of plasma waves which may not be reabsorbed locally, and an energy sharing process which results in a heating of the low energy electrons while cooling the high energy electrons. Electron energy loss in collisions with atmospheric molecules is negligible compared to rotational and vibrational excitation.

**Figure 3**

Electron energy exchange frequency per molecule versus characteristic electron energy. For a Maxwellian electron energy distribution the characteristic energy is equal to $kT_e$, the product of the Boltzmann constant and the electron temperature.

**Elastic and Total Scattering Cross Sections**

The total scattering cross sections of electrons by atmospheric gases are of interest in connection with aurora and airglow primarily through the effect of multiple scattering on the range of high energy electrons, i.e., on the altitude at which the incident auroral electrons give up their energy [Stolarski, 1968; Rees, 1969; Berger, Seltzer and Maeda, 1970] or on the altitude from which photoelectrons can escape from the atmosphere [Nagy and Banks, 1970] and in considerations of the relation between electron collision frequencies and electron temperatures [Reid, 1964; Gustafson, 1969].

Recent measurements of elastic and inelastic plus inelastic scattering cross sections include the differential elastic scattering cross sections for $N_2$ and CO at 500 eV [Bromberg, 1969] and for $N_2$ and $O_2$ at 37 and 60 KeV [Fink and Kessler, 1967], the differential cross sections for $N_2$ for all scattering processes at 40 KeV [Bonham, Fink and Kohl, 1969] and the elastic plus inelastic cross sections integrated over angle for atomic and molecular oxygen at moderate
energies [SUNSHINE, AUBRY and BEDERSON, 1967; SALOP and NAKANO, 1970]. The theoretical calculations of the scattering cross section integrated over angle for atomic oxygen [HENRY, BURKE and SIN- FALAN, 1969] are in good agreement with experiment [SUNSHINE, AUBRY and BEDERSON, 1967] for electron energies between about 0.5 eV and 12 eV. For electron energies below several eV electron transport coefficient data provide the most accurate means of determining electron collision frequencies for N$_2$ [ENGLEHAFT, PHELS and RISK, 1964], O$_2$, CO and CO$_2$ [HAKE and PHELS, 1967]. Theoretical investigations of molecular gases have been concerned with CO and CO$_2$ [SINGH, 1970; CRAWFORD and DALGARNO, 1971].

A number of measurements have been reported of the differential cross sections for elastic scattering in helium at energies above 100 eV [VRIENS, KUYATT and MIELCZAREK, 1968; BROMBERG, 1969; CHAMBERLAIN, MIELCZAREK and KUYATT, 1970]. The absolute measurements of Bromberg over a wide range of angles at 500 eV are being used as a reference for normalization of other differential scattering measurements [LASETTRE, 1969; OPAL, PETERSON and BEATY, 1971]. Recent theoretical calculations of elastic scattering cross sections for helium [CALLAWAY et al., 1968; LABAIN and CALLAWAY, 1969; GANAS, DUTTA and GREEN, 1970; PURCELL, BERG and GREEN, 1970; KHARI and SHOBKA, 1971] are in good agreement with these experimental values. At electron energies below 20 eV the measurements of total scattering cross section [GOLDEN and BANDEL, 1965] and momentum transfer cross section [CRUMPION, ELFORD and ROBERTSON, 1970] appear to agree with theory [MICHELS, HARRIS and SCOLESKY, 1969], but their consistency with measured angular distributions [GIB- SON and DOLDER, 1969] have been questioned [BRAN- DEN and McDOWELL, 1969]. It appears that the momentum transfer cross section determinations for electron energies below several electron volts [CRUMP- TON, ELFORD and ROBERTSON, 1970] are probably the most accurate elastic cross section determinations available [BEDERSON and KIEFFER, 1971] and can serve as a basis of normalization of other experiment. The energy range between 20 and 100 eV has also been investigated theoretically [LABAIN and CALLA- WAY, 1970].

**Electron-ion recombination**

The cross sections and rate coefficients for the recombination of electrons and ions of atmospheric gases are of interest here largely because of the possibility of the resultant production of excited atoms as occurs in the nightglow [NOXON and JOHANSON, 1970; FORBES, 1970] and in the dayglow [FELDMAN, DOERING and ZIPF, 1971; SCHAEFFER, FELDMAN and FASTIE, 1971] and to a lesser extent, in aurora [OMHOFT, 1968; PARKINSON, ZIPF and DONAHUE, 1970].Measurements of the spectral line width [HERNANDEZ, 1971] and of the variation of intensity with electron energy [BRODIE, SPIELER and HAKE, 1970] are evidence for the production of the O$^+$ ions (6300 Å) by dissociative recombination. Radiative and ion recombination have also been considered as sources of excited atoms [HANSON, 1970; OLSON, PETERSON and MOSELEY, 1971].

Experimental and theoretical studies of dissociative recombination have been reviewed recently by Bardsley and Biondi [1970]. Of particular interest are the measurements of the partial dissociative recombination coefficients for the production of the $1D$, $3S$ and $3P$ states of O from O$_2$ [KASNER, 1967], O$_3$ [KASNER and BIONDI, 1968] and NO$_2$ [WELLER and BIONDI, 1968] and on electron temperature for N$_2$ and O$_3$ [MEHR and BIONDI, 1969]. Bardsley [1968] has shown how dissociative recombination coefficients can be calculated theoretically when sufficient spectroscopic data are available. Bardsley [1970] was unable to obtain the rapid decrease in recombination coefficient observed experimentally when he used a model in which the recombination coefficient varied with vibrational excitation [CUN- NINGHAM and HORSE, 1969; O'MALLEY, 1969]. Unfortunately, studies of the temperature dependence of recombination coefficients which do not use mass spectrometric identification do not provide experimental data as to relative concentrations of cluster ions, such as N$_4^+$ and O$_3^+$, or of the degree of dissociation of the diatomic ions at high temperature [DUNN and LORDI, 1970 a, b].

**Other collision processes**

Electron attachment does not appear to be an important process at the altitudes of interest for airglow and aurora. Electron loss occurs primarily by recombination [BARDSLEY and BIONDI, 1970; PHARO et al., 1971]. The loss of electrons and the dissociation of O$_2$ by dissociative attachment is effectively balanced by associative detachment [FEHSENFELD et al., 1969]. The net effect is a very small contribution to the energy loss function for electrons and the production of excited O$_2$.

The generation of continuum radiation by electron collisions does not appear to have been observed in aurora or airglow experiments. Recent experimental measurements of continuum radiation in high temperature nitrogen and oxygen [MORRIS, KREY and GARRISON, 1969; TAYLOR and CALEDONIA, 1959] are in poor agreement with theory. In the case of radiation emitted in free-free transitions, a considerable body of theory is now available for calculations of intensities from elastic scattering cross sections [JOHNSTON, 1967; MIOLANESS and RUPPEL, 1969].
DISCUSSION

The preceding review of recent studies of electron collisions with atmospheric species shows that much progress has been made toward determining the cross sections needed for the analysis and prediction of auroral and airglow observations. An area in which there is a special need for experimental work is the measurement of electron excitation cross sections for atomic oxygen. In the meantime, improved theoretical calculations would be very useful. A second area is that of the excitation of molecules to ultraviolet emitting molecular and atomic states, e.g., the $a^3PI_g$ state of $N_2$ and the $3s^23p$ state of $N$. Comparisons of laboratory measurements of fluorescent yields from both optically allowed and forbidden states, e.g., $N_2^*B^2Σ^+_u$ and $N_2^*C^2Π_u$, with values calculated using auroral or dayglow models would serve as a very important test of the cross sections, calculation procedures, etc. which make up the models.

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REFERENCES


HOLLAND R. F., “Cross Sections for Electron Excitation of the 3914Å (0, 0) Band of the N₂ First Negative System,” Los Alamos Scientific Laboratory Report LA 3783, August 1967.


STOLARSKI R. S. and GREEN A. E. S., "Calculations of Intensity of the Electron Impact Excitation in 0.72, 967, 1967.


