Momentum-Transfer Cross Sections and Conductivity Ratios for Low-Energy Electrons in He, Ne, Kr, and Xe†

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Conductivity ratios have been measured in weakly ionized afterglows of repetitively pulsed, electrodeless, rf discharges in helium, neon, krypton, and xenon using a microwave resonant cavity (2.7 GHz). Maxwellian electron-energy distributions were obtained at temperatures from 300°K to 10 000°K, as measured with a gated microwave radiometer (4 GHz), Momentum-transfer cross sections for electrons of energy up to 2 eV in neon, krypton, and xenon were determined from the measured conductivity ratios by an iterative procedure. The results in helium support the momentum-transfer cross section determined from the electron-beam experiments of Golden and Bandel. Those for neon indicate a scattering length of $+0.20a_0$. The momentum-transfer cross sections for krypton and xenon agree best with, but are generally lower than, those of Frost and Phelps and indicate a deeper (approximately 2.5 times) Ramsauer minimum. An experimental check of the theoretical electron-ion collision frequency for high-frequency, low-temperature conditions has been made.

I. INTRODUCTION

Measurements of the high-frequency conductivity ratio of weakly ionized gases can be used to determine momentum-transfer cross sections for electrons colliding elastically with gas atoms. Such measurements have previously been made in hydrogen,[1] helium,[2] and neon[3] at average electron energies up to about 2 eV by using a microwave-resonant-cavity technique. The range of electron energies studied was obtained by the constant-temperature-bath method – for the lower energies – and by heating with a separate microwave field at the higher energies. In the former case it is assumed that the electrons in the afterglow of a pulsed discharge have reached thermal equilibrium with the neutral gas[4] while in the latter case the electron energy is computed from a knowledge of the heating-field configuration, the electron-loss mechanism and the neutral-gas temperature. The heating-field method is not easily adaptable and has not been applied to gases such as krypton and xenon which have, near the Ramsauer minimum, a cross section varying rapidly with electron energy.

In the work reported here the conductivity ratio has been measured using essentially the same resonant-cavity technique as that introduced by Gould and Brown.[2] However, unlike previous measurements, the electron temperature has been determined directly with a microwave radiometer. Helium, neon, krypton, and xenon have been studied at average electron energies from 0.04 up to about 1 eV. The measurements were made in the afterglow of a pulsed discharge where the electron-energy distribution function is observed to be closely Maxwellian. Momentum-transfer cross sections as a function of electron energy can then be simply extracted from the measured conductivity ratios using an iterative computation technique.

Previous determinations of electron-atom scattering cross sections have made use of electron-beam techniques and indirect methods. Electron-beam techniques[5-7] – considered difficult to use at electron energies below about 0.5 eV – yield the total and differential scattering cross sections from which the momentum-transfer cross section may be found over a limited range of energies by applying effective-range scattering theory.[8,9] Indirect methods[10] are of two kinds: ac (microwave) and dc (electron swarm), and yield momentum-transfer cross sections through analysis of measured electron transport coefficients. These methods are most useful at low electron energies inaccessible to electron-beam methods, but the electron-swarm methods have until recently[11,12] been handicapped by uncertainties regarding the distribution function, while the microwave methods, including that used in this work, have until now lacked a direct measurement of the electron temperature.

II. METHOD

We consider a weakly ionized afterglow plasma in which all electron collisions are elastic. Electron-neutral collisions dominate, but electron-ion collisions are taken into account. The plasma is stationary and the ions are cold. A static magnetic field B and a low-level, high-frequency electric field E are applied to the plasma with $\vec{E} \parallel \vec{B}$. For $(\nu_c/\omega)^2 \ll 1$ and a Maxwellian electron-energy distribution, the complex conductivity is[13]

$$\sigma_c = \sigma_r + j\sigma_i = (4/3\sqrt{\pi}\,\langle u\rangle^{2.5})(ne^2/m\omega) \times \int_0^\infty [\nu_c(u)/\omega - j]\,u^{1.5}e^{-u/\langle u\rangle}\,du\,, \quad (1)$$

where σ_r is the real part and σ_i the imaginary part, n is the electron density, e is the electronic charge, m is the electronic mass, ω is the radian frequency of the applied electric field, $\nu_c(u)$ is the electron momentum-transfer-collision frequency, u is the electron energy in volts, $\langle u\rangle = kT_e/e$, k is Boltzmann's constant, and T_e is the electron temperature.

In the case of a microwave resonant cavity containing a plasma which only slightly alters the resonant frequency and does not lower the quality factor excessively, the plasma can be represented in an equivalent circuit by the complex admittance[14]

$$g_d + jb_d = \frac{\beta}{\epsilon_0 \omega_0} \frac{\int (\sigma_r + j\sigma_i) E^2 dV}{\int E^2 dV} , \tag{2}$$

where β is the coupling coefficient, ϵ_0 is the permittivity of free space, E is the electric field of the empty cavity, ω_0 is its resonant frequency, and the integration is over the cavity volume V. In the high-frequency approximation $(\nu_c/\omega)^2 \ll 1$, we can write[15,16]

$$\nu_c = \nu_{en} + \nu_{ei} , \tag{3}$$

including contributions due to electron-neutral and electron-ion collisions. Defining

$$\langle \nu_c \rangle = \frac{4}{3\sqrt{\pi}\langle u \rangle^{2.5}} \int_0^\infty \nu_c u^{1.5} e^{-u/\langle u \rangle} du , \tag{4}$$

and using Eqs. (1), (2), and (3), we find

$$-\frac{g_d}{b_d} = \frac{\langle \nu_{en} \rangle}{\omega} + \frac{\int n(\langle \nu_{ei} \rangle / \omega) E^2 dV}{\int n E^2 dV} . \tag{5}$$

It has been assumed that the electron temperature is uniform,[17] and in order to calculate the last term in Eq. (5), it is also assumed that the density obeys a zero-order Bessel function in the radial direction[18] and is uniform in the z-direction (the direction of $\vec{E}$), the electric-field configuration is that of the TM_{010} cavity mode, and[19]

$$\langle \nu_{ei} \rangle = 2.90 \times 10^{-12} n \ln\Lambda / \langle u \rangle^{1.5} , \tag{6a}$$

$$\Lambda = 6.2 \times 10^{13} 2\pi \langle u \rangle^{1.5} / \omega . \tag{6b}$$

For the cavity employed (Sec. III), Eq. (5) becomes[20]

$$-g_d/b_d = \langle \nu_{en} \rangle / \omega + 1.47 \langle \nu_{ei} \rangle^* / \omega , \tag{7}$$

where $\langle \nu_{ei} \rangle^*$ is evaluated from (6a) using the average density $\bar{n} = 0.432 n_0$, and n_0 is the density at the chamber axis. Thus from Eqs. (1) and (7)

$$(\sigma_r/\sigma_i)_{en} = g_d/b_d + 1.47 \langle \nu_{ei} \rangle^* / \omega , \tag{8}$$

is the conductivity ratio due to electron-neutral collisions. For the experimental conditions of the present work $\langle \nu_{ei} \rangle^* / \langle \nu_{en} \rangle \lesssim 0.1$. The ratio g_d/b_d for the plasma is measured[2] by comparing the power transmitted through the microwave cavity to the incident power at frequencies near the resonant value.

The electron temperature is measured directly with a gated microwave radiometer.[21–23] In this technique the plasma is illuminated by blackbody radiation from a known-temperature noise source composed of a gas discharge tube mounted in a waveguide (radiation temperature T_s) and a calibrated variable attenuator of attenuation α_p. The noise power radiated by the plasma electrons in a narrow bandwidth is compared electronically by means of synchronous detection to that from the blackbody noise source. When the radiometer is balanced, the electron temperature is given by

$$T_e = \alpha_p T_s + (1 - \alpha_p) T_0 , \tag{9}$$

where T_0 is the ambient temperature. This result is independent of the reflectivity and the absorptivity of the plasma, although the sensitivity depends on these factors.

For the experimental conditions of this work, the conductivity ratio is related to the momentum-transfer cross section Q_m by

$$\rho \equiv -p_0^{-1} (\sigma_r/\sigma_i)_{en} = 9.15 \times 10^{13} \langle u \rangle^{0.5} \times \int_0^\infty Q_m(u) \left(\frac{u}{\langle u \rangle}\right)^2 e^{-u/\langle u \rangle} d\left(\frac{u}{\langle u \rangle}\right) , \tag{10}$$

where p_0 is the neutral-gas pressure in Torr normalized to 0°C and $Q_m(u)$ is in cm^2. [Equation (10) follows from Eq. (1) and the substitution $\nu_{en} = N Q_m v$, where N is the neutral-gas density, and v is the electron velocity.] To obtain the momentum-transfer cross section, a trial set of 50 values of Q_m versus u is used to calculate ρ versus $\frac{3}{2}\langle u \rangle$ for comparison with the experimental data. The values of Q_m versus u are successively adjusted until the experimental and calculated values of ρ agree. The first trial set of Q_m values was obtained from a polynomial fit[20] to the conductivity ratio data, making use of previous cross-section determinations at energies above 2 eV.

III. EXPERIMENTAL APPARATUS

A block diagram of the apparatus is shown in Fig. 1. The discharge tube is made from quartz tubing (20 mm o.d., 1 mm wall) bent in the shape of a racetrack with 200 mm straight sections and 150 mm U-bend radii. Three turns of wire wound around the racetrack and energized by pulses of rf (3.5 MHz, 6 kV amplitude, 100–500 μsec duration, 30 Hz repetition rate) inductively couple power into the gas to form the plasma. At a late time in the afterglow (> 2 msec), determined by the electron density desired, the rf turns are re-energized with a short burst of rf power (2 kV amplitude, 10 μsec duration) to heat the plasma electrons. The neutral gas is not significantly heated during the discharge or during the electron heating.[20] Measurements are made at times later than 40 μsec after the heating pulse. Electron temperatures up to 10^4 °K are obtained at densities of approximately 2×10^{16} m^{-3} by this means. A dc magnetic field of 0.12 T is used to obtain enhancement of the radiation from the plasma due to cyclotron emission and thereby improve the sensitivity of the radiometer. This magnetic field is not essential to the operation of the rf discharge and measurements made with and without it show,[20] as expected, that it does not affect the conductivity ratios.

The microwave cavity is a right circular phosphor-bronze cylinder 8.175 cm i.d. and 11.25 cm

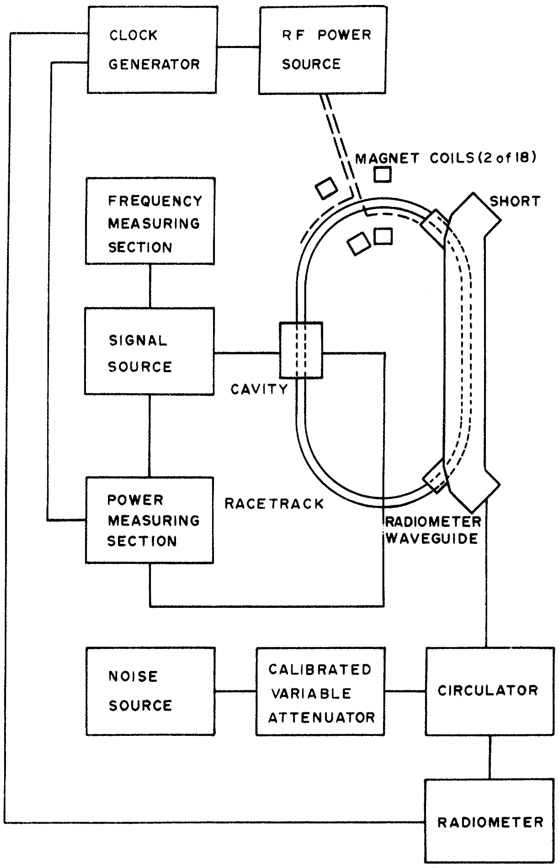

FIG. 1. Experimental apparatus.

long with 2.1-cm-diameter holes in the end walls to accommodate the plasma column. The TM_{010}-mode resonance frequency is 2.687 GHz, and the unloaded quality factor is 1450. The cavity perturbation theory[24] is well satisfied in the measurements; fringing field[25,20] and electron heating effects are not significant.

The C-band radiometer operates at 4.0 GHz, and the bandwidth of the receiver is 2 MHz. The repetition rate of 30 Hz allows sufficient decay time for the plasma to become transparent to the illuminating radiation from the noise source one-half cycle after the plasma radiation is sampled. The plasma column enters and leaves the radiometer waveguide through holes in the H-plane mitered corners.[26] Each hole has a circular waveguide beyond cut-off mounted over it to prevent radiation from escaping. The width of the waveguide about the racetrack is 0.197 in. larger than the standard C-band dimension. Double-section quarter-wavelength impedance transformers connect the enlarged section to standard C-band waveguide. The loss in the waveguide mounted about the racetrack and shorted at one end is 0.1 dB.

The vacuum system is bakeable and has a base pressure of approximately 5×10^{-8} Torr. Matheson of Canada, Ltd., research-grade gases are used without further purification,[27] except for passing them through cold traps and uranium metal (which acts as a getter for nonrare gases) in filling the chamber. The gas pressure is measured with a McLeod gauge (± 1% accuracy), which is isolated from the discharge tube by cold traps.

Simultaneous measurements of the conductivity ratio in both straight sections of the racetrack (the radiometer waveguide was replaced by a second cavity) show that the plasma has the same temporal behavior at the two locations.

Tests for a Maxwellian electron-energy distribution were made at early times following the heating pulse by using an S-band radiometer (3 GHz). The method[28] consists of measuring the electron radiation temperature as a function of ω_b/ω, where ω_b is the cyclotron frequency and ω is the operating frequency of the radiometer. The absence of resonance structure at $\omega_b/\omega = 1$ indicates a Maxwellian distribution (except in the special case that the collision frequency is independent of the electron energy). The results of the tests show[29] that the distribution is Maxwellian in the plasmas under consideration.

To minimize electron-ion collisions the microwave measurements are made at the smallest electron densities and largest neutral-gas pressures possible. The density limit is determined by the radiometer sensitivity and the pressure limit by one of the following: (1) the condition $(\nu_c/\omega)^2 \ll 1$ must be satisfied; (2) the quality factor of the cavity must remain large; (3) the electron-temperature decay must be slow enough to allow adequate time resolution in the radiometer measurements, i.e., ν_c must be small enough; (4) the plasma must be reproducible. These conditions are easily satisfied in all gases studied except in helium (see Sec. IV). For the plasma conditions of the present work, the time resolution of the microwave diagnostics (1 μsec) is adequate to ensure that changes in the electron temperature and density during a measurement are less than 1%.

IV. RESULTS

A. Helium

The measured conductivity ratios in helium are shown in Fig. 2. The energy range over which measurements could be made in this gas is limited by the problem of obtaining good time resolution; at higher values the electron energy decays too rapidly. Good agreement is found at 0.039 eV with the measurements of Gould and Brown.[2] Their measurements at higher energies – obtained with a microwave heating field – fall progressively lower than our results. For energies up to 0.1 eV Gould and Brown also measured conductivity ratios using the constant-temperature bath method. Although these measurements showed more scatter and were considered unreliable, owing to possible impurities released from the heated cavity walls, they are in somewhat better agreement with the present results.

Conductivity ratios calculated from momentum-transfer cross sections[9] obtained by applying effective-range theory[8] to the total cross sections

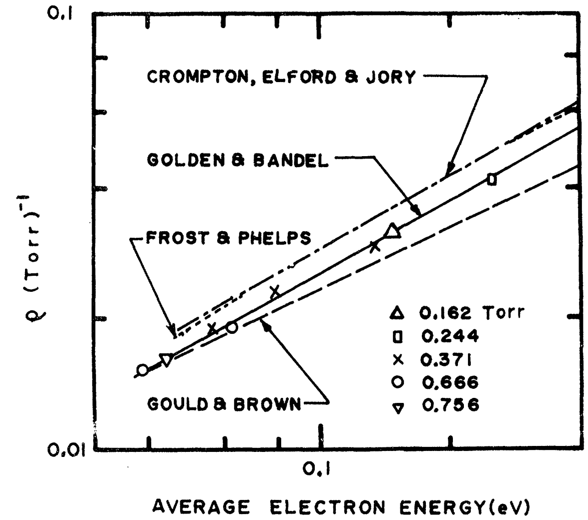

FIG. 2. Measured conductivity ratios in helium (points) compared with previous measurements (Gould and Brown) and values calculated from various determinations of the electron–helium-atom momentum-transfer cross section.

measured by Golden and Bandel[6] are in good agreement with the present measurements. Conductivity ratios calculated from recent electron-swarm cross-section determinations,[11,12] which have accurately accounted for the electron energy distribution, are about 10% higher than the present measurements.

B. Neon

The conductivity ratios measured in neon are shown in Fig. 3. As in the case of helium, good agreement with the earlier microwave measurements[3] is found at low electron energies. At higher energies a difference of up to 15% is observed.

The momentum-transfer cross section found from the present conductivity-ratio measurements is shown in Fig. 4 together with previous determinations. The difference between the present result and that of Gilardini and Brown[3] corresponds to the observed divergence in the conductivity ratio data. Our Q_m values are from 15 to 30% lower than O'Malley's,[8] which were calculated by applying effective-range theory to the total- and differential-cross-section data of Ramsauer and Kollath[30] obtained in electron-beam experiments. Measurements by Chen[31] at energies up to 0.15 eV agree with these calculated values. O'Malley suspects, however, that nitrogen impurities were present in the experiments of Ramsauer and Kollath, which would make the derived cross sections too large; owing to the relatively small cross section in neon, impurities would generally have this effect. Chen used a microwave-interferometer technique to measure the collision frequency; the electron temperature was determined indirectly with the constant-temperature-bath method. Momentum-transfer cross sections determined from drift-velocity measurements by Bowe[32] lie about 40% above the present measurements. Cross sections reported by Bowe for several gases are consistently higher than those of other workers.[33]

According to effective-range theory[8] the momentum transfer cross section at low electron energies is determined by the S- and P-wave phase shifts. The former is, for decreasing energy, increasingly dependent on the scattering length A of the atom. By fitting the theory to our measured cross section for neon, we find[34] a scattering length $A = +0.20a_0$ where a_0 is the electron Bohr radius. Previous determinations[8,31] range from $+0.03a_0$ to $+0.39a_0$ including the value $+0.24a_0$ found by O'Malley[8] from the data of Ramsauer and Kollath.[30]

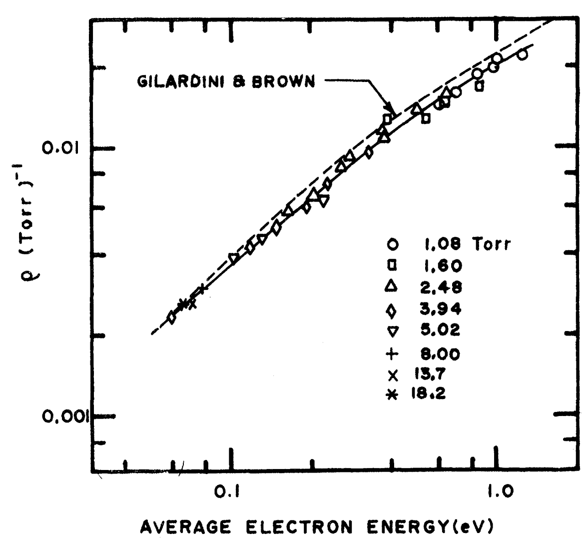

FIG. 3. Measured conductivity ratios in neon (points and solid-curve fit corresponding to the cross-section determination in Fig. 4) and previous measurements by Gilardini and Brown (dashed curve).

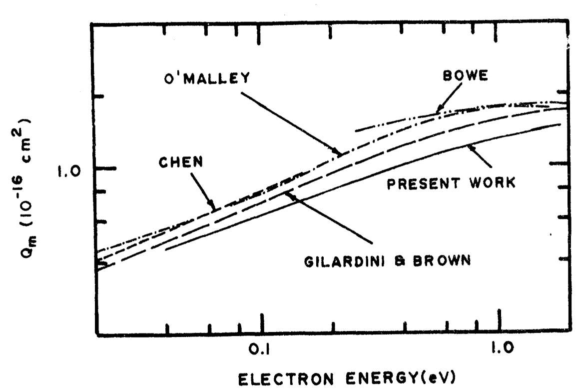

FIG. 4. Momentum-transfer cross sections for electrons in neon. The solid curve is the cross section used to give the fit to the conductivity-ratio data shown in Fig. 3. Previous cross-section determinations shown by the broken curves are discussed in the text.

C. Krypton

The measured conductivity ratios in krypton and xenon are presented in Fig. 5. Also shown are conductivity ratios calculated from the momentum-transfer cross sections derived from drift-velocity data[35] by Frost and Phelps.[11] The maximum disagreement between measured and calculated values is about 50% in krypton and 30% in xenon and occurs near the minimum corresponding to the Ramsauer effect in the cross sections. Momentum-transfer cross sections derived from the conductivity ratio data for krypton are shown in Fig. 6. For $u < 0.3$ eV various trial fits to the data showed that Q_m cannot differ much in shape or magnitude from the result shown.[36] However, near the Ramsauer minimum, the limited energy resolution of the experimental technique prevents a unique determination of the cross section; the insensitivity of the conductivity ratio to changes in the depth of the minimum is indicated by curves A (considered to represent the best fit), B, and C in Figs. 5 and 6. Nevertheless it is clear that the minimum in the cross section of Frost and Phelps is not low enough and does not occur at a high enough energy to fit the measured conductivity ratios. Below $u = 0.3$ eV the present Q_m determination agrees better with the results of Frost and Phelps than with those derived from microwave interferometer measurements by Chen,[37] or from the electron-beam experiments of Ramsauer and Kollath[30] by O'Malley.[8]

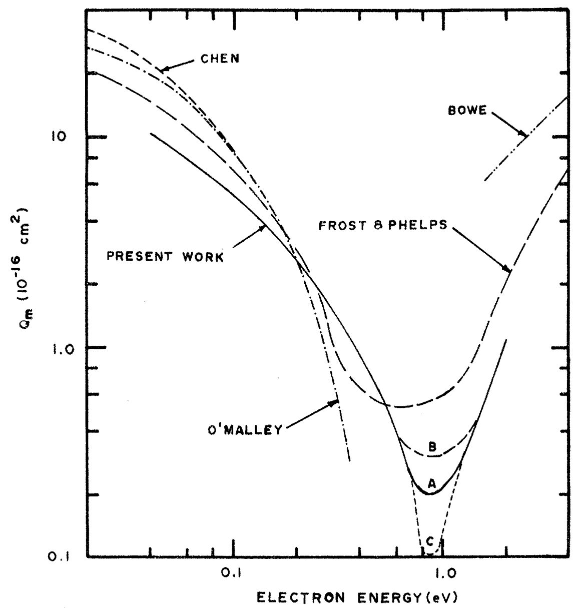

FIG. 6. Momentum-transfer cross sections for electrons in krypton. The solid curve (A) gives the best fit (A in Fig. 5) to the conductivity-ratio data for krypton. Curves B and C and the corresponding curves for krypton in Fig. 5 show the effect on the conductivity ratio of alterations in the depth of the minimum in the momentum-transfer cross section. Previous results shown are discussed in the text.

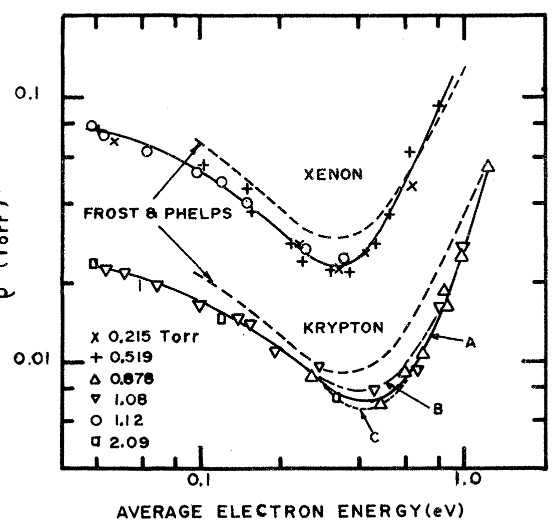

FIG. 5. Conductivity ratios in krypton and xenon. The solid curves indicate the best fits to the measured points for krypton and xenon and are obtained by using the cross sections shown by solid curves in Figs. 6 and 7. Curves B and C are obtained from the corresponding curves in Fig. 6 and illustrate the effect on the conductivity ratio of altering the depth of the minimum in the electron-krypton-atom momentum-transfer cross section. Conductivity ratios for krypton and xenon, calculated from the momentum-transfer cross sections of Frost and Phelps, are shown for comparison with the measured values.

The lowest-energy Q_m values[38] indicate a scattering length about 20% lower than the value found by O'Malley.

D. Xenon

The momentum-transfer cross section obtained from the conductivity ratio data for xenon is shown in Fig. 7. As for krypton, even though the cross-section determination near the Ramsauer minimum is not unique, owing to the finite energy resolution, it is clear (see Fig. 5) that the momentum-transfer cross sections derived by Frost and Phelps[11] from the drift-velocity data of Pack, Voshall, and Phelps[35] is not low enough in the Ramsauer minimum to fit the conductivity ratio data. However, the energy at which the minimum occurs is nearly the same in both cross-section curves. For $u < 0.15$ eV the present cross section measurements fall below those of Frost and Phelps (about 25%), as well as those derived by O'Malley[8] from electron-beam experiments[30] and the microwave-interferometer measurements by Chen.[37] As for krypton, the lowest-energy cross sections indicate a scattering length lower (about 15%) than that found by O'Malley.

E. Electron-Ion Collisions

Although the importance of electron-ion collisions in the conductivity-ratio measurements was mini-

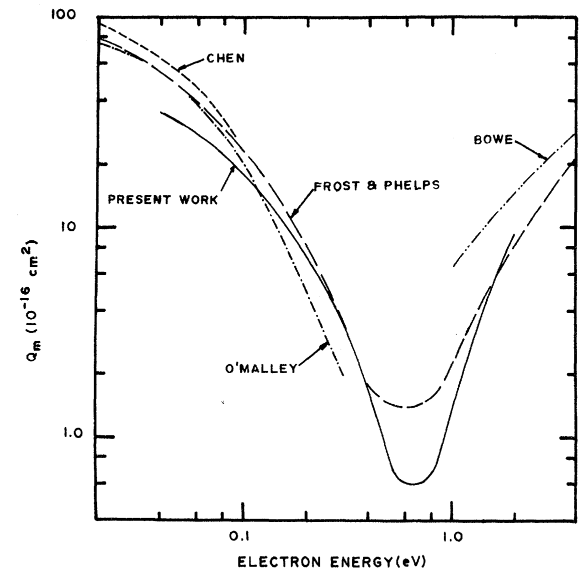

FIG. 7. Momentum-transfer cross sections for xenon. The solid curve shows the cross section used to obtain the fit (solid curve of Fig. 5) to the conductivity-ratio data. Previous results shown are discussed in the text.

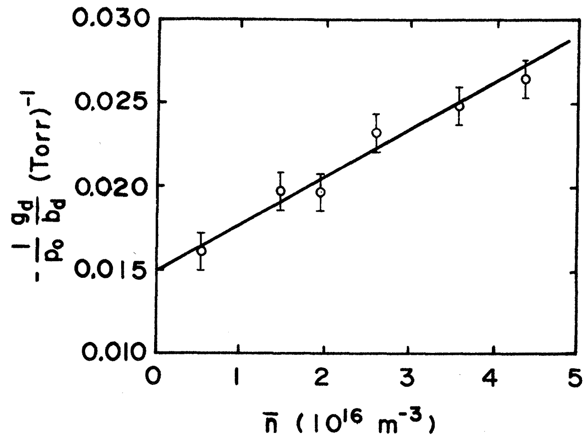

FIG. 8. Admittance ratio versus average electron density in helium. Measurements are for $p_0 = 0.756$ Torr, $\frac{3}{2}\langle u\rangle = 0.039$ eV and $B = 0.12$T. A straight line, whose slope is given by Eq. (7), has been fitted to the measured points.

mized by appropriate selection of the afterglow-plasma conditions (Sec. III), the procedure used to account for them was checked by measuring the ratio g_d/b_d at a fixed electron temperature and helium gas pressure, but for a range of plasma densities. The results are shown in Fig. 8. It is observed that a straight line, having the slope calculated from the last term in Eq. (7), gives a good fit to the experimental points. The intercept agrees with the lowest-energy conductivity-ratio measurement shown in Fig. 2. Finally, measurements at various plasma densities, with $B = 0.12$ T as well as with $B = 0$, showed no detectable differences in the ratio g_d/b_d. It is concluded that the electron-ion collision frequency given by Eq. (6) is appropriate for the conditions of this work and that the coefficient 1.47 in Eq. (7) is accurate to within 10%.

Electron-ion collision frequencies have been measured by Chen[31] at conditions for which the high-frequency low-temperature logarithmic term used here (Eq. 6b) should be applicable.[19] Chen's measured values are, however, higher (about 50%) than those expected from Eq. (6). The discrepancy is similar to that between his electron-atom momentum-transfer cross sections for Ne, Kr, and Xe, measured by the same technique, and those of the present work.

V. SUMMARY

The present conductivity-ratio measurements are in good agreement near room temperature with previous microwave cavity work in helium and neon. At higher electron energies – measured directly in the present work – some divergence from the previous results was found. The conductivity measurements in helium are consistent with momentum-transfer cross sections derived by Golden[9] from electron-beam measurements by Golden and Bandel.[6] For neon and at low electron energies in krypton and xenon, momentum-transfer cross sections[39] determined from the present conductivity-ratio measurements fall below those reported by other workers, but (in krypton) disagree least with the results of Frost and Phelps. The measurements for krypton and xenon indicate a deeper minimum (by a factor of 2 to 3) in the momentum-transfer cross section than was found by Frost and Phelps. Similar conclusions for argon have been reported by Golden.[9]

The scatter in the experimental points indicates a standard deviation of about 7% in a measurement of the conductivity ratio. A systematic error, no larger than 5%, may be present in the temperature T_S of the radiometer noise source. This error is not important at low energies where α_b is small (see Eq. 9), but can affect conductivity ratios at average electron energies above about 0.15 eV. The momentum-transfer cross sections have a measurement accuracy estimated at ±6% for neon and ±10% for krypton and xenon, except near the Ramsauer minima.

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Ionization and Attachment in O_2 and Airlike $N_2:O_2$ Mixtures Irradiated by 1.5-MeV Electrons*

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The production and removal of thermal electrons has been studied in O_2 and airlike $N_2:O_2$ mixtures between 1 and 10 Torr during continuous and intermittent irradiation by 1.5-MeV electrons. The use of a large reaction chamber and a spatially uniform electron beam flux reduces diffusion losses two orders of magnitude below those in previous experiments, and permits direct measurements of electron attachment at correspondingly lower total gas pressures. The observed rate coefficients for three-body attachment of thermal electrons at 300°K are $k_3(O_2) = (2.12 \pm 0.14) \times 10^{-30}$ cm^6/sec and $k_3(4N_2{:}\ O_2) = (1.10 \pm 0.07) \times 10^{-31}$ cm^6/sec, both during irradiation and in the afterglow. The effective cross sections for ionization by 1.5-MeV electrons and all resulting secondaries are $\sigma_e(O_2) = (2.83 \pm 0.7) \times 10^{-18}$ cm^2 and $\sigma_e(4N_2:O_2) = (2.45 \pm 0.7) \times 10^{-18}$ cm^2. These effective cross sections are larger than recently measured cross sections for primary ionization by a factor of 3.0 ± 0.8 in both gases.

I. INTRODUCTION

Charged particle production and loss mechanisms in atmospheric gases are being investigated in this laboratory under conditions relevant to the normal and the mildly perturbed ionosphere. This paper presents the results of measurements of ionization and electron attachment in O_2 and airlike $N_2:O_2$ mixtures irradiated by 1.5-MeV electrons.

Many ionospheric phenomena are initiated by the impact of energetic particles on the upper atmosphere. These include natural events such as auroras, and man-made disturbances such as the blackout of electromagnetic communications following a high-altitude nuclear detonation. The fast particles produce excited atoms and molecules as well as electrons and positive ions. The subsequent behavior of these newly formed species is controlled by various reactions, many of them dependent on the distribution of excitation in the reactants.

Previous laboratory investigations of thermal-energy reactions of charged particles have utilized low-energy electron-swarm techniques,[1,2] irradiation by γ rays,[3] flowing afterglows[4] and the afterglows of microwave discharges,[5-7] and of intense pulses of relativistic electrons.[8] Each of these techniques produces a characteristic distribution of charged particles, excited states, and new chemical species. None, however, duplicates the geophysically interesting situation of prolonged weak ionization by relativistic electrons. In particular, it is desirable to study electron-induced reactions both during irradiation and in the afterglow to evaluate the role of short-lived species created by the beam which may not persist into the afterglow. The technique employed in the present work is an attempt to reproduce the important features of the ionospheric situation in the laboratory and thus permit the direct evaluation of some of these effects.

II. EXPERIMENTAL TECHNIQUES

The experiment is shown schematically in Fig. 1. Gas is contained in a stainless-steel chamber 1.2 m in diameter and 0.6 m long, closed at one end by a 0.012-cm-thick aluminum foil. A diffuse beam of 1.5-MeV electrons from the Van de Graaff accelerator traverses the foil window and irradiates the gas, producing secondary electrons, ions, and excited species in collisions with the neutral molecules. The resultant ionization is studied by means of resonant cavity measurements of the free-electron density. Mass spectrometry, optical spectrometry, and low-frequency plasma-impedance measurements are also available for diagnostics; results obtained with these other techniques will be described in future publications. A detailed