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PHYSICAL REVIEW A VOLUME 7, NUMBER 3 MARCH 1973

Elastic Electron-Neutral-Atom Interaction Measurements in Helium at Ultralow Energies

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(Received 11 September 1972)

The cross section σ_{MT} for the elastic momentum transfer of electrons with helium atoms at ultralow energies has been deduced from measurements of the microwave absorptivity of a transient cryogenic afterglow plasma. The electrons were selectively heated by an adjustable-microwave electromagnetic field. This cross section can be approximated as a function of the incident electron kinetic energy u_e between 2×10^{-4} and 10^{-1} eV by $\sigma_{MT}(\text{cm}^2)=5.15\times10^{-16}[u_e(\text{eV})/2\times10^{-4}]^{0.02}$.

I. INTRODUCTION

There has been considerable recent theoretical interest in the energy dependence of the cross section for elastic scattering between low-energy electrons and helium atoms.[1-5] However, owing to many technical difficulties, most measurements at very low energies are not completely satisfactory. Following the pioneering works of Ramsauer and Kollath, of Brode, and of Normand,[6] Golden and Bandel[7] have made, in 1965, a very detailed direct measurement of the total electron-helium scattering cross section with electron-beam techniques. But these methods are difficult to extend to energies lower than 0.3 eV. In this low-energy range, elastic scattering cross sections are usually deduced from electron transport-coefficient measurements by dc or ac swarm methods; the corresponding analysis techniques have been considerably refined throughout the years. Measurements have been made down to electron temperatures of about 77 °K, yielding useful experimental data down to about 10^{-3} eV.[8]

Direct-current swarm techniques have been used recently by a variety of workers, down to gas temperatures near 77 °K. Extensive discussions of these techniques have been given in papers by Phelps and co-workers[9,10] and by Crompton *et al.*[11,12] Recent measurements by various groups are in good agreement with each other, and represent a consistent set of data down to 10^{-2} eV.[8]

Microwave methods—which are essentially ac swarm techniques—have been also used by many authors, following the pioneering works of Goldstein and co-workers[13,14] and of Gould and Brown.[15] Experimental problems associated with microwave techniques are summarized in the review article of Bederson and Kieffer[8]; most have been solved by now, particularly by Hoffmann and Skarsgard,[16] who have made measurements down to $T_e = 295\,^\circ$K, in good agreement with the results of Golden and Bandel,[7] and in fair agreement with accepted dc swarm results.

We have extended microwave transport-coefficient measurements down to electron average energies of 2×10^{-3} eV, obtaining useful results for the momentum-transfer cross section down to 2×10^{-4} eV. To this effect, we have made direct measurements of the microwave absorptivity of transient afterglow plasmas created at parent-gas temperatures near 4.2, 77, and 295 °K; the electrons were selectively heated by application of a microwave electromagnetic field of adjustable level.[13,15,16]

Our experimental system has been described in more detail elsewhere.[17–19] The plasma was formed by a high-voltage pulse of adjustable duration in a 45-cm-long cylindrical Pyrex tube of 0.75-cm i.d. We use high-purity commercial helium gas, further purified by cataphoresis. The whole experimental system in contact with ultrapure gases has typical ultrahigh-vacuum performances after 24 h of baking at 400 °C. Pressures are measured with a dibutylphtalate U-shaped manometer isolated from the high-vacuum system by a differential bellows manometer having a resolution of 5×10^{-3} Torr and a systematic error lower than 0.2% up to 20 Torr. The characteristic dimensions of the experimental system are such that pressure corrections due to thermomolecular effects are negligible.[20]

The plasma tube is contained inside a standard X-band waveguide used for diagnostics. This assembly is itself contained inside a sealed cylinder filled with gaseous helium to ensure thermal contact with the walls. This cylinder fits inside a metallic Dewar filled with liquid helium; for cryogenic work, the measured external temperature of the plasma tube was always between 4.2 and 4.3 °K, with or without plasma. The total power dissipated inside the plasma tube was kept low enough to ensure negligible heating of the helium gas.

II. MICROWAVE METHOD

All the plasma diagnostics relevant to the work reported here were made at X-band frequencies; electron densities and collision frequencies are deduced from the phase shift and the attenuation of a low-power-sensing microwave signal (1 μW at 8.77 GHz) measured by heterodyning at an intermediate frequency near 45 MHz.[21] We changed the electron temperature with a microwave "heating" field which only affects directly the free electrons.[22] The frequency of the heating field was $f_h = \omega_h/2\pi = 9.2$ GHz.

In a helium afterglow, heavy particles are neutral atoms and atomic and molecular ions. The monoenergetic electron-neutral collision frequency for binary collisions in a perfect gas ν is related to the electron-neutral collision cross section for momentum transfer σ_{MT}, to the neutral density n_0, and to the electron velocity v, assuming that the neutral atoms are at rest, by

$$\nu(v) = n_0 \sigma_{\text{MT}}(v)\, v \ . \tag{1}$$

An unambiguous determination of the electron-neutral collision frequency through measurement of the microwave complex dielectric constant is possible only if $\nu_{e0} \gg \nu_{ei}$, where ν_{ei} is the electron-ion collision frequency.[23,24] This gives a first experimental condition on n_0, n_e, and T_e for the applicability of the microwave method to the study of electron-atom interactions; however, the neutral density must remain low enough for relation (1) to be valid, i.e., for binary collisions to be dominant and for helium to be a perfect gas. This is easily met, even in our work at 4.2 °K.

Although they have no direct effect on the transfer of energy from the electron gas to the neutral gas, electron-electron collisions play a very important role, since they describe the transfer of energy *within* the electron gas. It can be shown[25] that they maintain a Maxwellian energy distribution for the electrons if the collision frequency for energy transfer ν_{ee} between electrons is substantially larger than the collision frequency for energy transfer $2m\nu_{e0}/M$ between electrons and neutrals of mass M. For an order-of-magnitude estimate, this can be written $\nu_{ee} \gg m\nu_{e0}/M$. Even in helium, the mass ratio $2m/M$ is low enough so that it is not difficult to choose a broad set of experimental situations where this condition is largely met, along with the other two already mentioned. Strictly speaking, this last condition is not necessary: If it were not met, it would still remain possible to solve Boltzmann's equation to obtain the electron distribution function; this is what has been done in recent dc swarm experiments. However, since it is not a very stringent condition in microwave work, where electron densities are usually fairly large, we prefer to impose it, since it eliminates another level of interpretation—and thus of uncertainty—in the analysis of experimental data.

When the electron energy distribution is Maxwellian at temperature T_e, the effective electron-atom collision frequency for momentum transfer, as measured by the microwave method,[23] is related to the cross section for momentum transfer,

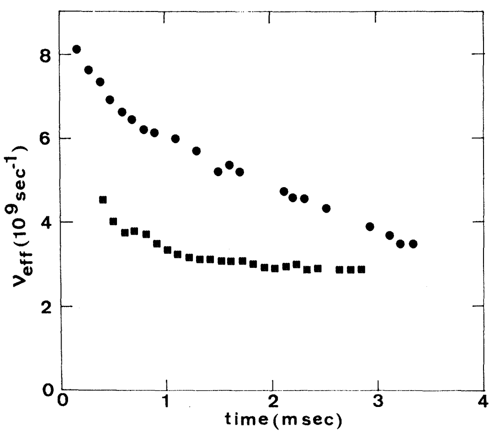

FIG. 1. Experimental variations of the effective collision frequency ν_{eff} with time in an afterglow at $T_0 = 295\,°K$ and $n_0 = 3.75\times10^{17}\ cm^{-3}$ (squares) and at $T_0 = 4.2\,°K$ and $n_0 = 1.26\times10^{18}\ cm^{-3}$ (dots).

σ_{MT}, by

$$\nu_{eff} = \frac{4}{3\sqrt{\pi}}\, n_0 \left(\frac{2}{m}\right)^{1/2} \frac{1}{(kT_e)^{5/2}} \int_0^\infty \sigma_{MT}(u) u^2 e^{-u/kT_e}\, du\,, \tag{2}$$

where $u = \frac{1}{2}mv^2$ is the incident electron energy.

It is of course necessary to have a very precise control of the average electron energy. For that, it is first possible to vary the temperature of the neutral gas, and to wait long enough in the afterglow for the electron temperature as measured with a microwave radiometer[26] to have relaxed to the neutral temperature. This is the technique we have used for cooling the electron gas near 300 °K. However, we will show later that the electron temperature relaxes very slowly to the neutral temperature at $T_0 = 4.2\,°K$; furthermore, a higher degree of control on electron temperature is necessary. For this reason, we also selectively vary the electron temperature by the well-known technique of microwave heating.[13]

When energy transfers by electron-electron interactions are strong enough to keep the energy distribution Maxwellian, a simple energy-balance equation[17,22] shows that in the absence of inelastic collisions the electron-temperature increase is proportional to the mean-square value of the microwave heating field averaged over the plasma volume. A detailed discussion, taking into account the necessary corrections, has been given elsewhere.[17,27–29]

III. EXPERIMENTAL RESULTS

Figure 1 gives the collision frequencies deduced from the measured microwave absorption in two typical afterglows in helium, at room temperature (near 295 °K, pressure 11.5 Torr corresponding to a neutral density $n_0 = 3.75\times10^{17}\ cm^{-3}$), and at liquid-helium temperature ($p = 0.55$ Torr, $n_0 = 1.26\times10^{18}\ cm^{-3}$). These results were obtained without microwave heating. It can be seen that the collision frequency relaxes rapidly toward a constant value in a room-temperature afterglow; simultaneous radiometric measurements[26] show this to correspond to the relaxation of the electron-gas temperature towards neutral-gas temperature. Systematic measurements of the microwave absorptivity of room-temperature helium afterglows, with or without continuous microwave heating, give very consistent and reproducible results, when the experimental conditions summarized in Sec. II are met: The collision frequency is linearly dependent on pressure at constant electron and gas temperatures, as shown in Fig. 2, as it should be in a perfect gas with only binary collisions. Furthermore, ν_{eff} is seen to vary very nearly as $T_e^{1/2}$. This indicates that the collision cross section is very nearly independent of energy.

The interpretation of experimental data such as those presented on Fig. 1 for afterglows near 4.2 °K is more difficult. The corresponding electron densities were much too low for the variation of collision frequency with time to be due to electron-ion collisions; furthermore, this interpretation would lead to a very inconsistent set of data. However, it may be noted that if σ_{MT} has a weak dependence on energy, as predicted by theory,[2] Eq. (2) reduces to

$$\nu_{eff} \cong \tfrac{4}{3} n_0 \sigma_{MT} (8kT_e/\pi m)^{1/2}\,. \tag{3}$$

If microwave heating is used to produce electron-temperature increments ΔT_e, experimental plots of ν_{eff}^2 as a function of ΔT_e should then fall very near straight lines having slopes proportional to the square of the neutral density n_0, and their

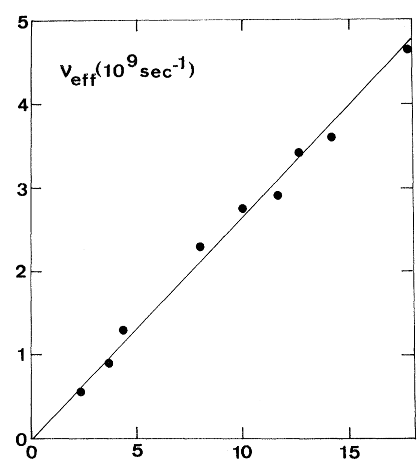

FIG. 2. Dependence of the measured effective collision frequency with pressure at $T_e = T_0 = 295\,°K$.

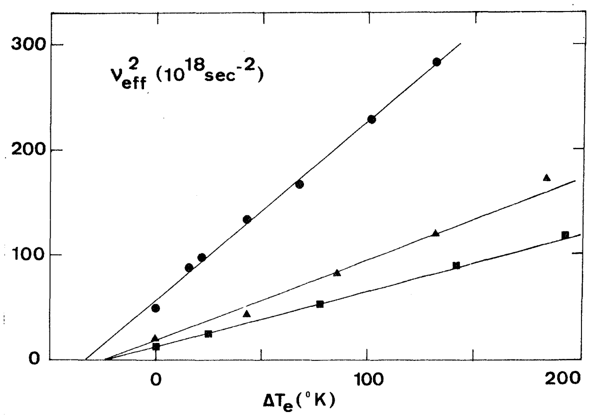

FIG. 3. Typical plot of ν^2_{eff} vs electron-temperature increments ΔT_e at $T_0 = 4.2$ °K with $n_0 = 2.3\times10^{18}$ cm^{-3} (dots), $n_0 = 1.6\times10^{18}$ cm^{-3} (triangles), and $n_0 = 1.2\times10^{18}$ cm^{-3} (squares). The times at which these measurements were made in the afterglow were, respectively, 1.3, 2.8, and 3.0 msec.

intercepts with the ΔT_e axis should give the value of the unperturbed electron temperature at the corresponding time in the afterglow.

In fact, this proves to be experimentally very well verified over the whole range of electron densities n_e, of neutral densities n_0, and of electron temperatures were the experimental criteria defined in Sec. II were met. As a sample, Fig. 3 gives three such experimental plots, randomly chosen between many others. The electron temperatures thus deduced are in good agreement with the temperatures independently deduced by a similar method from recombination measurements.[17] Radiometric confirmation of these measurements has not yet been possible, owing partly to the fact that a very low plasma absorptivity is associated here with a very low radiation temperature.

Figure 4 gives a log-log plot of the experimental values of the effective collision frequency ν_{eff} normalized to a neutral density $n_0 = 3.53\times10^{16}$ cm^{-3} as a function of the electron temperature T_e. For each electron temperature at $T_0 \cong 4.2$ °K, each experimental point was obtained by averaging data provided by plots of ν^2_{eff} vs ΔT_e (as described) at several pressures and at several electron densities. Above $T_e \sim 300$ °K a comparison can be made between our data obtained at $T_0 \cong 4.2$ and 295 °K; an experimental point summarizes also several measurements made around $T_0 = 77$ °K. It should be noted that no effort has been made to fit together the points obtained for different gas temperatures, since the electron-temperature scale was purely deduced, as indicated in this section and in Secs. I and II, from gas-temperature measurements and from the microwave electric field intensity, either directly ($T_0 = 295$ and 77 °K) or indirectly, through plots of ν^2_{eff} vs ΔT_e; the fact that they all fall very near a straight line of slope about $\frac{1}{2}$ is thus a strong indication of the internal consistency of these data and of their interpretation.

The results of Fig. 4 were obtained on a broad range of neutral densities (between $n_0 = 7.4\times10^{16}$ and $n_0 = 2.3\times10^{18}$ cm^{-3}) and of electron densities (between 10^{11} and 10^8 cm^{-3} near 300 °K and between 10^{10} and 10^9 cm^{-3} near 4.2 °K) reasonably scattered over the whoe range where the experimental conditions summarized in Sec. II are met. They show no measurable dependence on electron density or on neutral density.

Systematic errors on the measured collision frequency come from determinations of the pressure, of the absorptivity and the phase shift due to the plasma, and of their computed relationship with the collision frequency; they have been discussed in more detail elsewhere.[18] We estimate their total contribution to be less than ±7%.

Systematic errors on the measured electron-temperature dependence are more difficult to assess, since they are a function of the gas temperature: They are negligibly small around 300 °K, and become more important at low temperatures. The parent-gas temperature is known with good accuracy; however, there may be systematic errors in the relative microwave heating term ΔT_e owing to uncertainties in the exact power input to the plasma guide or in the quantities used to compute the actual electric field inside the plasma.[29] We estimate that this error may be as high as

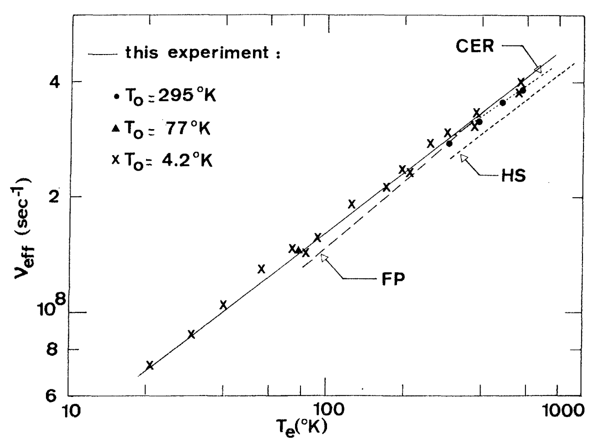

FIG. 4. Summary of our collision-frequency measurements reduced to a standard neutral density $n_0 = 3.53\times10^{16}$ cm^{-3}, as a function of the electron temperature. Each experimental point is the average of several plots such as those of Fig. 2 (for T_0 near 300 °K) or Fig. 3 (for T_0 near 4.2 °K). We have also included for reference purposes values deduced from the experimental results of Crompton, Elford, and Robertson, Ref. 12 (curve labeled CEJ); of Frost and Phelps, Ref. 9 (curve labeled FP); and of Hoffmann and Skarsgard, Ref. 16 (curve HS).

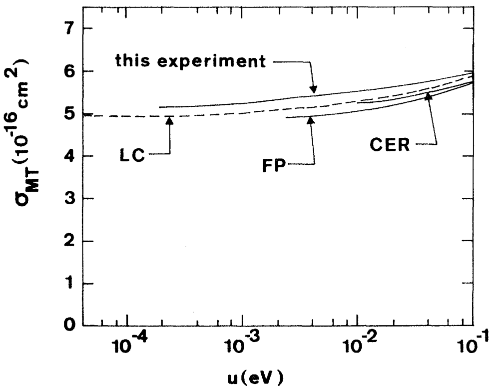

FIG. 5. Electron-neutral-atom momentum-transfer cross section deduced from our collision-frequency measurements. Comparison is made with experimental results of Frost and Phelps, Ref. 9 (curve labeled FP); and of Crompton, Elford, and Robertson, Ref. 12 (curve labeled CER); and with theoretical predictions of LaBahn and Callaway, Ref. 5 (curve labeled LC).

10%, although the agreement between points measured at 4.2, 77, and 295 °K gas temperatures (crosses, triangles, and dots, respectively, in Fig. 4) would indicate a somewhat lower systematic error.

In view of these systematic errors and of the scatter of experimental data, we evaluate the total uncertainties on the measured collision frequency and on its temperature dependence to be ± 7%. Our data yield finally for the effective collision frequency normalized to 1 Torr, 273 °K,

$$\nu_{eff}(\text{sec}^{-1}) = (2.86 \pm 0.20)\times 10^8 \frac{n_0(\text{cm}^{-3})}{3.53\times 10^{16}} \times \left(\frac{T_e(^\circ\text{K})}{295}\right)^{0.52\pm 0.02}$$

from $T_e = 20$ °K to $T_e = 600$ °K. We have computed the collision frequencies corresponding to the data given by Frost and Phelps[9] and by Crompton, Elford, and Robertson,[12] which appear to be the most reliable low-energy experimental data available today.[8,12] Our results are also compared to those of Hoffmann and Skarsgard.[16] Agreement with our data over their common range of validity is within the error bars quoted by ourselves and by these authors (Fig. 4).

IV. UNFOLDING OF EXPERIMENTAL DATA

Electron-atom scattering theories usually yield results in terms of cross sections. A satisfactory comparison with theory necessitates the "unfolding" of the dependence of ν_{eff} on the collision cross section for momentum transfer σ_{MT}, as given by Eq. (2). It is easy to see that this problem does not have a unique solution, even if ν_{eff} is known on a large energy range, in view of unavoidable experimental scatter on the data. This problem has been studied by many authors[9,11,16,30]; with the general availability of electronic computers, it seems to be generally accepted[11] that its best solution obtains through a successive approximation technique, by using a set of "reasonable" assumed cross sections as input to Eq. (2), by integrating it numerically, and by using the differences between the measured and the computed values of ν_{eff} to establish a new set of input cross sections. This procedure is stopped when the computed and the measured values of ν_{eff} agree within experimental error bars, and the resultant set of cross sections is taken as the final experimental cross sections.

The unfolding of our experimental data yields the results given in Fig. 5. The cross section σ_{MT} for momentum transfer of electrons with ground state $_4$He atoms can be approximated as a function of the incident-electron kinetic energy u_e between 2×10^{-4} and 10^{-1} eV by

$$\sigma_{MT}(\text{cm}^3) = 5.15\times 10^{-16}\left(\frac{u_e(\text{eV})}{2\times 10^{-4}}\right)^{0.02} .$$

Valid results obtain down to 2×10^{-4} eV, although the lowest electron temperature at which measurements were possible with a significant accuracy was 2×10^{-3}. This is due to the fact that the value of ν_{eff} at a given energy is substantially affected by the values of σ_{MT} at neighboring energies.[9–12] Our results are compared in Fig. 5 to those of Frost and Phelps[9] and of Crompton, Elford, and Robertson.[12] Agreement is within error bars over the common range of validity. Agreement is also good with the theoretical predictions of LaBahn and Callaway[5] using the extended-polarization-potential model without distortion effects. The inclusion of distortion effects[2] results in cross-section values which are consistently below experimental results.

ACKNOWLEDGMENTS

It is a pleasure to acknowledge many helpful discussions with Professor L. Goldstein, who suggested this work, and with members of the Groupe d'Electronique dans les Gaz at Orsay, particularly J.-C. Gauthier and C. Vauge.

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