ELECTRON MOBILITY IN HIGH DENSITY NEON GAS ☆

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Preliminary results on electron drift velocity in neon gas at T = 293 K and T = 77.4 K are reported. At the lower temperature, values of field-independent mobility at five different densities have been obtained. From these data the momentum-transfer cross section at ϵ = 0.01 eV can be calculated to be $\sigma_{MT} = 0.29 \pm 0.01$ Å^2.

Among the rare gases neon is known to exhibit a small electron–atom scattering cross section σ, the most recent estimate for the scattering length a being $a \approx 0.21$ au [1]. Moreover σ is strongly energy dependent, especially at low energies [1–3]. In usual swarm experiments therefore the energy that the electric field imparts to the electrons is not negligible in comparison to the thermal energy. As a result, even at low electric fields E and at high number densities N, the measured electronic mobility $\mu = v_D/E$ is strongly field dependent. In fact no data of the field-independent mobility μ_0 for electrons in neon have been published until now. The existing data cover a range of E and N where the drift velocity v_D is nearly proportional to $(E/N)^{1/2}$ [3–6].

The interest in the measurements of the zero-field mobility μ_0 is manifold. They can give useful information on the energy dependence of the electron–atom momentum-transfer cross section at thermal energies. They can contribute to enlighten the open problem of the density dependence of electronic mobility in high-density gases [7]. Moreover, because of the repulsive nature of the electron–neon interaction ($a > 0$), due to the density fluctuations localized electron states should appear when the critical region is approached, where a strong decrease of μ_0 should be observed.

In this paper we report preliminary results of the electron drift velocity at very low values of the reduced field E/N, for T = 293 K and T = 77.4 K. At the lower temperature it was possible to measure a field-independent mobility μ_0. A schematic of the electrode set up is shown in fig. 2. The drift velocity v_D was measured across the 0.5 cm drift distance G_2C with the modified square-wave method recently developed to investigate the electron attachment to oxygen molecular impurities in helium gas [8,9]. Fast electrons, produced by a ^{63}Ni radioactive source S, are injected into the drift space, while slow impurity ions are swept back by the properly polarized grids G_1 and G_2. The mean electronic current at the collector C follows the linear relation $i = I^*(1 - 2f\tau)$, where f is the frequency of the G_2 square-wave driving voltage, and τ is the electron transit time across G_2C. Some of the electrons are captured by oxygen molecules if these are present as impurities in the drift space. In this case the method allows simultaneous measurements of v_D and of the attachment frequency ν_A to the oxygen molecules.

Because the attachment is the result of a capture resonant process, ν_A exhibits a peak-shaped dependence on the gas density N. In helium gas at T = 77.4 K we found the maximum ν_A at a density $N_P \approx 3 \times 10^{21}$ cm^{-3} [8,9]. In neon the peak is expected at $N_P \approx 16 \times 10^{21}$ cm^{-3}. In the density range investigated in the present work we are at the low-density side of the peak, where ν_A increases with N. In helium gas we found that in this region

$$\nu_A \propto C_2 N^2 \exp[-b_1(N_1 - N)] ,$$

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where C_2 is the oxygen concentration, $N_1 \approx N_P$, and $b_1 = 3.5 \times 10^{-21}$ cm^3. The attachment frequency therefore increases very rapidly with the density N, and an analogous behaviour should result also in neon gas. We did observe it, at least qualitatively. We found also that the attachment is much more effective at room temperature than at liquid-nitrogen temperature.

In this situation the oxygen concentration C_2 must therefore be kept at a very low level, especially at high N and at high T, not simply to save a detectable fast electronic current, but also to avoid large space-charge effects due to the slow oxygen ions. Space charge can affect the measurements both by distorting the drift field, and by affecting the injection process through the grids. This becomes obviously important when low electric fields are applied to the drift space. In fact the collected electronic current at "zero frequency" is given by $I^* = \frac{1}{2}(I_0)\exp(-\nu_A\tau)$, where I_0 is the injected current at G_2 [9]. If E is reduced, the electronic transit time increases, the electrons have more time for an O_2 encounter, and I^* is strongly reduced. Decreasing E increases the fraction of lost electrons, thereby increasing the slow ionic current and the space-charge electric field. This can become of the same order of the applied injecting or drift fields. In this situation the injection behaves so incorrectly that the collected electronic current is no more a linear function of the driving frequency f. While at high fields we had no problems, for E smaller than 1 V/cm the purity of the gas became a critical parameter, especially at high densities. Space charge sets a lower limit to usable values of the applied electric fields, and it must therefore be reduced as much as possible by reducing the impurity concentration, and the intensity of the electronic currents used in the measurements.

To reduce the oxygen content to the required low level, the measuring cell was inserted in a closed loop where the neon gas can be forced to circulate, at the working pressure, through a cold activated trap. The sample gas was Matheson Research Grade, with $C_2 \approx 10^{-6}$ as stated by the manufacturer. We used an unlubricated gas booster as driving compressor, and after several circulations through the measuring cell and the trap we reached a satisfactory purification. The "zero frequency" current I^* ranged between 10^{-13} and 10^{-11} A, depending on the value of E. With these procedures the lowest reduced field attained within satisfactory experimental conditions was $E/N \approx 3 \times 10^{-22}$ V cm^2.

The experimental results are shown in fig. 1, where v_D is plotted as a function of E/N, and in fig. 2 where we show the mobility $\mu = v_D/E$ as a function of E. At $T = 293$ K the measurements were performed at several gas densities in the range $N = (0.38 - 1.56) \times 10^{21}$ cm^{-3}, down to $E/N \approx 10^{-20}$ V cm^2. Fig. 1a also shows the data obtained at room temperature by Robertson [3] for $E/N \geqslant 1.5 \times 10^{-19}$ V cm^2, and those of Pack and Phelps [4] in the range $10^{-20} \leqslant E/N \leqslant 10^{-19}$ V cm^2. There is substantial agreement between all the data. At the smallest (E/N) v_D starts bending to approach a linear dependence on E/N. The straight line tentatively drawn in the figure would correspond to a thermal averaged cross section $\sigma_{TH} = 0.51$ Å^2 to be compared to the values $\sigma_{MT} = 0.54$ Å^2 proposed by Ogawa et al. [2], and $\sigma_{MT} = 0.48$ Å^2 proposed by O'Malley and Crompton [1], for the momentum-transfer cross section at the mean thermal energy $\frac{3}{2}kT = 3.8 \times 10^{-2}$ eV. To reach definitive results at room temperature, data at lower E/N must be obtained by further improving the gas purification.

More interesting data have been obtained at $T = 77.4$ K. For graphic clarity we show in fig. 1b only the data obtained at our lowest and highest density, $N = 11.7 \times 10^{20}$ cm^{-3} and $N = 49 \times 10^{20}$ cm^{-3}, respectively. The data of Robertson [3] and those of Pack and Phelps [4] obtained at high E/N are also reported in the figure. The logarithmic plot shows that below $E/N \approx 10^{-20}$ V cm^2 the slope changes gradually from 0.5 to 1, indicating a transition from hot to thermalized electrons. The full set of data taken by us at $T = 77.4$ K is shown in fig. 2 as the mobility μ versus the electric field E. It is apparent that at small values of E the mobility saturates to a field-independent value μ_0 that depends on density. At high fields a constant slope in the logarithmic plot is approached, with a value ≈ -0.5 independent of the density. These high-field data correspond to an unique linear dependence with slope ≈ 0.5 in fig. 1b, where our data overlap with the previously published data.

At low densities N the "zero field" mobility μ_0 of thermalized electrons is known to follow the classical relation

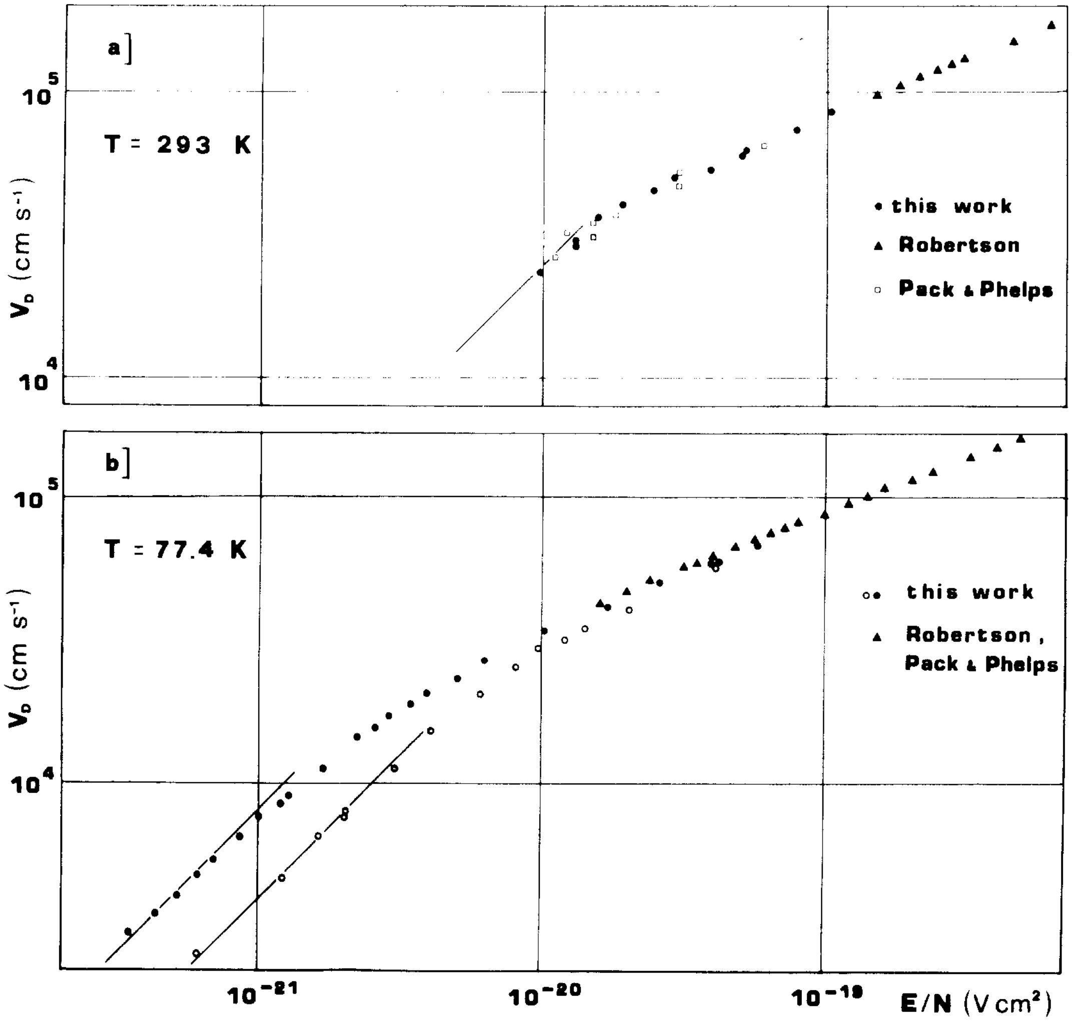

Fig. 1. Electron drift velocity v_D as a function of the reduced field E/N. (a) T = 293 K. (b) T = 77.4 K, Open circles: present work, $N = 49 \times 10^{20}$ cm^{-3}. Full circles: present work, $N = 11.7 \times 10^{20}$ cm^{-3}. The meaning of the straight lines is explained in the text.

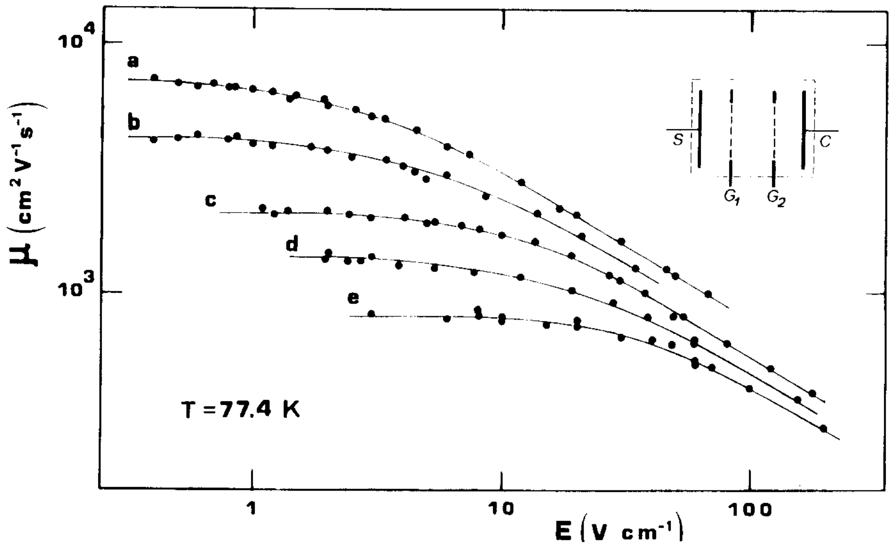

Fig. 2. Electron mobility $\mu = v_D/E$ versus applied electric field E, measured at different densities. (a) $N = 11.7 \times 10^{20}$ cm^{-3}, (b) $N = 18.0 \times 10^{20}$ cm^{-3}, (c) $N = 27.4 \times 10^{20}$ cm^{-3}, (d) $N = 38.8 \times 10^{20}$ cm^{-3}, (e) $N = 49.2 \times 10^{20}$ cm^{-3}. The curves are drawn as eye guidelines. In the insert a schematic drawing of the measuring cell is shown. The symbols are explained in the text.

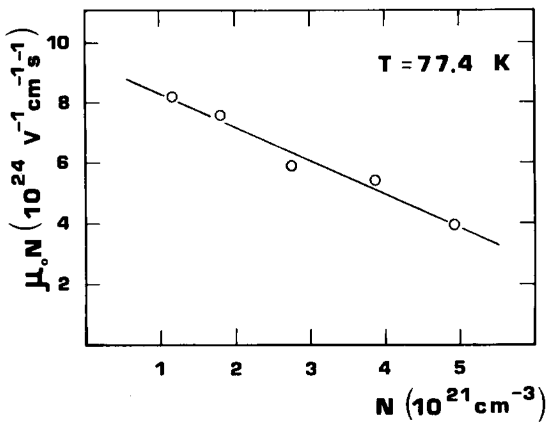

Fig. 3. The product $\mu_0 N$ versus N, as obtained from the data of fig. 2. μ_0 is the "zero field" electron mobility.

$$\mu_0 N = 4e/3(2\pi mkT)^{1/2}\sigma_{TH} , \quad (1)$$

where the "thermal averaged" scattering cross section is given by

$$\sigma_{TH}^{-1} = (kT)^{-2} \int_0^\infty \frac{\epsilon \exp(-\epsilon/kT)\, d\epsilon}{\sigma_{MT}(\epsilon)} .$$

Using the proposed energy-dependent momentum-transfer cross sections $\sigma_{MT}(\epsilon)$, it easy to show that σ_{TH} is very close to the value of $\sigma_{MT}(\bar{\epsilon})$ calculated for $\bar{\epsilon} = \frac{3}{2}\ kT$. For $T = 77.4$ K and the $\sigma_{MT}(\epsilon)$ of O'Malley and Crompton, for example, σ_{TH} and $\sigma_{MT}(\bar{\epsilon})$ differ only by 0.3%.

We cannot derive directly a value for σ_{TH} from the data of fig. 2, because the classical relation (1) is not followed at high densities. In fact the product $\mu_0 N$ results to decrease with N, as shown in fig. 3. An analogous behavior has been found in hydrogen and helium gas, where at moderately high densities the dependence was found to be approximately linear [10]. If we assume this dependence also in our case, a linear extrapolation to $N = 0$ gives us $\sigma_{TH} = 0.29 \pm 0.01$ Å^2, a value about 8% lower than $\sigma_{MT}(\bar{\epsilon}) = 0.314$ Å^2 given by O'Malley and Crompton at $\bar{\epsilon} = 0.01$ eV.

We believe that more measurements at various densities and temperatures will get in the future complete information on the scattering cross section at thermal energies, and on the interesting problem of the density dependence of the electronic mobility.

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