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The characteristic energy and momentum transfer cross section for low-energy electrons in neon

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Abstract. The characteristic energy of low-energy electrons in neon gas has been measured at room temperature by the Townsend method as a function of the reduced electric field E/N, where E denotes the field strength and N the number density of the gas atoms. The measured characteristic energy was 0.127 eV at $E/N = 0.014$ Td and increased monotonously with increasing E/N. The momentum transfer cross section for electrons in neon was derived from the data for an energy range from 0.01 to 1 eV. The result was found to be in excellent agreement with previous estimates obtained by different methods, particularly for the energy range from 0.1 to 0.5 eV. All of the four theoretical cross sections calculated by Thompson, Garbaty and LaBahn, Yau *et al* and McEachran and Stauffer agree with our experimental cross section within about ±20%.

1. Introduction

The characteristic energy ε_k of electrons in a gas, which is defined as the ratio of the transverse diffusion coefficient D to the mobility μ multiplied by the elementary charge e, i.e. $\varepsilon_k \equiv eD/\mu$, is a major swarm parameter of both physical and practical interest, another being the drift velocity. Not only is this energy indispensable as one of the fundamental transport parameters in describing quantitatively the electric discharge in gases and many atmospheric phenomena, it is also of great value, as is well known, in yielding information about the interaction with atoms of low-energy electrons below about 1 eV, for which a precise beam-scattering experiment is generally very difficult to carry out.

Particularly in inert gases, the momentum transfer cross sections for electrons q_m can be easily determined from the swarm data, because only elastic scattering is dominant in the electron–atom interaction over a wide range of electric field intensities and gas pressures. In fact, a number of investigations have been made over the years on the drift velocity of electrons in inert gases and the momentum transfer cross sections have been estimated from the experimental data (Huxley and Crompton 1974, ch 14). In contrast, no measurement has yet been reported of the characteristic energy of electrons in inert gases except in helium (Warren and Parker 1962, Crompton *et al* 1967) and in argon (Warren and Parker 1962, Milloy and Crompton 1977), in spite of its higher sensitivity to the magnitude and energy dependence of the cross section compared with the drift velocity, particularly in a higher energy region above some tenths of eV.

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In order to make up for this lack of data on ε_k and to obtain more accurate information on the energy dependence of the cross section q_m for collisions of electrons with inert gas atoms, measurements have been made in our laboratory of the characteristic energy of electrons in various inert gases, starting with neon. From the data obtained, the cross section q_m has been derived as a function of electron energy by means of a Boltzmann analysis. In the present article, the result for neon will be described in some detail.

2. Experimental

The characteristic energy ε_k was measured at room temperature by the Townsend method as a function of the reduced electric field E/N, where E is the field strength and N the number density of gas atoms. Figure 1 shows a schematic diagram of the apparatus used. Electrons were obtained photoelectrically by irradiating a thin gold film (photocathode) evaporated onto a quartz disc with UV radiation from a deuterium lamp. The electrons were led to the drift-diffusion space through an aperture hole and eventually collected by one of the annular rings of the collector. The output current from each ring was measured with a vibrating-reed electrometer. From the observed current ratios between different collector rings, the parameter $\lambda \equiv w/2D$, where w denotes the drift velocity, was determined for each field strength and gas pressure, by referring to the Huxley solution of the drift–diffusion equation (Huxley and Crompton 1974, ch 11). The ε_k values were readily obtained from that equation as $\varepsilon_k = eE/2\lambda$.

Figure 2 shows the details of the drift–diffusion space. All the electrodes were made of gold-plated stainless steel to eliminate the effect of the contact potential. The aperture plate was located 48.3 mm away from the collector surface and had an aperture

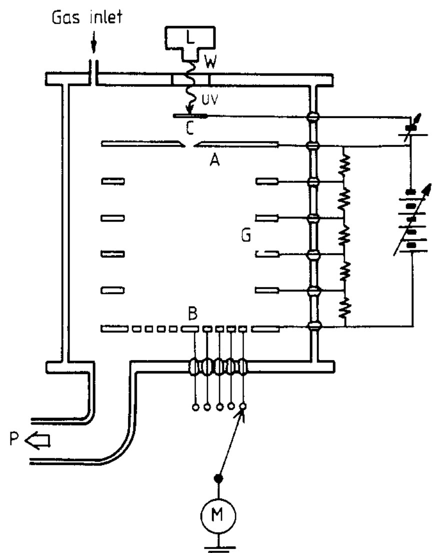

Figure 1. Schematic diagram of the apparatus. L: deuterium lamp, W: quartz window, C: photocathode, A: aperture plate, B: collector rings, G: guard rings, M: vibrating-reed electrometer, P: sputter-ion pump.

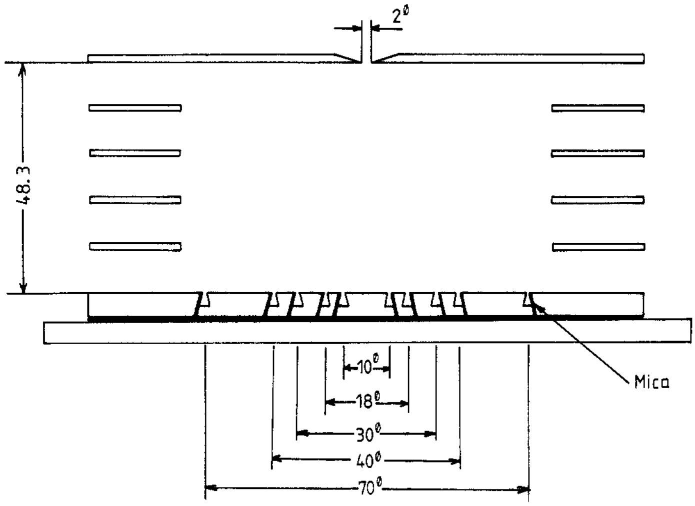

Figure 2. Details of the drift–diffusion space.

2.0 mm in diameter at the centre with a tapered edge to maximise the conductance for electrons. The electron collector consisted of five mutually insulated concentric rings. Thin mica films were used as an insulator. The size of each ring is shown in figure 2. Four guard rings were provided to make a uniform electric field in the drift–diffusion space.

The chamber was evacuated by a sputter-ion pump to about 10^{-6} Pa after baking at about 150 °C for several hours. The original purity of the neon gas used was stated to be higher than 99.9999%. The gas was further passed through a charcoal trap cooled with liquid nitrogen before being introduced into the chamber. The ultimate purity is uncertain but is believed to have been better than 99.9999%. The gas pressure was measured with a mercury manometer.

When the chamber was filled with the gas, the total collected current was of the order of 10^{-12} A. This was large enough to assure a reasonable accuracy in the measurement but small enough to neglect the space charge effect in the drift–diffusion space. To eliminate the effect of electrons emitted from anything other than the photocathode and also of leakage current due to incomplete insulation at the collector, the collector-ring current was observed with a reverse field between the photocathode and the aperture plate, and this was always subtracted from the net ring current as a background.

The field strength and the pressure were chosen so as to make λ fall within the optimum range from 15 to 30 cm^{-1}, in order to minimise the effects and errors due to diffusion anisotropy and the finite size of the aperture. Under these conditions, the error of the Huxley solution was estimated to be less than 2%.

3. Results

The observed characteristic energies of electrons in neon gas are shown in table 1. The measurement was performed for E/N ranging from 0.014 to 0.4 Td (1 Td =

Table 1. The observed characteristic energy ε_k for electrons in Ne at room temperature T. a: obtained from I_1/I_2, b: obtained from $(I_1+I_2)/I_3$, where I_n is the collected current from the nth ring.

	ε_k (eV)										
	Pressure (kPa)										Best estimate
	60.8		74.9		94.9		121		122		ε_k
E/N (Td)	a	b	a	b	a	b	a	b	a	b	(eV)
0.014							0.130	0.124	0.131	0.123	0.127
0.017							0.149	0.142	0.151	0.141	0.146
0.020							0.165	0.159	0.165	0.158	0.162
0.025							0.189	0.186	0.190	0.184	0.187
0.030					0.213	0.212	0.215	0.211	0.214	0.210	0.213
0.035					0.235	0.236	0.239	0.235	0.239	0.232	0.236
0.040					0.261	0.258	0.262	0.258	0.261	0.257	0.260
0.050			0.298	0.289	0.303	0.303	0.306	0.301	0.302	0.300	0.300
0.060			0.340	0.332	0.342	0.340	0.345	0.344	0.344	0.343	0.341
0.070			0.376	0.374	0.384	0.384	0.386	0.385	0.385	0.383	0.382
0.080			0.418	0.413	0.419	0.419	0.423	0.423	0.422	0.422	0.420
0.10	0.495	0.486	0.489	0.489	0.491	0.493					0.491
0.12	0.568	0.565	0.560	0.557	0.561	0.561					0.562
0.14	0.632	0.632	0.628	0.628	0.627	0.632					0.630
0.17	0.732	0.736	0.724	0.731	0.726	0.731					0.730
0.20	0.833	0.833	0.825	0.825	0.824	0.827					0.828
0.25	0.987	0.992	0.987	0.987	0.982	0.988					0.987
0.30	1.13	1.15	1.14	1.15							1.14
0.35	1.30	1.31									1.31
0.40	1.45	1.46									1.46
T(K)	290		294		293		289		292		

10^{-17} V cm^2) under several pressures between 60.8 and 122.1 kPa. The current ratio was observed for two different combinations of collector rings. As is seen from table 1, no systematic pressure effect was observed; nor was there any significant difference between the data for different combinations of collector rings. This means that the effects due to drift inequilibrium, contact potential, and so forth, are all negligible. The scatter of the data at the same E/N was within about 1%. Meanwhile, the systematic error in the measurement was estimated to be less than ±2%. For each value of E/N, the simple average of the ε_k values obtained at various pressures with different current ratios was considered as the best estimate of ε_k. This is plotted in figure 3 as a function of E/N.

4. Discussion

The characteristic energy ε_k may be written

$$\varepsilon_k = -\int_0^\infty \frac{\varepsilon f(\varepsilon)}{q_m}\,\mathrm{d}\varepsilon \left(\int_0^\infty \frac{\varepsilon}{q_m}\frac{\mathrm{d}f}{\mathrm{d}\varepsilon}\,\mathrm{d}\varepsilon\right)^{-1} \qquad (1)$$

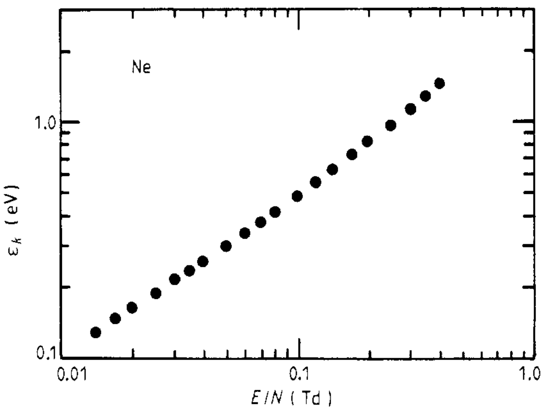

Figure 3. Characteristic energy of electrons in neon gas obtained at room temperature.

where ε is the collision energy between an electron and an atom, while $f(\varepsilon)$ denotes the energy distribution function for electrons. If only elastic collisions between electrons and gas atoms need be considered, the function $f(\varepsilon)$ is simply given by

$$f(\varepsilon) = A \exp\left\{ -\int_0^{\varepsilon} \left[\frac{M}{6m\varepsilon} \left(\frac{eE}{Nq_m} \right)^2 + kT \right]^{-1} \mathrm{d}\varepsilon \right\} \tag{2}$$

where M and m are the mass of a gas atom and an electron, respectively, k is the Boltzmann constant and T is the gas temperature. The constant A is the normalisation factor.

The cross section q_m was determined as a function of ε by adjusting an arbitrarily chosen cross section close to previous (earlier) estimates until the values of ε_k obtained from equation (1) agree with the measured ε_k values within the experimental error. The cross section values deduced in this way from the present results are given in table 2 and plotted against ε in figure 4. The calculated ε_k values proved to change by 1%

Table 2. The momentum transfer cross section q_m for electrons in neon as a function of electron energy ε derived from characteristic energy data.

ε(eV)	q_m(10^{-16} cm^2)	ε(eV)	q_m(10^{-16} cm^2)
0.010	0.381	0.120	0.783
0.016	0.426	0.160	0.868
0.020	0.451	0.200	0.944
0.022	0.463	0.220	0.979
0.026	0.484	0.260	1.04
0.030	0.504	0.300	1.11
0.035	0.527	0.350	1.18
0.040	0.548	0.400	1.24
0.045	0.567	0.450	1.30
0.050	0.586	0.500	1.35
0.060	0.620	0.600	1.50
0.070	0.652	0.700	1.53
0.080	0.681	0.800	1.60
0.090	0.709	0.900	1.65
0.100	0.734	1.00	1.68

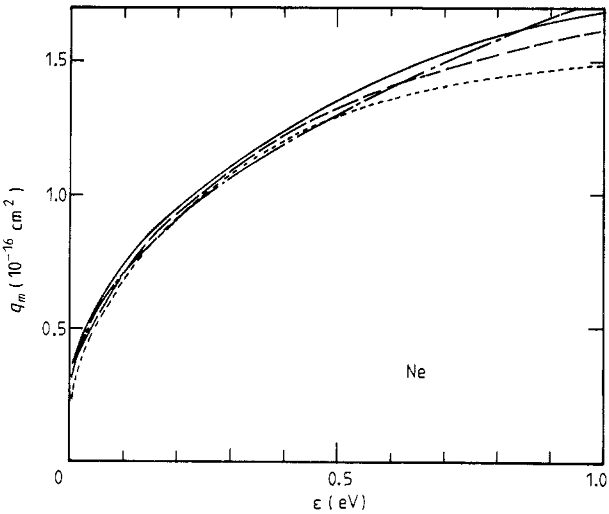

Figure 4. Momentum transfer cross sections for electrons in neon. The results of other experimental investigations are shown for comparison. ——, present work; – –, Robertson (1972); – – –, Sol *et al* (1975); ------, Golovanivsky and Kabilan (1981).

on changing the values of q_m at every value of ε by 2%. Since the experimental error in ε_k is estimated to be 2%, the ultimate ambiguity of the present determination of q_m is about ±4%.

The cross section q_m has been derived from a few independent experimental results, for example, by Robertson (1972) from electron drift velocity, by Sol *et al* (1975) from microwave afterglow, and by Golovanivsky and Kabilan (1981) from electron cyclotron resonance. These cross sections are also plotted in figure 4 for comparison. As is seen in figure 4, the present result is in excellent agreement with previous estimates within their and our claimed limits of error, particularly for the energy range from 0.1 to 0.5 eV. The present result also agrees fairly well with all of the four existing theoretical results over the entire energy range from 0.01 to 1 eV as shown in figure 5, being about 10–20% larger than that of Thompson (1971) and 0–20% smaller than those of Garbaty and LaBahn (1971), Yau *et al* (1978), and McEachran and Stauffer (1983).

The s-wave scattering length a in an electron–neon-atom collision was roughly estimated from the present q_m data to be about 0.24 a_0, where a_0 denotes the Bohr radius, by a least-squares fit of the data either to the so-called MERT (modified effective-range theory) formula or to its improved version, the EMERT (extended MERT) formula (O'Malley 1963, O'Malley and Crompton 1980).

The accuracy of the present estimate of a is rather limited since the measurement of ε_k was made only for values of E/N above a lower limit as large as 0.014 Td, at which the mean energy of electrons already amounted to about 0.1 eV. Nevertheless, the present result of $a \simeq 0.24\ a_0$ is in very good agreement with previous experimental values of 0.24 a_0 by Robertson (1972), 0.24 a_0 also by Sol *et al* (1975), 0.21 a_0 by O'Malley and Crompton (1980) and 0.20 a_0 by Golovanivsky and Kabilan (1981). It is also the same order of magnitude as the theoretical values of 0.17 a_0 by Thompson (1971), 0.28 a_0 by Garbaty and LaBahn (1971), 0.27 a_0 by Yau *et al* (1978), and 0.31 a_0 by McEachran and Stauffer (1983).

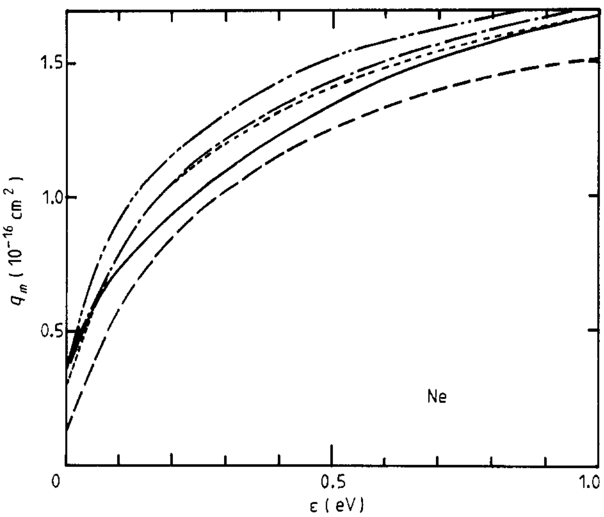

Figure 5. Comparison between our momentum transfer cross section and theoretical ones. ——, present work; – –, Thompson (1971); – · – · –, Garbaty and LaBahn (1971); - - - - - -, Yau *et al* (1978); – – – –, McEachran and Stauffer (1983).

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