Electrons in Inert Gases

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Studies of the behaviour of an electron swarm in various inert gases are not only important in practical applications such as the electrical discharge engineering and the development of radiation detectors or gaseous lasers, but also of great value, or even indispensable, in obtaining precise information about collision processes, especially the elastic scattering, of low-energy electrons with gas atoms.

Since inert gases are monatomic and their atoms are of closed-shell structure, the analysis to be used for deriving cross sections from swarm data naturally becomes the simplest and hence the best established, and may be performed quite accurately since only elastic collisions are essentially relevant.

Theoretically, also, the collision of an electron with an inert gas atom is the most typical case of electron-atom collision processes and has long been investigated in detail by a number of authors. The presence of remarkable Ramsauer-Townsend effect in Ar, Kr, and Xe adds a particular interest to these gases.

In spite of these significances and interest, however, agreement among the reported values of various swarm parameters and derived cross sections for electrons in inert gases has not been very satisfactory in many cases, owing to several experimental difficulties related, for example, to the extreme sensitivity of various swarm properties for these gases to the gaseous impurity. A substantial disagreement remains to be seen, in particular, with regard to the position and the shape (the depth, in particular) of the Ramsauer minimum in the momentum transfer cross section for electrons in Ar, Kr, and Xe as a function of electron energy. Also, no modernized measurement had ever been reported until very recently of the characteristic energy, $\varepsilon_k \equiv eD/\mu$, for electrons in Ne, Kr and Xe, one of the most important swarm

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parameters which may be ranked with the drift velocity, w. In the definition made above, e denotes the elementary charge, D the "transverse" diffusion coefficient for electrons in a direction perpendicular to the applied electric field, and μ the electron mobility.

Recently, however, these experimental difficulties have been gradually overcome technically and some long-lacking swarm data became first available with a high accuracy, including, for example, the characteristic energy data for Ne and Xe. This will certainly contribute greatly to the resolution of the existing discrepancy among the reported swarm data and derived cross sections, and also to the evaluation of different theoretical estimates.

In the present article, the present status of such a recent progress will be reviewed briefly, after summarizing the general features of an electron swarm in inert gases. Attempts will be made on the way to point out the tasks still remaining to be pursued. Because of the limited available space, our discussion will be concentrated on the case of electron swarms in complete drift-equilibrium under lower reduced electric fields, E/N, where any inelastic process may safely be neglected. Here, E denotes the strength of the applied electric field and N the number density of gas atoms.

1. Feature of an Electron Swarm in Inert Gases

1.1 General Features

In the absence of any inelastic interaction between an electron and a gas atom, the approximate solution of the Boltzmann transport equation becomes greatly facilitated and the distribution function $f(\varepsilon)$ of electron energy ε proves to be given by a simple closed formula (known as the Davydov distribution /1/):

$$f(\varepsilon) = A \exp \{ -\frac{6m}{M} \int_0^{\varepsilon} \frac{\varepsilon}{\varepsilon_1^2 + \frac{2m}{M} kT\varepsilon} d\varepsilon \}, \tag{1}$$

where m and M denotes, respectively, the mass of an electron and an atom, k the Boltzmann constant, T the gas temperature, $\varepsilon_1 \equiv eE/Nq_m$, and q_m the momentum transfer cross section for electrons as defined below, while A is the normalizing constant to be determined from the condition $\int f(\varepsilon)d\gamma = 1$. Here, $d\gamma$ denotes the infinitesimal volume in the velocity space.

As a result, the procedure to determine the momentum transfer cross section

$$q_m \equiv \int q(\theta)\ (1 - \cos\theta)\ d\omega = q_s\ (1 - \overline{\cos\theta}) \tag{2}$$

as a function of electron energy from the observed swarm data (*e. g.*, the drift velocity and/or the characteristic energy as a function of E/N and T) becomes remarkably simplified. Here, $q(\theta)$ denotes the differential scattering cross section, θ the scattering angle, $q_s = \int q(\theta)\, d\omega$ the total scattering cross section, and $d\omega = 2\pi \sin\theta \, d\theta$ the infinitesimal solid angle.

This is the great merit of inert gases in investigating the relevant collision processes from the observed swarm behaviours as compared with molecular gases. At the same time, however, the following facts make electron swarm experiments with inert gases considerably difficult in a peculiar way:

(1) The absence of inelastic processes like rotational or vibrational excitation of a molecule makes the achievement of drift equilibrium much slower than in molecular gases. Such an effect manifests itself most strongly in Ramsauer gases like Ar, Kr and Xe.

(2) The presence of an extremely small amount of molecular (not necessarily electron-attaching) impurities, sometimes as low as a few ppm, may well affect strongly the electron energy distribution and hence exert a serious influence upon the magnitude of various swarm parameters, deteriorating the accuracy of estimated cross sections, especially in the case of Ramsauer gases.

(3) By the same reason as in (1), the average random energy, and hence the average random velocity of electrons in inert gases, is much greater than in molecular gases, resulting in a strong diffusivity of swarm electrons. This often hinders the passage of electrons through a narrow slit, a small aperture hole, or a dense grid, the electrons being readily trapped by the periphery or grid wires, reduces the swarm current, and eventually lower the accuracy in measuring swarm parameters particularly at lower gas pressures. The only practical solution of this problem would be to use higher gas pressures, which in itself involves various experimental troubles.

(4) Again by the same reason, the drift velocity of electrons in inert gases is generally much slower than in molecular gases, and the diffusion (longitudinal, in particular) often takes place rapidly during their drift, thus limiting sometimes the accuracy of the time of flight (exactly,drift) method widely employed to measure the drift velocity, or impairing some basic performances of applicational instruments like the spatial or temporal resolution of a radiation detector.

Fortunately, however, these difficulties have been gradually surmounted and the lacking important data are being steadily acquired in recent years.

1.2 Comparison of Swarm Parameters for Individual Species of Inert Gases

Let us consider semiquantitatively how the two major swarm parameters, *i.e.*

the drift velocity w and the characteristic energy ε_k, depend upon the mass M of a gas atom and the rough magnitude of the momentum transfer cross section $\bar{q}_m$ for electrons in individual inert gases, by neglecting for simplicity the gas temperature T and by following an elementary treatment similar to the one attempted early by Alfven /2/.

Denoting by m the electron mass, by v the average random velocity of electrons, and by $\nu_m \equiv N\bar{q}_m v$ the momentum transfer collision frequency, the two parameters may be readily shown (See the Appendix) to be approximately given by

$$\begin{aligned} w &\cong c_1\ eE/(m\nu_m) = c_2\ (m/M)^{\frac{1}{4}}\ [(2/m)(eE/N\bar{q}_m)]^{\frac{1}{2}} \\ &= c_3\ [M(\mathrm{amu})]^{-\frac{1}{4}}[\bar{q}_m(\mathrm{A}^2)]^{-\frac{1}{2}}[(E/N)(\mathrm{Td})]^{\frac{1}{2}} \quad \mathrm{cm}/\mu\mathrm{s} \end{aligned} \tag{3}$$

and

$$\begin{aligned} \varepsilon_k &\cong c_4 (M/m)^{\frac{1}{2}}(eE/N\bar{q}_m) \\ &= c_5\ [M(\mathrm{amu})]^{\frac{1}{2}}[\bar{q}_m(\mathrm{A}^2)]^{-1}[(E/N)(\mathrm{Td})] \quad \mathrm{eV}, \end{aligned} \tag{4}$$

respectively. Here, c_i's (i = 1,2,...,5) are numerical constants of the order of unity and $\bar{q}_m$ represents the momentum transfer cross section averaged over an energy region where the substantial part of electron energy distribution spreads depending on the magnitude of E/N.

According to these results, the drift velocity should be roughly proportional to the square root of E/N with a factor inversely proportional to the product of the fourth root of the atomic mass and the square root of the averaged momentum transfer cross section $\bar{q}_m$, provided that E/N (and hence ε_k) is large enough to neglect the thermal motion of gas atoms.

For smaller E/N's, $v \cong \sqrt{3kT/m}$ approximately, so that w is given as

$$w \cong c_6 (e/\sqrt{3mkT})(\bar{q}_m)^{-1}(E/N), \tag{5}$$

where c_6 is a numerical constant close to unity, i. e., w becomes proportional to E/N with a factor independent of M, inversely proportional to $\bar{q}_m$, and also inversely proportional to the square root of gas temperature.

Thus, $w \propto E/N$ for lower E/N's and $\propto \sqrt{E/N}$ for higher E/N's if $\bar{q}_m$ varies little with electron energy. This is indeed approximately the case with He and Ne, but no longer with Ramsauer gases like Ar, Kr and Xe, for which the observed w vs. E/N curve shows a peculiar shoulder near a particular value of E/N where $\bar{q}_m$ becomes minimum.

As regards the characteristic energy, the above result shows that it is roughly proportional to the squre root of the atomic mass divided by the averaged momentum transfer cross section $\bar{q}_m$ for sufficiently large E/N's. Therefore,

ε_k is generally more sensitive to $\bar{q}_m$ when compared with w which is inversely proportional to the square root of $\bar{q}_m$. It should be noted here that the quantity $\varepsilon_k/(E/N) = (eD/\mu)/(E/N)$, which is often referred to in order to indicate the "diffusivity" of drifting electrons in a gas, may be taken as a measure of microscopic quantity $\sqrt{M} / \bar{q}_m$ for larger E/N's for which $\varepsilon_k >> kT$.

In He and Ne, experimental data show indeed that ε_k is roughly proportional to E/N for sufficiently large E/N's (For Ne, see Fig. 1). Furthermore, the ratio of the observed values of ε_k for Ne and He at E/N = 0.2 Td, for example, i. e. $\varepsilon_k(\mathrm{Ne})/\ \varepsilon_k(\mathrm{He}) = 0.83/0.11 \cong 7.6$, is in fact in good agreement with the calculated ratio of $(\sqrt{M}/\bar{q}_m)(\mathrm{Ne})/(\sqrt{M}/\bar{q}_m)(\mathrm{He}) = \sqrt{20/4}\ (6.08/1.69) \cong 8.0$ from eq.(4).

In Ar, Kr and Xe, however, ε_k is no longer proportional to E/N as a result of Ramsauer effect and increases first rapidly at a certain value of E/N as is seen in Figs. 2 and 3 and then continues to rise slowly. In these gases, the magnitude of the averaged cross section $\bar{q}_m$ for each value of E/N cannot readily be estimated definitely by inspection because of the violent variation in $q_m(\varepsilon)$ and the resulting ambiguity in the shape of energy distribution for electrons. In spite of these unfavourable circumstances, the preceding semiquantitative result is still capable of explaining fairly well the general trend of the observed ε_k vs. E/N characteristics for individual inert gases including even those with Ramsauer effect.

For instance, the values of E/N at which ε_k is expected to take on a common value of 0.3 eV, as calculated from eq.(4) assuming tentatively as $c_5 = 1.5$, are in fact fairly close to the observed values as shown in Table 1. Thus, they reproduce fairly well the observed order followed by $(E/N)_{obs}(\varepsilon_k = 0.3\ \mathrm{eV})$'s as well as their relative ratios for individual gas species, except for a minor disorder (reversal in order) for Ne and Xe.

Table 1. Comparison of E/N's for various inert gases giving the same value of $\varepsilon_k = 0.3$ eV as calculated from eq.(4) with $c_5 = 1.5$.

	He	Ne	Ar	Kr	Xe
M (amu)	4	20	40	84	131
$\bar{q}_m(A^2)$	6.4	1.1	0.16	0.75	3.5
$(E/N)_{calc}$ (Td)	0.64	0.05	0.005	0.016	0.06
$(E/N)_{obs}$ (Td)	0.66	0.050	0.0053	0.012	0.032

2. Present Status of the Measurement of Major Swarm Parameters

The most important transport parameters for an electron swarm in a gas in drift equilibrium are the drift velocity w and the characteristic energy ε_k as defined earlier. Among other useful parameters are the "longitudinal" diffusion coefficient D_L in the direction parallel to the electric field, the "longitudinal" characteristic energy $\varepsilon_L \equiv eD_L/\mu$, the anisotropy ratio $S \equiv D_L/D$ for diffusion, and the "magnetic" drift velocity w_M to be obtained under a transverse magnetic field. In the present subsection, a brief review is given of the present status of measurement only of the three major parameters w, ε_k and D_L in high purity inert gases.

Table 2 lists the names of author of some significant papers worthy of particular attention for each item. The references are given at the end of the present article. A more comprehensive list of references before about 1979 has been published by Beaty, Dutton and Pitchford /3/. A compilation of swarm data prior to 1972 has been made earlier by Dutton /4/. Reference may be also made to the critical surveys given in the textbooks written by Gilardini /5/ and by Huxley and Crompton /6/, although the data and references collected there are limited to those earlier than about 1971 - 2.

As is seen in the Table, the drift velocity has already been measured most accurately for almost all the inert gases, usually by means of electrical shutter method. Phelps and his colleagues /7/,/8/ are among the first who gave the best w data available at that time for all of He, Ne, Ar, Kr and Xe at room and lower temperatures as early as 1961 - 2. For He, Ne and Ar, however, Crompton et al. /9/,/10/ and Robertson /11/,/12/ have later attempted improved measurements and their results are now believed to be most accurate.

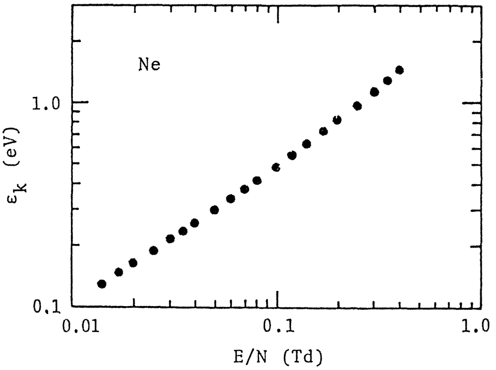

Fig. 1. The characteristic energy of electrons in Ne as observed by Ogawa, Koizumi, Murakoshi, Yamamoto and Shirakawa /15/ at 292 ± 1 K.

Table 2. Present status of the measurement of basic swarm parameters and the determination of the momentum transfer cross section for electrons in inert gases. References are given at the end of the present article.

Gas	Drift velocity, w	Characteristic energy $\varepsilon_k \equiv eD/\mu$	Longitudinal diffusion coefficient, D_L	Momentum transfer cross section, q_m	
				experimental	theoretical
He	Pack and Phelps('61) /7/ Crompton, Elford and Jory ('67; 293K) /9/ Crompton, Elford & Robertson('70;77K)/10/	Warren and Parker ('62) /13/ Crompton, Elford and Jory ('67; 293K) /9/	Wagner, Davis and Hurst ('67) /18/ Elford ('74) /19/	Crompton, Elford and Jory ('67) /9/ Crompton, Elford and Robertson ('70) /10/ Milloy and Crompton ('77) /22/	Yau et al.('78) /27/ Nesbet ('79) /28/ O'Malley, Burke and Berrington ('79) /29/ McEachran and Stauffer ('83) /30/
Ne	Pack and Phelps('61) /7/ Robertson('72;77K & 293K) /11/	Ogawa, Koizumi, Murakoshi, Yamamoto and Shirakawa ('83) /15/	No data available	Robertson ('72) /11/ O'Malley and Crompton ('80) /23/ Sol et al.('75) /24/ Golovanivsky('81)/25/ Ogawa et al.('83)/15/	McDowell ('71) /31/ Thompson ('71) /32/ Garbaty et al.('71)/33/ Yau et al. ('78) /27/ McEachran and Stauffer ('83) /30/
Ar	Pack and Phelps('61) /7/ Robertson ('77) /12/	Warren and Parker ('62) /13/ Milloy and Crompton ('77) /14/	Wagner, Davis and Parker ('67) /18/ Robertson and Rees ('72) /20/	Frost and Phelps('64) /17/ Milloy, Crompton,Rees and Robertson ('77) /26/	Thompson ('71) /32/ Garbaty et al.('71)/33/ Yau, McEachran et al. ('80) /34/ McEachran and Stauffer ('83) /35/
Kr	Pack, Voshall and Phelps ('62) /8/	Ogawa, Koizumi and Shirakawa ('83) /16/	No data available	Frost and Phelps('64) /17/	Yau, McEachran and Stauffer ('80) /34/ Sin Fai Lam ('82) /36/ McEachran and Stauffer ('83) /37/
Xe	Pack, Voshall and Phelps ('62) /8/	Ogawa, Koizumi and Shirakawa ('83) /16/	No data available	Frost and Phelps('64) /17/	Yau, McEachran and Stauffer ('80) /34/ Sin Fai Lam ('82) /36/ McEachran and Stauffer ('83) /37/

Meanwhile, the characteristic energy ε_k had not been measured at all until very recently for high purity inert gases except for He /9/,/13/ and Ar /13/, /14/, in spite of the fact that this quantity is much more sensitive to the magnitude of q_m than the drift velocity, particularly for relatively higher energies from about 0.1 to a few eV as was pointed out earlier, and therefore the more useful in deriving q_m's for these energies.

This situation prompted the author and his colleagues to attempt a measurement of ε_k in Ne, Xe and Kr by the Townsend method /6/ at room temperature. The result for Ne is plotted in Fig. 1. Full data are given in Ref./15/. The momentum transfer cross section $q_m(\varepsilon)$ derived from the data as a function of energy ε proved to be in excellent agreement with previous estimates by other methods as will be described in the next subsection.

As for Xe and Kr, the author and his colleagues are still carrying on the measurement, but some preliminary data are shown in Fig. 2 (Xe) and Fig. 3 (Kr) /16/. Although there still remain a considerable scatter of data (presumably due to the insufficiency of collected current, particularly in Kr) and a certain pressure dependence of unknown origin, the observed characteristic energy clearly exceeds the early estimates from the drift velocity data by Frost and Phelps /17/, being twice or thrice as large as the latter, both in Xe and in Kr, except for lower E/N's.

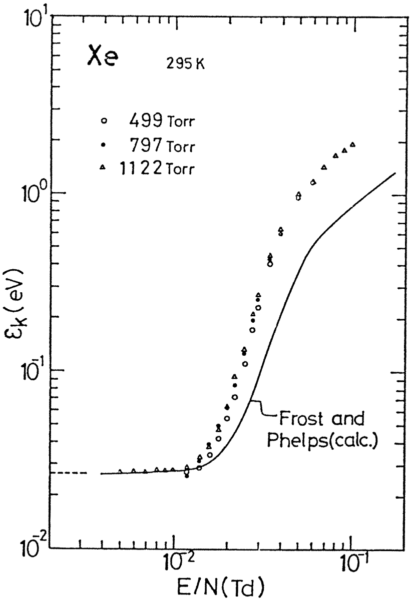

Fig. 2. The characteristic energy of electrons in Xe as observed by Ogawa et al. /16/.

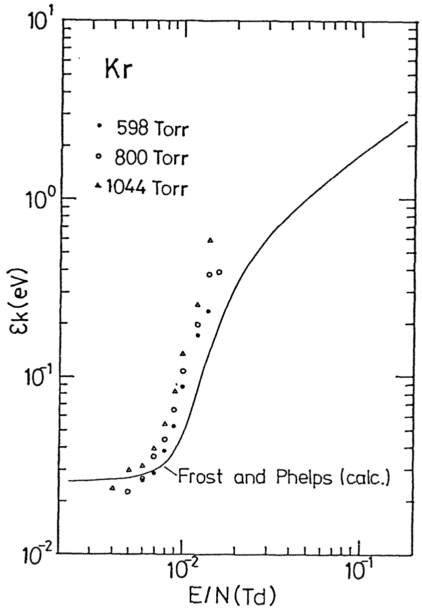

Fig. 3. The characteristic energy of electrons in Kr as observed by Ogawa et al. /16/ (preliminary data)

As concerns the "longitudinal" diffusion coefficient D_L or its related quantities such as $\varepsilon_L \equiv eD_L/\mu$ and $S \equiv D_L/D$, experimental data are even scantier, especially for lower E/N's for which the Ramsauer effect, if any, becomes most important. Apart from the pioneer work by Wagner, Davis and Hurst /18/ (only on He and Ar as for inert gases) over a rather limited range of E/N, the only available data at present appear to be those on D_L in He by Elford /19/ and in Ar by Robertson and Rees /20/ extended to lower E/N's to observe the peculiar peak due to the Ramsauer effect.

Since the parameters like D_L, ε_L, and S are all particularly sensitive, even more than ε_k, to rapid variations with energy ε of the momentum transfer cross section $q_m(\varepsilon)$ for the electrons, as has early been shown theoretically by Lowke and Parker /21/, they are expected to be extremely useful in determining the fine structure of $q_m(\varepsilon)$ such as the exact position and the shape (depth, width, etc.) of a Ramsauer minimum. It would be highly desirable, therefore, to measure these parameters as accurately as possible especially for Xe and Kr, in order to investigate in detail the Ramsauer minimum for these gases.

Measurements of basic swarm parameters for mixtures of inert gases appear to have hardly been attempted so far, despite their possible utility in examining closely the cross sections already proposed for individual inert gases. The author et al. have recently measured ε_k for He-Ne mixtures /15/.

3. Momentum Transfer Cross Section for Low Energy Electrons in Inert Gases

3.1 General Remarks

The momentum transfer cross section (MTCS) q_m for low energy electrons in most of the inert gases has been derived since 1960's usually from drift velocity data, though sometimes also from some other swarm data like the characteristic energy data, the results of microwave afterglow experiments or the observations of electron cyclotron resonances (ECR). For higher energies (above a few or several eV, say), the MTCS has also been derived, at least for He, Ne and Ar, from the differential scattering cross section obtained by beam experiments. In He and Ar, the MTCS's derived independently from recent swarm and beam data are in good agreement with each other, indicating a high reliability of the both results.

Of the two major swarm parameters, the drift velocity w depends more strongly upon the MTCS's at lower energies, while the characteristic energy ε_k is expected to be more sensitive to the MTCS values for higher energies, as is readily seen from the basic relationships $w \propto \langle 1/(q_m v) \rangle$ and $\varepsilon_k \propto \langle v/q_m \rangle / \langle 1/(q_m v) \rangle$, where <> denotes the average over electron energy (or velocity) distribution and v the random velocity of an electron.

Moreover, w decreases approximately linearly (as E/N) with decreasing E/N. Hence, even under very weak fields, the mobility $\mu \equiv w/E$ may well yield information about the MTCS for thermal energies. In contrast, ε_k approaches the common thermal (Einstein) limit of kT when E/N tends to zero, irrespective of the gas species. Therefore, it is essentially difficult to obtain information about q_m for very low energies from ε_k data. Meanwhile, ε_k values for slightly higher E/N's are extremely sensitive to the magnitude and the shape of $q_m(\varepsilon)$ in a rather higher energy region such as the Ramsauer minimum in Ar, Kr and Xe as was already emphasized repeatedly. This is due to the fact that even a slight difference in $q_m(\varepsilon)$ may well affect drastically the shape of electron energy distribution, in the higher energy side in particular, and consequently the values of ε_k. This makes the measurement of ε_k particularly suited to the detailed study of the MTCS in Ramsauer gases.

Quantum mechanical calculation of the MTCS in various inert gases has been attempted by many authors for long years as is seen in Table 2 shown before. For He, recent results by Nesbet /28/ and also by some other authors /29/, /30/ are in excellent agreement with experimentally derived cross sections over an energy range from about 0.01 to 12 eV. For other inert gases, theoretical results are not so satisfactory in general as in He, although considerable improvement has been made in the latest years.

3.2 Present Status of Cross Section Determination for Each Gas Species

A brief but broad critical review has been presented by Phelps in 1979 on the determination of cross sections for various gases, atomic and molecular, from swarm data at the first International Swarm Seminar held in Tokyo /39/. Besides, Itikawa has attempted in 1974 and 1978 a relative evaluation of various proposed values of $q_m(\varepsilon)$ for several familiar gases including five inert gases /40/. Similar attempts are also made for some common gases in the monographs written by Gilardini /5/ as well as by Huxley and Crompton /6/. Meanwhile, Hayashi /40/ has recently proposed a series of recommended cross sections (including $q_m(\varepsilon)$) in five inert gases as well as in some molecular gases for practical purposes by compromising among a few conflicting estimates, some based on swarm data while others on beam data.

3.2.1 Helium

Helium is the inert gas for which the electron swarm parameters have long been investigated most thoroughly. The values of the MTCS, which are widely approved to be most reliable and accurate at the present time for low energies below about 12 eV, are those derived by Crompton, Elford and Robertson /10/ and also by Milloy and Crompton /22/ from their own drift velocity data together with their characteristic energy data /9/. They are in satisfactory agreement with the cross section derived from beam experiments performed by Andrick and Bitsch /42/. Also they are reproduced very well within about 2 % or less by a theoretical calculation made by Nesbet /28/ as was mentioned earlier. At higher energies, the swarm-based MTCS is much less certain /41/.

3.2.2 Neon

The values of the MTCS for electrons in neon that have been most widely accepted are those which were derived by Robertson /11/ from his drift velocity data using the modified effective range theory (MERT) for energies ranging from 0.03 to 7.00 eV. Later, however, O'Malley and Crompton /23/ made an attempt to apply an improved MERT approximation (the extended MERT, EMERT) to the same drift velocity data and derived a slightly different set of q_m values, together with the estimated s-wave scattering length of 0.214 ± 0.005 a. u.

The author and his colleagues /15/ have recently measured the characteristic energy for the first time and have derived the MTCS for energies ranging from 0.01 to 1.00 eV from the experimental result with an estimated error limit of about ± 4 %, as was mentioned earlier in Sec. 2. As is shown in Fig. 4, the obtained q_m values proved to be in very good agreement not only with those derived by Robertson /11/ as well as those by O'Malley and Crompton /23/, but also with those estimated by Sol, Devos and Gauthier /24/ from

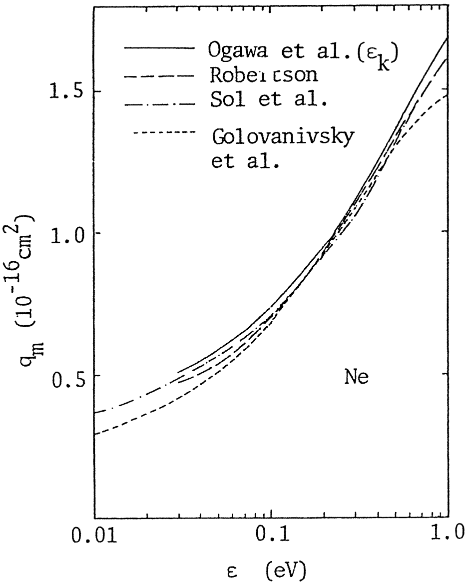

Fig. 4. The momentum transfer cross section for electrons in Ne derived from characteristic energy data /15/, as compared with some previous estimates.

microwave afterglow experiments and those by Golovanivsky and Kabilan /25/ from electron cyclotron resonance, each with the relevant error limits. This means that the values of the MTCS have been almost established with an accuracy of about ± 4 - 5 % at least in the energy range from 0.1 to 1.0 eV. As regards the s-wave scattering length a_0, however, the author et al. /15/ have estimated it to be about 0.24 a. u., in considerable disagreement with O'Malley et al.'s result of 0.214 a.u./23/.

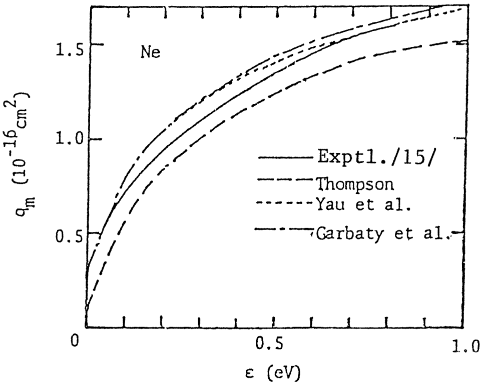

Fig. 5. Comparison of the momentum transfer cross section for electrons in Ne derived experimentally from characteristic energy data /15/ with some theoretical results /27/,/32/, /33/.

As is seen in Fig. 5, these experimental results, including the one obtained by the author et al., are all in fair agreement with any of the three existing theoretical results /27/,/32/,/33/ reported so far for energies ranging from 0.01 to 1.0 eV. On finer inspection, however, it is seen in Fig. 5 that the experimental results are about 10 - 20 % greater than Thompson's theoretical results /32/ and about 0 - 10 % smaller than those reported by Garbaty and La Bahn /33/ and also by Yau, McEachran and Stauffer /27/. Also, the experimental value of $a_0 \cong 0.24$ a.u. is somewhat larger than expected from any of the three theories.

3.2.3 Argon

With respect to this familiar inert gas which is also well-known as a typical Ramsauer gas, the momentum transfer cross section for 0 - 4 eV as derived by Milloy, Crompton, Rees and Robertson /26/ from the drift velocity data obtained by Robertson /12/ and the characteristic energy data by Milloy and Crompton /14/ is considered to be most accurate at the present time.

In their paper, Milloy et al./26/ have emphasized that the characteristic energy ε_k is much more sensitive to the depth of the Ramsauer minimum in the MTCS than the drift velocity and demonstrated clearly that none of the MTCS's derived previously from the data other than ε_k, e.g. the one by Frost and Phelps from the drift velocity data /17/,the one by Golden from beam experiments /43/, and the one by McPherson from microwave experiments /44/, were compatible with the ε_k data used by Milloy et al. to derive their cross section.

It should also be mentioned that the same authors /26/ have calculated from their derived MTCS the "longitudinal" diffusion coefficient D_L, a quantity more sensitive to the Ramsauer minimum, as a function of E/N and compared it with the experimental results observed by Robertson and Rees /20/.

3.2.4 Xenon and Krypton

Figures 6 and 7 show some of the estimated momentum transfer cross sections $q_m(\varepsilon)$ for electrons in Xe and Kr, respectively, in a low energy region including the Ramsauer minimum, that have been either derived experimentally or calculated theoretically.

Of these, the one shown by a solid line was derived as early as 1964 by Frost and Phelps /17/ from the drift velocity measured by Pack, Voshall and Phelps /8/ and has long been widely accepted as the almost single reliable experimental estimates in this energy region where beam experiments are extremely difficult to carry out.

In Figs. 8 and 9 are shown with a solid line as a function of E/N the characteristic energy of electrons in Xe and Kr, respectively, as calculated by a Boltzmann analysis employing the MTCS just mentioned. In the same Figures

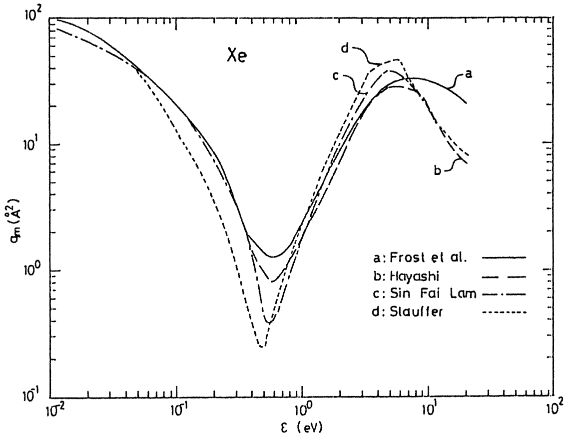

Fig. 6. Momentum transfer cross sections for electrons in Xe. a: experimental, Frost and Phelps /17/; b: experimental, Hayashi /38/; c: theoretical, Sin Fai Lam /36/; d: theoretical, McEachran and Stauffer /37/.

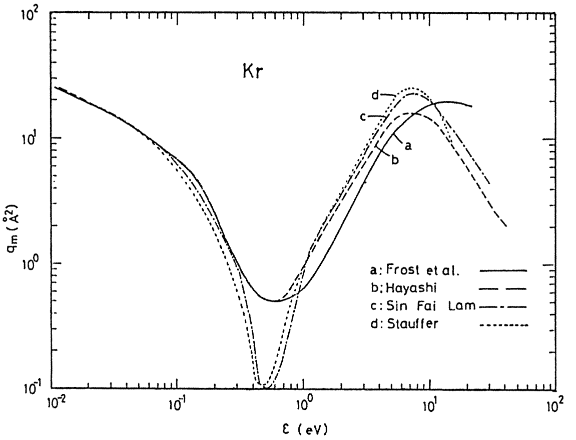

Fig. 7. Momentum transfer cross sections for electrons in Kr. a: experimental, Frost and Phelps /17/; b: experimental, Hayashi /38/; c: theoretical, Sin Fai Lam /36/; d: theoretical, McEachran and Stauffer /37/.

(Figs. 8 and 9) are also plotted with a broken line the calculated ε_k values based on slightly revised values of q_m that were proposed by Hayashi /38/ referring to the recent results of beam experiments in the higher energy region.

Meanwhile, Sin Fai Lam /36/ and McEachran and Stauffer /37/ have recently carried out a theoretical calculation of the MTCS for electrons in Xe and Kr quite independently. The results are plotted with a dot-&-dash line in Figs. 6 and 7. The ε_k values calculated by using these theoretical cross

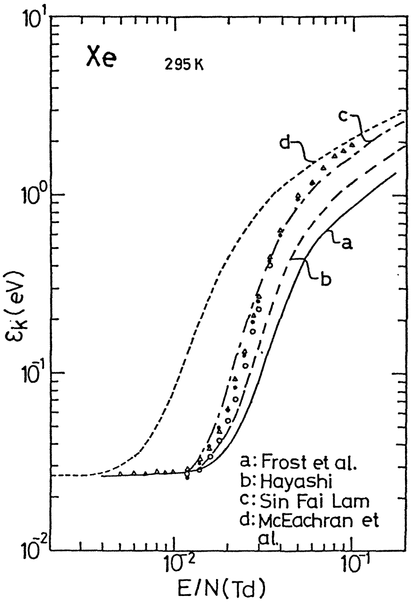

Fig. 8. The characteristic energy of electrons in Xe as a function of E/N. Comparison with the calculated values based on the various proposed momentum transfer cross sections shown in Fig. 6.

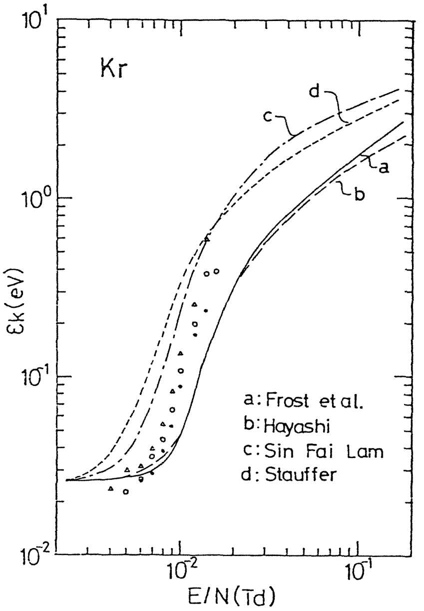

Fig. 9. The characteristic energy of electrons in Kr as a function of E/N. Comparison with the calculated values based on the various proposed momentum transfer cross sections shown in Fig. 7.

sections are shown with a dot-&-dash line for Sin Fai Lam's case and with a dotted line for McEachran et al's case in Figs. 8 and 9, respectively. As is seen in Figs. 8 and 9, the observed ε_k values for Xe are closest to the calculated values obtained with Sin Fai Lam's theoretical cross section, whereas those observed for Kr are definitely smaller than either of the two sets of calculated values based on theoretical cross sections, one by Sin Fai Lam /36/ and the other by McEachran and Stauffer /37/. Also, the observed ε_k's for Kr are considerably greater than the calculated values based on the cross section derived experimentally by Frost et al. and also the one recommended by Hayashi.

Numerical calculations are in progress in the author's laboratory to derive the MTCS capable of giving best fit to the observed characteristic energy data. It should be noted in passing that, both in Xe and Kr, the MERT or the EMERT approximation is not applicable unfortunately to the derivation of the MTCS near and above the Ramsauer minimum which lies in an energy region as high as 0.5 - 0.7 eV in both gases.

3.2.5 Radon

Because of its peculiar nature as the "daughter" element of the radioactive decay of Ra and also of its own alpha-radioactivity with a half-life of about 3.8 days, it is extremely difficult to make an electron swarm experiment with this gas and no swarm parameters for Rn have ever been measured so far. It is of interest to note, however, that Sin Fai Lam predicts theoretically /36/ that the Rn gas will exhibit the Ramsauer-Townsend effect also in the vicinity of 1 eV.

Appendix: Derivation of Equations (3) and (4) in the Text

During a free flight between two successive momentum transfer collisions with gas atoms, an "average" electron under an electric field E moves (on the average) toward the anode by a distance $s = c_1 (eE/m)\,\tau^2$ $(c_1 \cong \tfrac{1}{2})$ approximately. Here, c_1 denotes a numerical constant with the magnitude of the order of unity depending on the degree of approximation, m the electron mass, and τ the mean free time for electrons from momentum transfer collision.

Let us denote by $\nu_m \equiv 1/\tau$ the momentum transfer collision frequency, by N the number density of gas atoms, by v the average random velocity of electrons, and by $\bar{q}_m$ the momentum transfer cross section averaged over an energy region in which the substantial part of electron energy distribution is contained. Then $\nu_m = N\bar{q}_m v$ and the drift velocity w is given as

$$w = s/\tau = c_1(eE/m)\tau = c_1(eE/(m\nu_m)) = c_1(e/\bar{q}_m)(E/N)(1/(mv)). \qquad (A1)$$

Meanwhile, the diffusion constant D for electrons (assumed as isotropic, for simplicity) is well known to be approximately given by $D \cong \lambda v/3 = v/(3N\bar{q}_m)$ from the conventional kinetic theory of gases, where λ denotes the momentum transfer mean free path for an electron, and the mobility μ is derived immediately from Eq.(A1) as $\mu \equiv w/E = c_1(e/N)/(m\overline{vq_m})$. Combining these two expressions, the characteristic energy ε_k is expressed simply as

$$\varepsilon_k \equiv eD/\mu = (2/3)m\overline{v^2}. \tag{A2}$$

On the other hand, the energy given to an "average" electron from the electric field per unit time is eEw. In a steady state, this must be equal to $\overline{\Delta\varepsilon}\ \nu_m$, the energy lost by the electron through momentum transfer (elastic) collisions per unit time, so that

$$eE\ w = \overline{\Delta\varepsilon}\ N\overline{q_m v}, \tag{A3}$$

where $\overline{\Delta\varepsilon}$ denotes the mean energy loss per collision for an electron.

For elastic collisions of an electron of mass m with a gas atom of mass M (>> m) at rest, $\overline{\Delta\varepsilon}$ is again well known to be given in good approximation by

$$\overline{\Delta\varepsilon} = 2(m/M)\varepsilon, \quad \text{with} \quad \varepsilon \equiv (1/2)m\overline{v^2}. \tag{A4}$$

Substituting (A4) in (A3) and solving simultaneous equations (A1), (A2) and (A3) for w, ε_k and v, we readily obtain the formulae (3) and (4) in the text.

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