J. Phys. B: At. Mol. Phys. 19 (1986) 2331-2342. Printed in Great Britain

Momentum transfer cross sections for low-energy electrons in krypton and xenon from characteristic energies

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Received 4 June 1985

Abstract. Characteristic energies of low-energy electrons in krypton and xenon gases have been measured at room temperature by the Townsend method as a function of reduced electric field. For both gases, observed characteristic energies were twice or even three times as large as the early estimates by Frost and Phelps based on the momentum transfer cross sections for electrons in these gases derived from drift velocity data. The cross sections were determined from the present experimental data over an energy range from 0.01 to 6.0 eV for krypton and from 0.01 to 5.0 eV for xenon. The minimum values and positions of Ramsauer minima in the derived cross sections were 1.0×10^{-17} cm^2 at 0.5 eV for krypton and 4.0×10^{-17} cm^2 at 0.6 eV for xenon. These minimum values are both definitely smaller than the previous experimental results of Frost and Phelps, while being rather close to, but still somewhat smaller than, those of Hoffmann and Skarsgard. Theoretical cross sections calculated for krypton and xenon by Sin Fai Lam and by McEachran and Stauffer and those for krypton by Fon *et al* all agree with the present experimental ones within ±30% for energies below about 5 eV in both gases.

1. Introduction

It has long been well known that a prominent Ramsauer effect is seen in the elastic scattering of low-energy electrons by a krypton or xenon atom in an energy region near about 0.5 eV, just as in their scattering by an argon atom. From physical interest in the effect as well as from its practical importance in various applications, several attempts have so far been made to determine experimentally the cross section for the scattering process as precisely as possible with different methods.

Thus, more than 50 years ago, Ramsauer and Kollath (1929, 1932) made the now well known pioneer measurements of the scattering cross section q_s for krypton and xenon with a beam technique. More recently, several experiments have been carried out with similar beam scattering techniques in a modern fashion for an energy region covering the Ramsauer minimum. The differential cross sections have been obtained by Weyhreter *et al* (1983), and the total cross sections have been reported by Guskov *et al* (1978), Dababneh *et al* (1980), Jost *et al* (1983) and Nickel *et al* (1985). However, owing to the limited range of the scattering angle in the former experiment and to the use of an attenuation method in the latter ones capable only of giving the total scattering cross section q_s, it is difficult to compare their results with those of swarm experiments which can yield only the momentum transfer cross section defined as $q_m \equiv q_s\overline{(1-\cos\theta)}$, where θ denotes the scattering angle. There have been no attempts to determine q_m from a beam experiment except for two estimates, one by Braglia (1965) and the other by O'Malley (1963).

0022-3700/86/152331+12\$02.50

As regards swarm experiments, Frost and Phelps (1964) have estimated the momentum transfer cross sections for electrons in krypton and xenon from the drift velocity of electrons observed in these gases (Pack *et al* 1962). The cross section q_m has also been derived from the observed microwave conductivity in these gases, first by Chen (1963) and later by Hoffmann and Skarsgard (1969), and from electron cyclotron resonance experiments by Golovanivsky and Kabilan (1981).

Although there are in fact some problems, such as about the uniqueness of the derived cross section and the impossibility of drawing angular information, these swarm techniques are generally believed to be more appropriate for determining the cross section for low-energy electrons below about 1 eV as compared with beam techniques (see, for example, Huxley and Crompton 1974), not only because of their higher precision in measuring a macroscopic parameter due to the enormous number of electrons and gas atoms concerned, but also because of the simplicity of data analysis, particularly for inert gases in which elastic scattering is the only dominant collision process for electrons.

In spite of these expected merits, the swarm-based momentum transfer cross sections reported so far differ greatly from each other, especially in the position and depth of the Ramsauer minimum. For instance, the minimum value as obtained by Hoffmann and Skarsgard is half or even only one-third of the value estimated by Frost and Phelps.

Meanwhile, all of the few recent theoretical calculations made on electron-krypton and electron-xenon scattering agree well with each other and equally give Ramsauer minima substantially deeper than any of the aforementioned experimental results. To examine the experimental validity of such a theoretical prediction and also to meet various practical needs, it would seem to be a rather urgent task to clarify the true causes of mutual discrepancy among reported experimental cross sections and to acquire as accurate a value as possible.

The reason for the disagreement is not clear, but the following facts may well be considered to be at least a part of the background.

(1) The drift velocity as used by Frost and Phelps in deriving the cross section is a swarm parameter primarily dependent on the magnitude of the momentum transfer cross section for a lower energy component of electrons (i.e. the so-called suprathermal or near-thermal electrons) below about 0.1 eV and is not very sensitive to, for instance, the detailed shape of its Ramsauer minimum lying around 0.3–0.8 eV, as has been pointed out by Milloy *et al* (1977) with respect to argon.

(2) The microwave conductivity data are again not very sensitive to the position and depth of the Ramsauer minimum. In fact, Hoffmann and Skarsgard (1969) could not determine the minimum value uniquely because of the limited energy resolution in their experiment.

(3) The accuracy of the modified effective range theory (MERT) approximation as employed by O'Malley (1963) and also by Golovanivsky and Kabilan (1981) in analysing experimental results deteriorates rapidly for energies higher than about 0.2–0.5 eV depending on the species of target atoms.

In contrast, the characteristic energy $\varepsilon_k \equiv eD/\mu$, where e denotes the elementary charge, D the transverse diffusion coefficient for electrons and μ their mobility (which is another important swarm parameter at steady state, besides the drift velocity), is very sensitive to the behaviour of the cross section in the energy range from about 0.1 to 1.0 eV, as has been demonstrated by Milloy *et al* (1977) for argon. It is considered to be suited far better, compared with the drift velocity, to the precise determination of such behaviour, including in particular the position and depth of the Ramsauer minima in inert gases. Needless to add, the characteristic energy is in itself an indispensable parameter in describing the macroscopic behaviour of an electron swarm together with the drift velocity.

Notwithstanding the physical and practical significance of the characteristic energy, mentioned above, no measurements have ever been reported of this quantity for either krypton or xenon. In view of these circumstances, we undertook to carry out its measurement for the first time over a wide range of reduced electric field E/N, where E denotes the field strength and N the number density of gas atoms; and we attempted to determine from the results the momentum transfer cross section as precisely as possible, paying special attention to the position and depth of the Ramsauer minima.

In § 2, a brief account is given of the experimental method and apparatus used and, in § 3, experimental results are shown both graphically and numerically. In §§ 4 and 5, a description and discussion of the derived cross section are presented, together with a comparison with previous estimates by other methods and theoretical prediction.

2. Experimental method

The characteristic energy ε_k was measured at room temperature by the Townsend method as a function of reduced field E/N. The outline of the experimental method and apparatus is given below. The details have been described in a previous paper (Koizumi *et al* 1984).

Electrons were produced photoelectrically by irradiating a photocathode in a diffusion chamber with UV radiation from a deuterium lamp, and passed into the drift-diffusion space of the chamber through an aperture hole, 2 mm in diameter. Four guard rings were provided to make a uniform field in the drift-diffusion space. The drifting electrons were eventually collected by one of the annular rings of the collector, which consisted of five mutually insulated concentric rings. 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 stands for electron drift velocity, was determined by referring to the Warren-Parker solution of the drift-diffusion equation (Warren and Parker 1962). The energy ε_k was readily obtained from the parameter as $\varepsilon_k = eE/2\lambda$.

In view of the extreme sensitivity of ε_k values to minor impurities in both the krypton and the xenon due to the Ramsauer effect, particular attention was paid to the purity of gases. The chamber was evacuated to about 10^{-6} Pa after baking for several hours and the gases were admitted to the chamber after passing through a heated Ba-Zr getter purifier and a dry-ice cold trap. The ultimate purity of gases is uncertain but is believed to have been better than 99.995%. The gas pressure was measured with a mercury manometer. The filling pressures ranged from 80 to 200 kPa.

The Warren-Parker solution used in the present work to determine the parameter λ does not take into account the effect of diffusion anisotropy nor of finite aperture size. We examined the influence of the former effect on λ and hence on ε_k by using Lowke's (1971) solution of an anisotropic diffusion equation. In view of the absence of direct experimental data for the longitudinal diffusion coefficient D_L in krypton or in xenon, we first estimated the anisotropy ratio $S \equiv D_L/D$ for these gases at room temperature from the drift velocity data of Pack *et al* (1962) using Robson's (1972) approximate formula: $S = \mathrm{d} \log w/\mathrm{d} \log(E/N)$. For both krypton and xenon, the ratio obtained increased from unity with increasing E/N and reached a maximum value of about 2.5 at around 0.02 Td for krypton and about 2.0 at around 0.04 Td for xenon. Then the ratio decreased rapidly and took on a nearly constant value of about 0.2 for E/N greater than about 0.2 Td in both gases. Keeping these results in mind, we calculated the parameter λ and hence ε_k by using Lowke's solution in the case of $S = 0.1$ and 3.0 for both gases and compared them with those that neglect diffusion anisotropy. For $S = 0.1$, the deviation of the obtained λ or ε_k values from those based on the Warren-Parker solution was found to be 5% at $\lambda = 5\ \mathrm{cm}^{-1}$ and to decrease rapidly with increasing λ under the present experimental conditions. For $S = 3.0$, the deviation became somewhat larger, being about 10% at $\lambda = 10\ \mathrm{cm}^{-1}$, and decreased with increasing λ.

On the other hand, the effect of finite aperture size can be readily estimated from the Warren-Parker solution with a finite wall radius to increase nearly linearly with increasing λ. For an aperture diameter of 2 mm, as used in the present experiment, the deviation of the derived λ or ε_k values from the point surce approximation proved to be smaller than 0.5% so long as $\lambda < 90\ \mathrm{cm}^{-1}$. The field strength and the gas pressure were always chosen so as to make λ fall within the optimum range from 6 to 90 cm^{-1}, in order to minimise the effects and errors due to diffusion anisotropy and finite aperture size.

3. Results of the measurement of characteristic energy

Tables 1 and 2 show numerically the observed characteristic energy ε_k of electrons in krypton and xenon, respectively. The measurements were performed under various pressures and in the E/N range from 0.005 to 0.90 Td ($1\ \mathrm{Td} = 10^{-17}\ \mathrm{V\,cm}^2$) for krypton and from 0.012 to 0.60 Td for xenon. In krypton, ε_k could not be measured accurately enough in the E/N range from 0.015 to 0.090 Td with our low-pressure diffusion chamber, which is for use only below about 200 kPa, because of insufficient collector current due to diffusion loss of electrons near the aperture hole. Each ε_k value shows the average of those obtained from the current ratios for different combinations of collector rings.

As is seen from the tables, no appreciable pressure effect was observed. The scatter of the data at the same E/N is within about $\pm 5\%$. For each value of E/N, the simple average of ε_k values obtained at various pressures was adopted as the best estimate of ε_k. The error caused by diffusion anisotropy becomes larger when S is large and λ is small. According to Robson's formula, S has a maximum around 0.02 Td for krypton and around 0.04 Td for xenon. The diffusion anisotropy may affect the measured ε_k in the E/N range from 0.01 to 0.08 Td for krypton and from 0.03 to 0.05 Td for xenon. This systematic error can be estimated to be less than 10% from Lowke's solution. For E/N outside this range the error of the best estimate value is estimated to be $\pm 5\%$. The best estimate values of ε_k are plotted in figures 1 and 2 as a function of E/N.

There are no experimental ε_k data to be compared with the present ones, although Frost and Phelps (1964) did estimate the value of ε_k in krypton and xenon on the basis of the momentum transfer cross section derived from the observed drift velocity (Pack *et al* 1962). Their results are also shown in figures 1 and 2. As is seen in the figures, the present results are about two or three times as large as their estimates for both krypton and xenon. These discrepancies will be discussed in § 5.

Table 1. The characteristic energy ε_k observed for electrons in krypton at room temperature and various pressures.

	ε_k (eV)				
E/N (Td)	81.2 kPa	133 kPa	149 kPa	202 kPa	Best estimate of ε_k (eV)
0.005			0.0337	0.0338	0.0337
0.006			0.0397	0.0394	0.0396
0.007			0.0494	0.0503	0.0497
0.008			0.0676	0.0753	0.0715
0.009			0.0912	0.107	0.0989
0.010			0.136	0.151	0.144
0.012			0.258	0.276	0.269
0.014			0.410	0.430	0.418
0.018				0.670	0.670
0.080				2.67	2.67
0.090				2.89	2.89
0.10			2.81	3.06	2.94
0.12			3.28	3.22	3.25
0.14			3.56	3.45	3.50
0.16			3.61	3.60	3.61
0.18		3.85		3.84	3.85
0.20		3.90	3.96	4.10	3.99
0.22			4.11	4.24	4.18
0.25		4.44	4.55	4.43	4.47
0.28				4.71	4.71
0.30		4.71		4.82	4.76
0.35				5.12	5.12
0.40	5.22	5.40			5.31
0.50	5.54	5.78			5.66
0.70	6.56				6.56
0.90	6.92				6.92

4. Determination of momentum transfer cross sections

The momentum transfer cross sections q_m for electrons in krypton and xenon were determined by a Boltzmann analysis as a function of electron energy in the region from 0.01 to 6.0 eV for krypton and from 0.01 to 5.0 eV for xenon by adjusting a plausible trial cross section and calculating the characteristic energy as a function of E/N until the results agree with the observed value within experimental error.

Since the ε_k value in the low E/N region always tends to the Einstein limit kT with vanishing E/N, where k denotes the Boltzmann constant and T the absolute temperature, independently of the gas species (and hence of the cross section), the accuracy of the cross section derived from ε_k data for energies below 0.05 eV will become increasingly worse with decreasing E/N. In a low-energy region such as below 0.05 eV, therefore, we assumed essentially the same cross section as determined by Frost and Phelps (1964) from the drift velocity data. In contrast, however, the ε_k values are surprisingly sensitive to the depth and position of the Ramsauer minimum. This can be seen in figure 3, which shows the effect on w and ε_k of varying the minimum depth. The fractional differences between the calclated values of w and ε_k based on

Table 2. The characteristic energy ε_k observed for electrons in xenon at room temperature and various pressures.

E/N (Td)	ε_k (eV) 107 kPa	147 kPa	193 kPa	Best estimate of ε_k (eV)
0.012	0.0305	0.0332	0.0324	0.0320
0.014	0.0332	0.0344	0.0353	0.0343
0.016	0.0373	0.0396	0.0417	0.0395
0.018	0.0460	0.0482	0.0529	0.0490
0.020	0.0588	0.0629	0.0680	0.0632
0.022	0.0789	0.0850	0.0906	0.0848
0.025	0.125	0.128	0.140	0.131
0.028	0.200	0.195	0.185	0.194
0.030	0.255	0.258	0.274	0.262
0.035	0.439	0.428	0.441	0.436
0.040	0.607	0.606	0.631	0.613
0.050		0.941	0.946	0.943
0.060			1.19	1.19
0.070			1.43	1.43
0.090		1.76	1.78	1.77
0.12		2.16	2.21	2.18
0.16		2.68	2.69	2.69
0.20		3.03	3.11	3.07
0.25	3.51	3.49	3.48	3.49
0.30	3.83	3.84	3.82	3.83
0.40	4.46	4.40		4.43
0.50	4.93	4.93		4.93
0.60	5.38			5.38

two trial cross sections, which are shown in the inset of the figure, are plotted as a function of E/N. As is seen in the figure, the variation of w is less than 5% over the entire E/N region while ε_k was almost doubled when the minimum value was changed from 0.4×10^{-16} cm^2 to 0.2×10^{-16} cm^2. We attempted to determine the momentum transfer cross section paying special attention to the depth and position of the Ramsauer minima.

The results obtained are tabulated numerically in tables 3 and 4 for krypton and xenon, respectively, and are plotted graphically in figures 4 and 5, respectively. As is seen in the tables and graphs, the present results indicated, as expected, distinct Ramsauer minima for both krypton and xenon, the minimum values and positions being 1.0×10^{-17} cm^2 at 0.5 eV for krypton and 4.0×10^{-17} cm^2 at 0.6 eV for xenon.

The uniqueness of the derived cross section near the minimum is another serious problem for Ramsauer gases, as has earlier been noted by Milloy *et al* (1977). To estimate the upper and lower limits of the minimum value compatible with the observed characteristic energy data, we proceeded as follows. First the cross section at the minimum was changed tentatively by a few per cent without varying the minimum position. Then the rest of the cross section was adjusted variously until the calculated values ε_k agreed satisfactorily with the observed data within the claimed error limits. In this way, the upper limit was estimated to be 1.6×10^{-17} cm^2 for krypton and 4.5×10^{-7} cm^2 for xenon, and the lower limit to be 0.7×10^{-17} cm^2 for krypton and

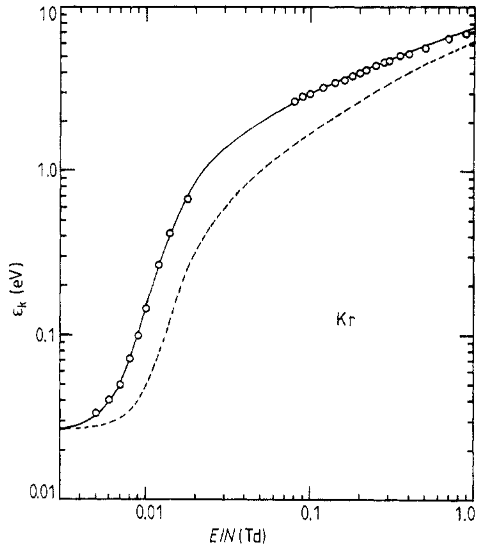

Figure 1. Characteristic energy for electrons in krypton gas observed at room temperature. The full curve shows the calculated value from the present cross section q_m. The broken curve shows the early estimate of Frost and Phelps (1964).

2.7×10^{-17} cm^2 for xenon. For any minimum values beyond these limits, the calculation could not reproduce the observed ε_k data. To recover a satisfactory agreement between the calculation and experimental data with a changed minimum depth of the cross section, the cross section for energies higher than 1 eV had to be somewhat corrected.

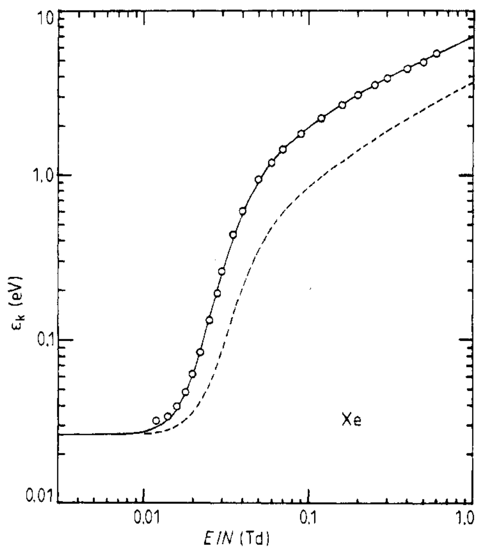

Figure 2. Characteristic energy for electrons in xenon gas observed at room temperature. The full curve shows the calculated value from the present cross section q_m. The broken curve shows the early estimate of Frost and Phelps (1964).

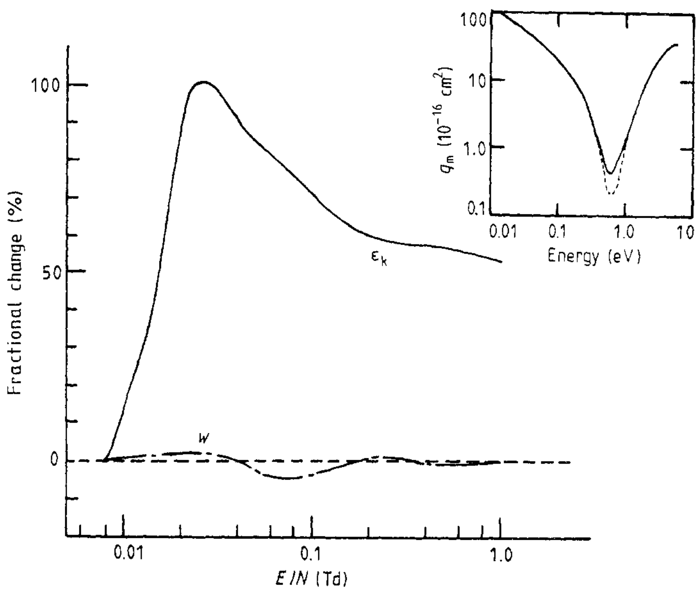

Figure 3. Sensitivity of w and ε_k to the change in the cross section minimum, as demonstrated using the cross sections shown in the figure.

Table 3. The momentum transfer cross section q_m for electrons in krypton as a function of electron energy ε derived from the characteristic energy data.

ε (eV)	q_m (10^{-16} cm^2)	ε (eV)	q_m (10^{-16} cm^2)
0.010	26.0	0.450	0.15
0.020	19.7	0.500	0.10
0.030	16.0	0.540	0.11
0.040	13.4	0.600	0.15
0.050	11.4	0.700	0.27
0.060	10.0	0.800	0.45
0.080	8.20	1.00	1.00
0.100	6.80	1.20	1.50
0.120	5.70	1.60	2.80
0.160	3.97	2.00	4.40
0.200	2.47	2.50	6.00
0.250	1.50	3.00	8.00
0.300	0.95	4.00	13.0
0.350	0.55	5.00	18.5
0.400	0.26	6.00	22.0

However, the necessary amount of correction was at most 15% so far as the assumed minimum depth lay between the above limits. The claimed error limit for the proposed cross section above 1 eV (and under 0.4 eV) may therefore be considered to be less than ±15%.

5. Discussion

The cross sections q_m for krypton and xenon have so far been derived by other workers from only the two independent experimental results mentioned in § 1. These cross

Table 4. The momentum transfer cross section q_m for electrons in xenon as a function of electron energy ε derived from the characteristic energy data.

ε (eV)	q_m (10^{-16} cm^2)	ε (eV)	q_m (10^{-16} cm^2)
0.010	116.0	0.50	0.55
0.020	80.0	0.60	0.40
0.030	61.0	0.70	0.40
0.040	48.0	0.80	0.60
0.050	39.5	0.90	1.10
0.070	29.0	1.00	1.60
0.090	23.0	1.20	3.00
0.110	18.0	1.50	5.50
0.150	13.0	2.00	11.0
0.200	8.3	2.50	18.0
0.250	5.7	3.00	24.0
0.300	3.7	4.00	33.0
0.400	1.5	5.00	37.0

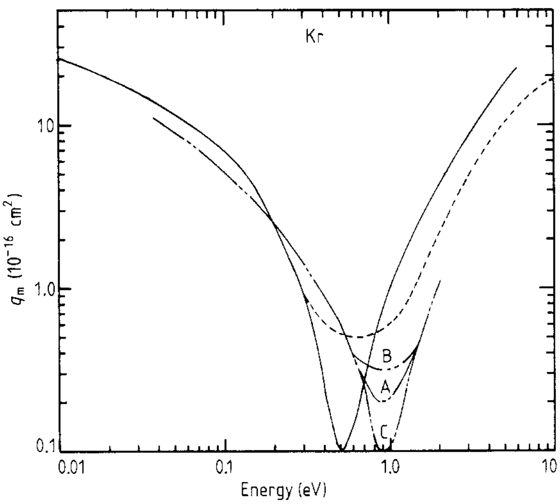

Figure 4. Momentum transfer cross sections for electrons in krypton. The results of other experimental investigations are shown for comparison: ——, present result; - - - -, Frost and Phelps (1964); —— - - ——, Hoffmann and Skarsgard (1969). The symbols A, B and C on the curves of Hoffmann and Skarsgard indicate the best fit, and the upper and lower limits of the cross section curve, respectively.

sections, one estimated by Frost and Phelps (1964) from electron drift velocity data and the other by Hoffmann and Skarsgard (1969) from microwave conductivity ratios, are plotted in figures 4 and 5 for comparison with the present results. In the case of krypton, the agreement among these three cross sections is fairly good for energies below about 0.2 eV. For higher energies near the Ramsauer minimum, however, the cross sections show a great deal of spread. The one derived by Frost and Phelps gives a minimum substantially broader and shallower than either of the other two. Hoffmann and Skarsgard could not determine the minimum value uniquely because of limited energy resolution in their experiment, but they estimated the lowest limit for the

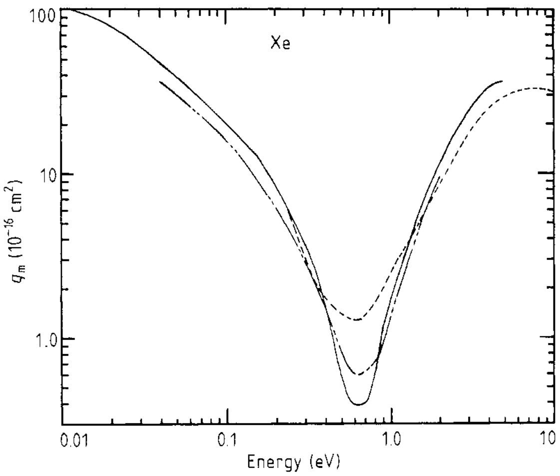

Figure 5. Momentum transfer cross sections for electrons in xenon. The results of other experimental investigations are shown for comparison: ——, present result; - - - -, Frost and Phelps (1964); —— - - ——, Hoffmann and Skarsgard (1969).

minimum value as 1.0×10^{-17} cm^2. This coincides exactly with the minimum value obtained in the present work, although the position of their minimum (about 0.9-1.0 eV) is considerably higher in energy than in the latter.

The reason for these discrepancies is not very clear. It should be borne in mind, however, that the drift velocity and microwave conductivity are both much less sensitive to the depth and position of the Ramsauer minimum when compared with the characteristic energy. In fact, the drift velocity calculated for krypton from the present cross section agrees with the experimental result of Pack *et al* (1982) within about 10%, whereas the characteristic energy calculated from the cross section derived by Frost and Phelps from observed drift velocities is considerably smaller than the present experimental result, as is seen in figure 1.

For xenon, the present cross section is in remarkable agreement with the result of Hoffmann and Skarsgard, although the minimum in the former is about 30% deeper than in the latter. The cross section derived by Frost and Phelps shows a minimum shallower than either of the other two, similarly to the case of krypton, although all three are nearly at the same energy for xenon. This may be attributed again to the insensitivity of the drift velocity to the minimum value of the cross section, as mentioned above. Meanwhile, it became clear through the present work that the minimum in Frost and Phelps' cross section is too shallow to reproduce the observed characteristic energy data.

Finally, it remains to compare the present cross section with various theoretically calculated ones that have been published recently. These include the one reported by Sin Fai Lam (1982) using a semi-relativistic method with Dirac-Fock (relativistic Hartree-Fock) wavefunctions to describe the atoms; another by McEachran and Stauffer (1984), who used an exact adiabatic exchange method including only the dipole part of the polarisation potential both for krypton and xenon; and still another by Fon *et al* (1984) based on the *R*-matrix method for krypton, as mentioned in the introduction. Figures 6 and 7 show the results of these calculations together with the present experimental results for krypton and xenon, respectively. It is seen in figure 6 that, in the case of krypton, all three theoretical results agree rather well with the

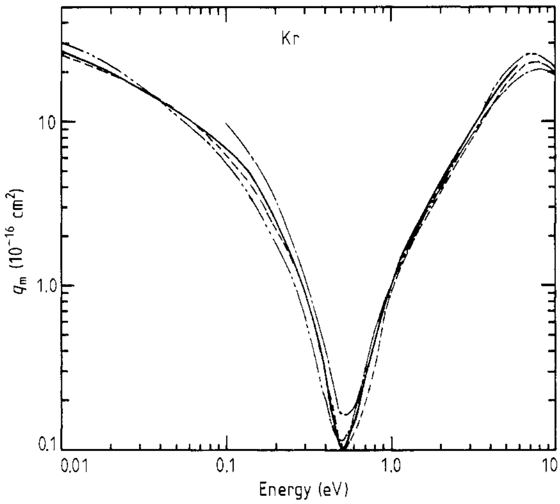

Figure 6. Comparison between our momentum transfer cross section and theoretical ones for krypton: ——, present result; - - - -, Sin Fai Lam (1982); ——- - -——, McEachran and Stauffer (1984); ——- -——, Fon *et al* (1984).

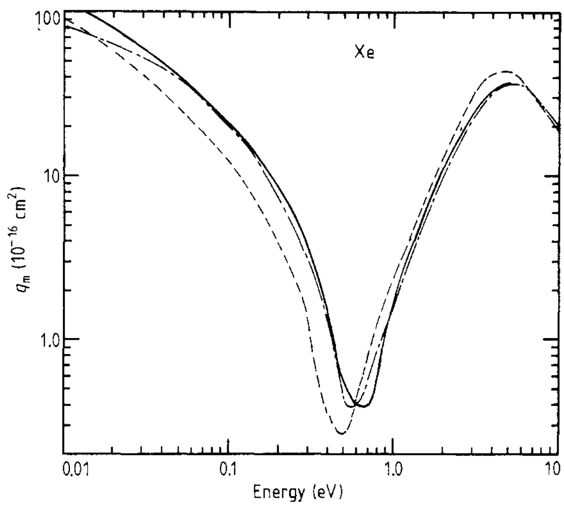

Figure 7. Comparison between our momentum transfer cross section and theoretical ones for xenon: ——, present result; ——- -——, Sin Fai Lam (1982); - - - -, McEachran and Stauffer (1984).

present cross section. For xenon, the result of Sin Fai Lam is in excellent agreement with the present one, as is seen in figure 7; his result shows a minimum depth almost exactly equal to that of the latter, though the minimum position is very slightly lower (about 0.1 eV smaller) in energy. Meanwhile, the one obtained by McEachran and Stauffer also gives a roughly similar minimum, but for energies below about 0.5 eV, it gives a definitely smaller cross section than the experimental one. These results seem to indicate that the relativistic effect may in fact become important in the case of heavy atoms such as xenon as studied in the present work.

Acknowledgments

The authors would like to thank Mr N Kuribayashi and Mr N Miyamoto for their great help in performing the experiment. They are also very grateful to Professor G Lehman of Rikkyo University for proofreading the original manuscript. This work was supported in part by a Grant-in-Aid for Scientific Research from the Ministry of Education, Science and Culture, Japan. Numerical calculations were carried out at the Rikkyo University Computer Center.

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