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Determination of electron–xenon total excitation cross-sections, from threshold to 100 eV, from experimental values of Townsend's α

Makoto Hayashi
Nagoya Institute of Technology, Gokiso-cho, Syowa-ku, Nagoya, 466 Japan

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Abstract. Recommended values are presented for q_m, q_t and Q_T (momentum transfer cross-sections for elastic collisions, total cross-sections for elastic collisions and total collision cross-sections, respectively) of electrons in xenon for electron energies from 0 to 10^4 eV. Recommended values of ionisation cross-sections q_i are also presented. Using these values of q_m together with values of q_i and Townsend ionisation coefficients α, recommended values of total excitation cross-sections q_e are determined. The values of q_m for electron energies from 5 to 20 eV are smaller than those of Frost and Phelps by a considerable amount. The values of q_e for energies from about 20 to 100 eV are much larger than those of de Heer *et al*.

1. Introduction

There is still a lack of reliable experimental and theoretical swarm parameters for xenon. There are large discrepancies between measured and calculated values of the first Townsend ionisation coefficient α in this gas. There has also been a lack of reliable elastic and inelastic electron–atom cross-sections for use in calculating swarm parameters in xenon.

In this paper values of the necessary electron–xenon cross-sections for electron energies up to 10^4 eV have been assembled from various swarm and cross-beam experiments as well as from theoretical calculations. After selecting recommended values of elastic momentum transfer cross-sections q_m and ionisation cross-sections q_i, the values of total excitation cross-sections q_e were determined for electron energies from threshold to 10^2 eV from Townsend ionisation coefficients and connected smoothly with the values of q_e at high electron energies, up to 4×10^3 eV, obtained from theoretical calculations. Unless otherwise specified all cross-sections discussed in this paper refer to xenon.

2. Values of elastic momentum transfer cross-sections

Values of elastic momentum transfer cross-sections q_m below about 10 eV have been given by Bowe (1960), Frost and Phelps (1964), Braglia *et al* (1965), Hoffmann and Skarsgard (1969), Coffey (1970), Geltman (1973), Itikawa (1974) and Guskov *et al* (1978). The values of q_m for electron energies from 1 to 10^4 eV were determined from the absolute differential cross-section data of Williams and Crowe (1975), Riley *et al*

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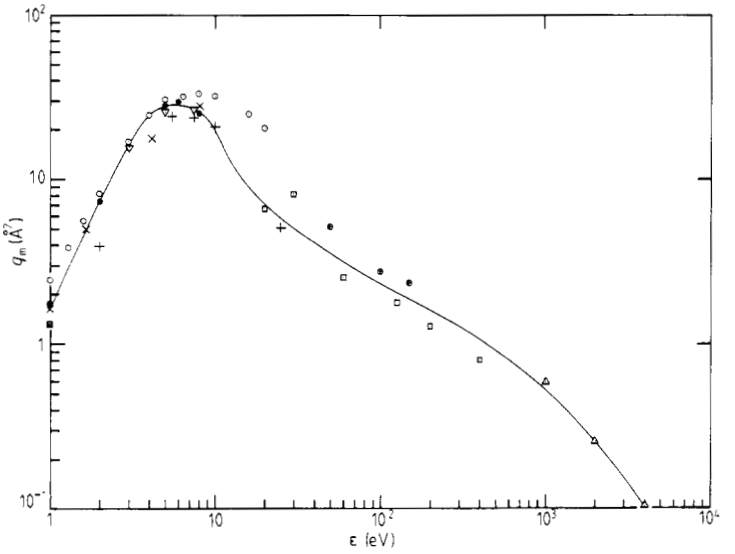

Figure 1. Momentum transfer cross-sections in xenon. (×) Ramsauer and Kollath (1932), (⊙) Frost and Phelps (1964), (●) Braglia *et al* (1965), (⊕) Schackert (1968), (⊡) Williams and Crowe (1975), (△) Riley *et al* (1975), (▽) Heindorff *et al* (1976), (+) Klewer *et al* (1980). Full curve, q_m recommended values.

(1975) and Jansen and de Heer (1976), and also from the elastic total collision cross-section (q_t) values of Bromberg (1974), Williams and Crowe (1975), de Heer *et al* (1979) and Dababneh *et al* (1980) using the relative differential cross-section data of Ramsauer and Kollath (1932), Schackert (1968), Heindorff *et al* (1976) and Klewer *et al* (1980). The values of relative differential cross-sections were integrated and relative values of

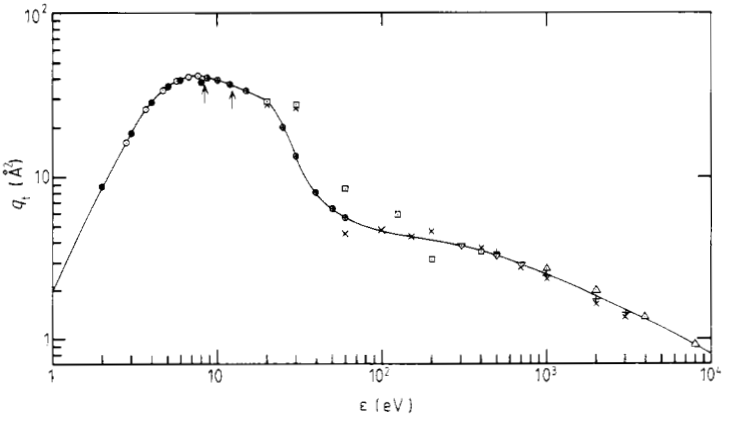

Figure 2. Elastic total collision cross-sections in xenon. (●) Braglia *et al* (1965), (▽) Bromberg (1974), (⊡) Williams and Crowe (1975), (△) Riley *et al* (1975), (+) Jansen and de Heer (1976), (×) de Heer *et al* (1979), (⊙) Dababneh *et al* (1980), (⊕) Dababneh's Q_T, minus recommended values of ($q_e + q_i$). Full curve, q_t, recommended values. Arrows indicate the excitation and ionisation potentials.

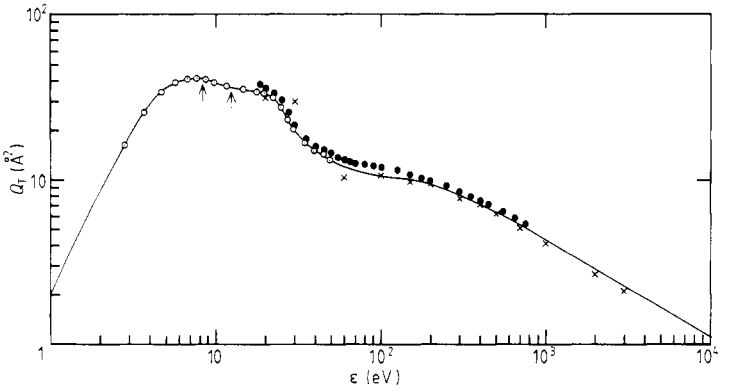

Figure 3. Total collision cross-sections in xenon. (×) de Heer *et al* (1979), (●) Wagenaar and de Heer (1980), (⊙) Dababneh *et al* (1980). Full curve, Q_T recommended values. Arrows indicate the excitation and ionisation potentials.

Table 1. Momentum transfer cross-section of electrons in xenon.

ε (eV)	q_m (Å^2)	ε (eV)	q_m (Å^2)
0	176	12	13.5
0.01	116	15	9.5
0.02	80	20	7.0
0.03	61.3	25	5.9
0.04	48.0	30	5.1
0.05	39.5	40	4.2
0.06	33.5	50	3.6
0.08	25.6	60	3.2
0.1	20.4	80	2.7
0.13	15.1	100	2.4
0.16	12.0	120	2.15
0.2	8.4	150	1.9
0.25	5.35	200	1.65
0.3	3.3	250	1.45
0.4	1.6	300	1.3
0.5	0.955	400	1.08
0.6	0.80	500	0.94
0.7	0.82	600	0.83
0.8	1.05	800	0.70
1	1.7	1000	0.58
1.2	2.55	1200	0.48
1.5	4.0	1500	0.37
2	7.5	2000	0.255
2.5	11.5	2500	0.19
3	16	3000	0.15
4	24.5	4000	0.103
5	28	5000	0.075
6	28	6000	0.057
8	26	8000	0.038
10	20	10000	0.027

q_t and q_m were obtained. Unknown values of q_m were calculated by recommended values of q_t at given electron energies. The total collision cross-sections Q_T (as well as q_e, q_i and q_t) were presented by de Heer *et al* (1979). Recent measurements of Q_T were reported by Wagenaar and de Heer (1980) and Dababneh *et al* (1980). From these papers, recommended values of q_m and also q_t and Q_T were determined and published by the present author (Hayashi 1981). Values of q_m from 0 to 10^2 eV have also been given previously by the author (Hayashi 1982). Previously published values of q_m, q_t and Q_T are shown in figures 1, 2 and 3 together with the presently recommended values. The recommended values of q_m are given in table 1. More exact measurements of drift velocities of electrons, ratio of electron radial diffusion to mobility for wide E/N ranges and also differential elastic scattering cross-sections for wide energy ranges, especially from 5 to 50 eV, are needed to reduce the uncertainty in q_m. It is roughly estimated that errors in the values of q_m are about 20 to 30% for electron energies below 10 eV, about 20% from 10 to 10^2 eV and about 10 to 20% from 10^2 to 10^3 eV. The values of q_m from 1 to 30 eV are important and are shown by the curve in figure 4, together with the values given by Frost and Phelps (1964).

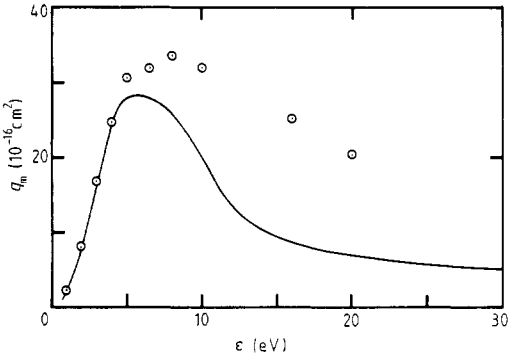

Figure 4. Recommended values (full curve) of q_m below 30 eV, compared with those of Frost and Phelps (1964) (⊙).

3. Values of ionisation cross-sections

Total ionisation cross-sections q_i have been measured by Hanle and Riede (1952) (900 to 2×10^4 eV), Tozer and Craggs (1960) (threshold to 100 eV), Asundi and Kurepa (1963) (threshold to 100 eV), Rapp and Englander-Golden (1965) (threshold to 10^3 eV), Schram *et al* (1965) (600 to 2×10^4 eV), Schram *et al* (1966) (100 to 600 eV) and Märk *et al* (1977) (threshold to 180 eV). Recently, de Heer *et al* (1979) presented recommended values for q_i from 15 to 4×10^3 eV. In the present work, the values of Rapp and Englander-Golden (1965) were used for energies between threshold and 30 eV and the values recommended by de Heer *et al* (1979) between 30 and 4×10^3 eV. Values of q_i of Tozer and Craggs (1960) and Asundi and Kurepa (1963) give values of Townsend's α which are much too high and were therefore disregarded. Values of Schram *et al* (1966) are slightly higher than de Heer *et al*'s (1979) recommended values and Märk *et al*'s (1977) single published value (at 136 eV) agree with that of Rapp and Englander-Golden. Theoretical values of q_i given by Vriens (1965) and Khare *et al* (1974) are also too large. The error in the values of q_i used is estimated to about 10%.

4. Values of excitation cross-sections

There are papers on the values of total excitation cross-sections q_e by Dixson and von Engel (1968), Schaper and Scheibner (1969), Elston *et al* (1973), Rostovikova *et al* (1973), Williams W *et al* (1975), McCarthy *et al* (1977), Al-Shamma and Kleinpoppen (1978), Makabe and Mori (1978), de Heer *et al* (1979) and Specht *et al* (1980). Feltsan and Zapesochnyi (1968) reported the cross-sections of spectral line excitation of 34 lines over a range of 4500–9930 Å at collision energies below 100 eV. Swanson *et al* (1976) measured the excitation functions for the four lowest excited states at a scattering angle of 45° in the near threshold energy region. However, there is at present no information about the values of excitation cross-sections for each specific electronic excitation level.

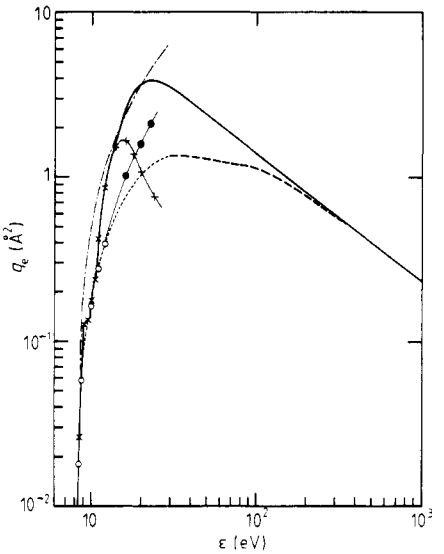

Figure 5. Total excitation cross-sections in xenon. V_e = 8.32 eV. (— — —) Dixson and von Engel (1968); (—●—) Pfau and Rutscher (1969); (○) Schaper and Scheibner (1969); (+) Makabe and Mori (1978); (– – –) de Heer *et al* (1979); (- - - -) extrapolation between the values of Schaper and Scheibner (1969) and de Heer *et al* (1979); (×) Specht *et al* (1980); full curve, q_e recommended values.

The values of q_e of Schaper and Scheibner (1969) from threshold to 14 eV and de Heer *et al* (1979) from 30 to 4 × 10^3 eV were first chosen and values for electron energies between 14 to 30 eV were interpolated smoothly. These values of q_e are chosen in figure 5 by the broken curve. However, according to Dixson and von Engel (1968), Makabe and Mori (1978) and Specht *et al* (1980), there is a very strong possibility that the values of q_e for electron energies of about 10 to 30 eV are much higher than values represented by the broken curve in figure 5. However values of Townsend's α were calculated from these values of q_e by a Monte Carlo method (Hayashi 1982). Large discrepancies exist between the calculated and experimental values of Townsend's α when these broken curve values are used, as shown in figure 6. It is important to note that the values of Townsend's α are very sensitive to q_e at low E/N. The errors in the values of q_e are larger than in those of q_m and q_i. Therefore, the values of q_m and q_i were not changed and the values of q_e were adjusted. In the low electron energy regions around 10 eV these values

are almost the same as those of Specht *et al* (1980) and Makabe and Mori (1978). The values of q_e from about 10 to 100 eV, especially around 20 eV, are much higher than the original q_e values. The values of q_e of electron energies greater than 300 eV are not changed from those of de Heer *et al* (1979), and are not sensitive to the values of Townsend's α.

Townsend ionisation coefficients α were measured by Kruithof (1940), Derenzo *et al* (1974), Bhattacharya (1976), Makabe and Mori (1978, 1981) and Jacques (1982).

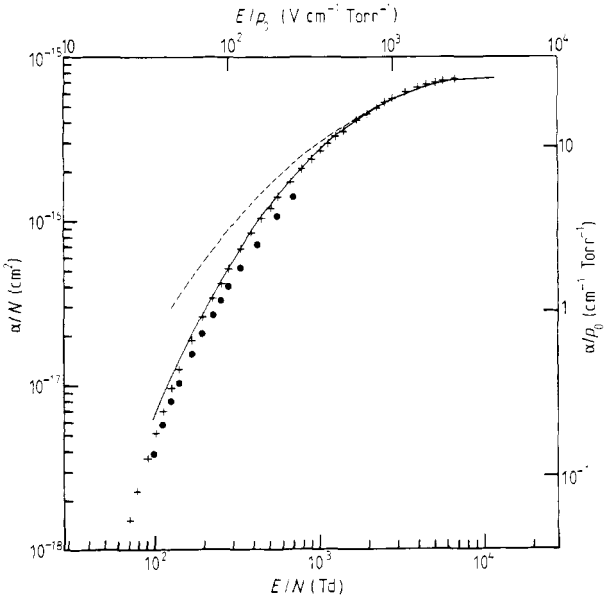

Figure 6. Townsend ionisation coefficient α in xenon. Experiment: (+) Kruithof (1940), (●) Bhattacharya (1976). Theory: – – – – present calculated results using original values of q_e, ——— present calculated results using final recommended values of q_e.

Unpublished values of α were measured by the author by Townsend's current measurements method and the data lie between those of Kruithof (1940) and Jacques (1982). These data coincide very well, and these values were used for determination of q_e.

Eggarter (1975) discussed the excitation cross-sections in argon in detail. The work is a good model for the correction of q_e in xenon. The values of q_e of Eggarter (1975) are about twice the values of de Heer *et al* (1979) in argon at the energy range from 20 to 50 eV. The same calculations of electron swarm parameters in argon have been carried out by the author by using Eggarter's values of q_e slightly corrected (about 10% reduced for all energy ranges) and the results almost coincided with experimental swarm parameters. Accordingly it is believed that the values of q_e of de Heer *et al* (1979) are smaller than the true values of q_e in xenon.

Using the argon excitation cross-section of Eggarter and the fact that $q_e V_e$ is a universal function of ε/V_e, as described by de Heer *et al* (1979), calculations of q_e in xenon were carried out, where ε is the electron energy and V_e is the excitation potential. The results are almost the same as those of the adjusted values of q_e, mentioned above.

Using the adjusted values of q_e, values of α in xenon were recalculated and the results almost coincided with the experimental values of Kruithof (1940) as shown in figure 6. The final values of q_e are shown in figure 5 as a full curve and also in table 2. The swarm parameters were calculated by these corrected values of q_e.

According to the electron energy loss spectrum of Swanson *et al* (1976), there are large peaks at about 9.57 and 9.92 eV. The values of total excitation cross-sections are determined, and when an excitation occurs the energy loss of electrons is always assumed to be V_e, that is 8.32 eV (Hayashi 1982). Therefore there is a possibility that the values of q_e used are slightly overestimated.

The calculated values of α by Pfau and Rutscher (1969) are very large compared with those of Kruithof (1940). The reason for this large discrepancy seems to be the poor cross-sections used, especially q_m and q_e for electron energies from 10 to 30 eV.

Table 2. Total excitation cross-section in xenon.

ε (eV)	q_e (Å^2)	ε (eV)	q_e (Å^2)
8.32	0	60	2.10
8.5	0.026	70	1.85
9	0.126	80	1.66
9.5	0.131	90	1.52
10	0.18	100	1.38
10.5	0.24	150	1.00
11	0.42	200	0.80
11.5	0.62	300	0.568
12	0.84	400	0.465
12.5	1.05	500	0.395
13	1.28	600	0.344
14	1.70	700	0.302
15	2.14	800	0.277
16	2.55	900	0.252
18	3.35	1000	0.231
20	3.73	2000	0.132
25	3.85	3000	0.095
30	3.57	4000	0.075
40	2.85	5000	0.063
50	2.40	10000	0.036

5. Check of q_t, q_e and q_i with total collision cross-sections Q_T

The values of total collision cross-sections, including inelastic collision cross-sections, Q_T have been obtained by experiments by many authors within an error of about 5%, as mentioned above. The error is very small compared with those of q_t, q_i and of course q_e.

The sum of q_t, q_e and q_i is Q_T. Using the values used above, the values of Σq were calculated and compared with the experimental values of Q_T. Typical values are shown in table 3, along with roughly estimated errors. The values of Σq and Q_T coincide very well within a limit of error.

Table 3. The values of q_t, q_e, q_i and their sum Σq, which is the total collision cross-section, compared with the recommended values of total collision cross-section, Q_T, obtained by experiments.

ε (eV)	q_t (Å^2)	q_e (Å^2)	q_i (Å^2)	Σq (Å^2)	Q_T (Å^2)
10	38.7	0.18	0	39 ± 5	38.8 ± 1.9
15	34.0	2.14	0.906	37 ± 4	35.6 ± 1.8
20	28.8	3.73	2.28	35 ± 4	33.3 ± 1.7
30	13.3	3.57	3.85	20.7 ± 2.1	19.8 ± 1.0
50	6.45	2.40	4.85	13.7 ± 1.4	13.0 ± 0.7
100	4.6	1.38	5.57	11.6 ± 1.1	10.7 ± 0.5
200	4.1	0.80	4.85	9.8 ± 1.0	9.5 ± 0.5
300	3.85	0.568	4.06	8.5 ± 0.9	8.1 ± 0.4
500	3.35	0.395	3.05	6.8 ± 0.6	6.4 ± 0.3
1000	2.55	0.231	1.94	4.7 ± 0.5	4.4 ± 0.2

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