2.5 Momentum transfer cross sections

2.5.1 Introduction

2.5.1.1 Definition in terms of the differential cross section

The momentum transfer cross section, σ_m, for electron scattering is defined as

$$\sigma_m(E) = 2\pi \int_0^\pi \frac{d\sigma}{d\Omega}(1 - \frac{c'}{c}\cos\theta)\sin\theta\, d\theta \tag{1}$$

where $d\sigma/d\Omega$, the differential cross section, is defined as that fraction of a beam of electrons of energy E which are scattered at an angle θ into the element of solid angle $d\Omega = 2\pi \sin\theta\, d\theta$; c and c' are the electron velocities before and after the collision respectively. The name of this cross section arises from the fact that the term $[1 - (c'/c)\cos\theta]$ is the fractional loss of directed momentum of the electron in a collision.

In general electron collisions may be elastic, inelastic or superelastic. Relation (1) can thus be written as the sum of the momentum transfer cross sections for specific scattering processes, i.e.

$$\sigma_m(E) = \sigma_m(E)^{el} + \sum_k \sigma_m^k(E)^{in} + \sum_k \sigma_m^k(E)^{sup} \tag{2}$$

where $\sigma_m(E)^{el}$ is the elastic momentum transfer cross section and $\sigma_m^k(E)^{in}$ and $\sigma_m^k(E)^{sup}$ are the momentum transfer cross sections for the k^{th} inelastic and superelastic scattering processes, respectively. Superelastic collisions can be neglected for the scattering of electrons in atomic gases because of the relatively high energy of the thresholds for electronic excitation.

There are a number of special cases:

(a) if the scattering is isotropic (i.e. $d\sigma/d\Omega$ is independent of θ) then

$$\sigma_m(E) = \sigma(E) \tag{3}$$

where $\sigma(E)$ is the integral elastic cross section which is given by

$$\sigma(E) = 2\pi \int_0^\pi \frac{d\sigma}{d\Omega}\sin\theta\, d\theta \tag{4}$$

(b) if the scattering is elastic only, then

$$\sigma_m(E) = \sigma_m(E)^{el} = 2\pi \int_0^\pi \frac{d\sigma}{d\Omega}(1 - \cos\theta)\sin\theta\, d\theta \tag{5}$$

The entries in the accompanying tables of momentum transfer cross sections are values of $\sigma_m(E)^{el}$, i.e. the elastic component of $\sigma_m(E)$.

The momentum transfer cross section arises most often, but not exclusively, in the description of the motion of electrons in a gas at a given temperature and number density, usually in the presence of electric and/or magnetic fields. For a detailed description of the electron motion see Huxley and Crompton [74Hux1].

2.5.1.2 Definition in terms of the scattering phase shifts

In the quantum mechanical description of elastic scattering the wave function of an electron, at a distance r from a scattering centre, after being scattered at an angle θ, is given (in its simplest form) by

$$\Psi = \mathrm{e}^{\mathrm{i}kz} + \frac{f(\theta)}{r}\mathrm{e}^{\mathrm{i}kr} \tag{6}$$

where $f(\theta)$ is the amplitude of the scattered wave, k is the wave vector and the z axis is in the direction of the incoming particle. The angular part of the outgoing wave may be expressed in partial waves [27Fax1] corresponding to specific values of the angular momentum quantum number l. The differential cross section is given by

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = |f(\theta)|^2 \tag{7}$$

where

$$f(\theta) = \frac{1}{2\mathrm{i}k}\sum_l (2l+1)(\mathrm{e}^{2\mathrm{i}\eta_l} - 1)P_l(\cos\theta) \tag{8}$$

from which it follows that

$$\sigma_{\mathrm{m}}(E) = \frac{4\pi}{k^2}\sum_l (l+1)\sin^2(\eta_l - \eta_{l+1}) \tag{9}$$

where η_l is the additional shift introduced into the asymptotic phase of the l^{th} partial wave by the scattering. $\mathrm{P}_l\,(\cos\theta)$ are the Legendre polynomials.

For elastic electron scattering from atoms without permanent electric dipole moments O'Malley and co-workers [62OMa1, 63OMa1] have shown that the phase shifts at low energies may be expanded in terms of the wave number (the resulting relations are known as modified effective range (MERT) formulae). These formulae have been used in fitting routines to derive the momentum transfer cross section at low energies, the scattering length, and to enable conversion from $\sigma_{\mathrm{m}}(E)$ to $\sigma(E)$ and vice versa. An extended version of their formulae (see for example [95Pet1]) is as follows (atomic units are used):

$$\tan\eta_0 = -Ak[1 + (4\alpha/3a_0)k^2\ln(ka_0)] - (\pi\alpha/3a_0)k^2 + Dk^3 + Fk^4 \tag{10}$$

$$\tan\eta_1 = (\pi\alpha/15a_0)k^2 - A_1k^3 \tag{11}$$

where A (the scattering length), A_1, D and F are fitting parameters, a_0 is the Bohr radius and α is the dipole polarizability. For higher order phaseshifts ($l \geq 2$) the Born expansion is used

$$\tan\eta_l = \frac{\pi\alpha k^2}{(2l+3)(2l+1)(2l-1)} \tag{12}$$

The scattering length is also related to the zero energy momentum transfer and integral cross sections via the relation

$$\sigma_{\mathrm{m}} = \sigma = 4\pi A^2 \tag{13}$$

2.5.2 Experimental determinations

2.5.2.1 Swarm experiments

The momentum transfer cross section, $\sigma_m(E)$, can be obtained from transport coefficients measured in electron swarm experiments by using a solution of the Boltzmann equation, and an iterative procedure, to match calculated values of the transport coefficients (commonly the drift velocity, v_{dr}, and the ratio of the lateral diffusion coefficient, D_T, to the electron mobility, μ, i.e. D_T/μ) to the experimental data. Problems involving non-uniqueness of the fitted cross sections, due to the form of $\sigma_m(E)$ or the presence of inelastic processes, have been discussed by Huxley and Crompton [74Hux1]. The energy range over which $\sigma_m(E)$ can be derived from swarm data is limited by the range of values of E/N (E is the electric field strength and N the gas number density) for which transport coefficient data are available. This range is limited by the onset of electric discharge.

Two types of solution of the Boltzman equation have been used:

(a) the "two-term" solution

This is the most commonly used solution and involves the assumption that the electron velocity distribution can be expanded in spherical harmonics and truncated after two terms. If the cross section for elastic scattering is very much greater than those for inelastic collisions then the angular scattering in such collisions does not significantly affect $\sigma_m(E)$. In these circumstances the inelastic scattering may be assumed to be isotropic and thus

$$\sigma_m(E) = \sigma_m(E)^{el} + \sum_k \sigma^k(E)^{in} \qquad (14)$$

where $\sigma^k(E)^{in}$ is the integral cross sections for the k^{th} inelastic collision process.

If the present tables are used for calculations of transport coefficients in atomic gases under conditions where inelastic scattering is a significant process, the $\sigma_m(E)$ used should be the sum of the tabled values of $\sigma_m(E)^{el}$ and the sum of the integral cross sections for the specific inelastic processes.

(b) the "multiterm" solutions

In certain cases (e.g. D_T/μ calculations for argon) the two-term representation of the velocity distribution function is inadequate and a more complex representation is required. In multiterm solutions the isotropic scattering assumption for all the inelastic processes is not made and $\sigma_m(E)$ is given by relation (1).

2.5.2.2 Crossed beam and attenuation experiments

The momentum transfer cross section, $\sigma_m(E)$, can be derived from absolute measurements of $d\sigma/d\Omega$ and relation (1). The main complication with this technique is that most measurements of $d\sigma/d\Omega$ cannot cover the entire range of scattering angles between 0 and π, due to the presence of the primary beam and other geometrical constraints, and some extrapolation procedure is required to extend these measurements to 0 and π. Various techniques have been applied to enable this extrapolation and they, and the uncertainties involved have been discussed by various authors (e.g. [83Tra1]). One common technique which has been applied to many atomic species is the so-called phaseshift analysis. In this technique, the experimental differential cross sections are fitted with an expression such as (7) and (8), where the first few (perhaps 2…4) phaseshifts are treated as free parameters. Higher-order phaseshifts are obtained by the use of (12). The results of the fitting process can then be used to calculate the differential cross section over the entire angular range as well as the total and momentum transfer cross sections. This process has been applied, for instance, in electron-rare-gas atom collisions for energies up to the first inelastic threshold (see for example

[75And1, 80Reg1, 96Gib1]). It generally can enable a reasonably accurate derivation of $\sigma_m(E)$ at higher energies which may not be possible using electron swarm methods.

Momentum transfer cross sections can also be derived, in certain circumstances, from measurements of the total elastic cross section using beam attenuation techniques. In this case, a phaseshift analysis is applied at the total cross section level using equations (10)-(12) and the $\sigma_m(E)$ is derived from the resulting phaseshifts. Examples of this approach can be found in Buckman and Mitroy [89Buc1].

A previous, critical review of momentum transfer cross sections in atoms and molecules has been provided by Itikawa [74Iti1, 78Iti1].

References for 2.5.1 and 2.5.2

27Fax1 Faxén, H, Holtsmark, J.: Z.: Phys. **45** (1927) 307.
62OMa1 O'Malley, T.F., Rosenberg, L., Spruch, L.: Phys. Rev. **125** (1962) 1300.
63OMa1 O'Malley, T.F.: Phys. Rev. **130** (1963) 1020.
74Hux1 Huxley, L.G.H., Crompton, R.W.: The diffusion and drift of electrons in gases, NewYork: Wiley-Interscience 1974.
74Iti1 Itikawa, Y.: At. Data. Nucl. Data. Tables **14** (1974) 1.
75And1 Andrick, D., Bitsch, A.: J. Phys. B **8** (1975) 393.
78Iti1 Itikawa, Y.: At. Data. Nucl. Data. Tables **14** (1978) 69.
80Reg1 Register, D.F., Trajmar, S., Srivastava, S.K.: Phys. Rev. A **21** (1980) 1134.
83Tra1 Trajmar, S., Register, D.F., Chutjian, A.: Phys. Rep. **97** (1983) 219.
89Buc1 Buckman, S.J., Mitroy, J.: J. Phys. B **22** (1989) 1365.
95Pet1 Petrovic, Z.Lj., O'Malley, T.F., Crompton, R.W.: J. Phys. B **28** (1995) 3309.
96Gib1 Gibson, J.C., Gulley, R.J., Sullivan, J.P., Buckman, S.J., Chan, V., Burrow, P.D.: J. Phys. B **29** (1996) 3177.

2.5.3 Determination of preferred cross sections

The preferred momentum transfer cross section for each atom has been derived from a consideration of all available (published) experimental and theoretical work. In general, we do not consider those cases where only theoretical values exist, unless there is substantial corroboration between two or more diffferent calculations. More weight has been placed on recent measurements which have realistic and well quantified uncertainties. The uncertainty estimates on the preferred cross sections indicate the level of concurrence between the various individual measurements and calculations.

2.5.4 Units

Cross sections are given in square Ångström (1 $Å^2 = 10^{-16}$ cm^2) and electron energies in electron volt [eV]. Where applicable, scattering lengths are given in atomic units (1 $a_0 = 5.2918 \cdot 10^{-9}$ cm) as is customary.

2.5.5 The elements

2.5.5.1 Hydrogen

Whilst there have been several measurements of absolute elastic differential cross sections for atomic hydrogen, there are no published experimental values of σ_m. The preferred cross sections, listed in Table 2.5.1 and shown in Fig. 2.5.1, are theoretical values obtained using the convergent close-coupling approach [98Bra1]. This has been shown to provide excellent agreement with a range of experimental cross sections in atomic hydrogen [92Bra1].

No estimate of the uncertainty is provided in this case.

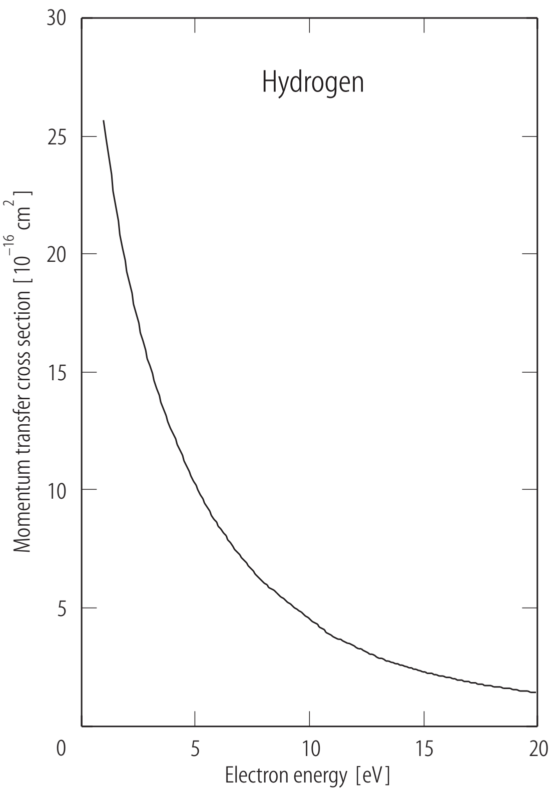

Fig. 2.5.1. Preferred values of σ_m for atomic hydrogen.

Table 2.5.1. The preferred values of the elastic momentum transfer cross section (σ_m) for electrons in atomic hydrogen.

E [eV]	σ_m [Å^2]
1	25.7
2	19.3
3	15.3
4	12.4
5	10.2
6	8.52
7	7.16
8	6.09
9	5.29
10	4.54
11	3.82
12	3.37
13	2.91
15	2.30
16	2.07
17	1.86
18	1.69
19	1.54
20	1.41
21	1.29

References for 2.5.5.1

92Bra1 Bray, I., Stelbovics, A.T.: Phys. Rev. A **46** (1992) 6995.
98Bra1 Bray, I.: Private Communication 1998.

2.5.5.2 Helium

The preferred elastic momentum transfer cross section for helium is presented over the energy range 0.008 to 100 eV. The data are tabulated in Table 2.5.2 and presented graphically in two ranges, 0.008 to 1.0 eV in Fig. 2.5.2 and 0.008 to 100 eV in Fig. 2.5.3. At lower energies (< 10 eV) the preferred cross section is based on the swarm cross sections of [67Cro1, 70Cro1, 77Mil1]; the crossed beam measurements of [80Reg1, 92Bru1], and the theoretical calculations of [79Nes1, 93Sah1, 97Fur1]. At higher energies (10…100 eV) the preferred cross section is based on the crossed beam measurements of [80Reg1, 92Bru1] and the calculation of [97Fur1].

The uncertainty is estimated to be: ± 2 % for 0.008 ≤ E ≤ 5 eV, ± 3 % for 5 < E ≤ 12 eV, ± 5 % for 12 < E ≤ 20 eV and ± 10 % for E > 20 eV. The best estimate scattering length for helium is considered to be 1.18 ± 0.01 a_0.

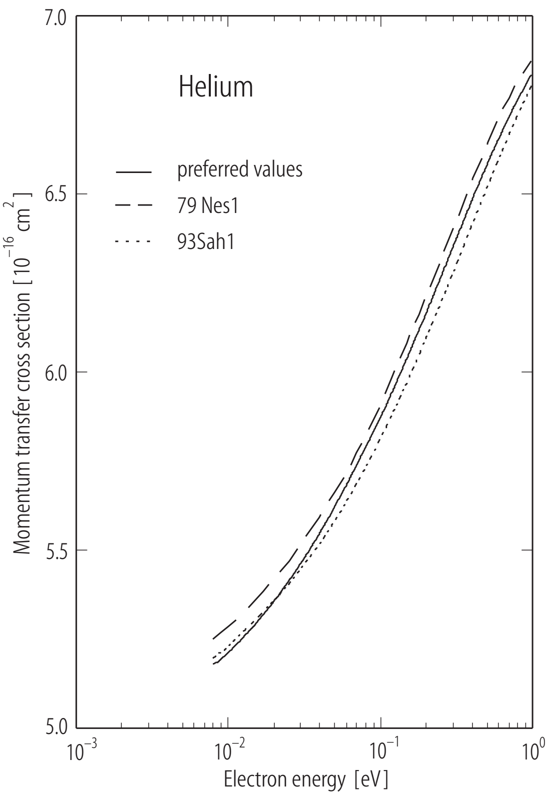

Fig. 2.5.2. Preferred values of σ_m for helium over the range 0.008 to 1 eV together with the theoretical calculations of [79Nes1] and [93Sah1].

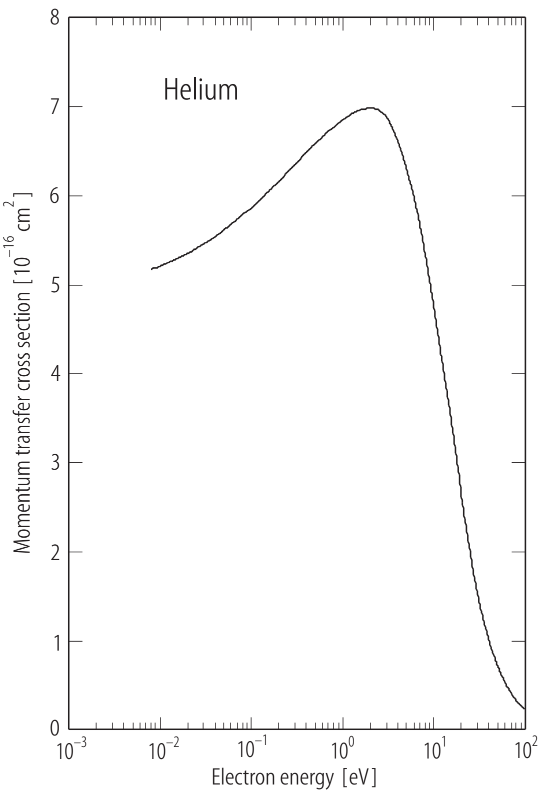

Fig. 2.5.3. Preferred values of σ_m for helium over the range 0.008 to 100 eV.

Table 2.5.2. The preferred values of the elastic momentum transfer cross section (σ_m) for electrons in helium.

E [eV]	σ_m [Å^2]	E [eV]	σ_m [Å^2]	E [eV]	σ_m [Å^2]
0.008	5.18	0.25	6.27	9	5.03
0.009	5.19	0.3	6.35	10	4.74
0.010	5.21	0.4	6.49	12	4.21
0.012	5.25	0.5	6.59	15	3.56
0.015	5.29	0.6	6.66	16	3.36
0.018	5.33	0.7	6.73	17	3.18
0.020	5.35	0.8	6.77	18	3.01
0.025	5.41	0.9	6.82	19	2.84
0.03	5.46	1.0	6.85	20	2.63
0.04	5.54	1.2	6.91	25	1.98
0.05	5.62	1.5	6.96	30	1.53
0.06	5.68	1.8	6.98	40	1.01
0.07	5.74	2.0	6.99	50	0.713
0.08	5.79	2.5	6.96	60	0.535
0.09	5.83	3	6.89	70	0.411
0.10	5.86	4	6.62	80	0.326
0.12	5.94	5	6.31	90	0.271
0.15	6.04	6	6.00	100	0.231
0.18	6.12	7	5.68		
0.20	6.16	8	5.35		

References for 2.5.5.2

64Fro1 Frost, L.S., Phelps, A.V.: Phys. Rev. **136** (1964) 1538.

67Cro1 Crompton, R.W., Elford, M.T., Jory, R.L.: Aust. J. Phys. **20** (1967) 369.

70Cro1 Crompton, R.W., Elford, M.T., Robertson, A.G.: Aust. J. Phys. **23** (1970) 667.

75And1 Andrick, D., Bitsch, A.: J. Phys. B **8** (1975) 393.

77Mil1 Milloy, H.B., Crompton, R.W.: Phys. Rev. A **15** (1977) 1847.

79Nes1 Nesbet, R.K.: Phys. Rev. A **20** (1979) 58.

80Reg1 Register, D.F., Trajmar, S., Srivastava, S.K.: Phys. Rev A **21** (1980) 1134.

92Bru1 Brunger, M.J., Buckman, S.J., Allen, L.J., McCarthy, I.E., Ratnavelu, K.: J. Phys. B **25** (1992) 1823.

93Sah1 Saha, H.P.: Phys. Rev. A **48** (1993) 1163.

97Fur1 Fursa, D.V., Bray, I.: J. Phys. B **30** (1997) 757.

2.5.5.3 Lithium

The only published experimental values for the elastic momentum transfer cross section for lithium are those of [76Wil1] and these are subject to substantial uncertainty. The preferred cross section, listed in Table 2.5.3 and shown in Fig. 2.5.4, are theoretical values obtained using the convergent close-coupling approach [98Bra1].

No estimate of the uncertainty is provided in this case.

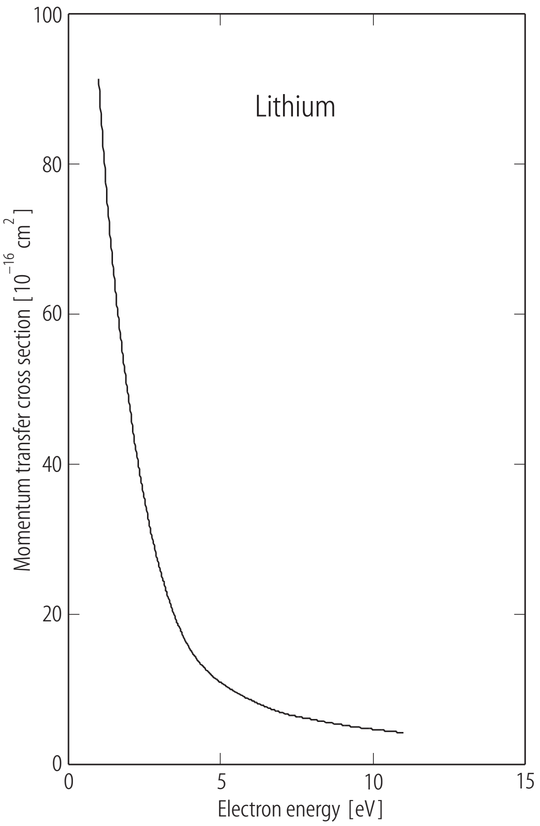

Fig. 2.5.4. Preferred values of σ_m for lithium.

Table 2.5.3. The preferred values of the elastic momentum transfer cross section (σ_m) for electrons in lithium.

E [eV]	σ_m [Å^2]
1	91.4
2	46.3
3	25.2
4	14.6
5	10.7
6	8.49
7	6.72
8	5.94
9	5.17
10	4.62
11	4.19

References for 2.5.5.3

76Wil1 Williams, W., Trajmar, S., Bozinis, D.: J. Phys. B **9** (1976) 1529.
98Bra1 Bray, I.: Private Communication 1998.

2.5.5.4 Oxygen

There appears to be only one experimental determination of the elastic momentum transfer cross section, σ_m, for atomic oxygen, that of [89Wil1]. This was obtained from a phaseshift analysis of absolute differential cross sections. The preferred cross section is listed in Table 2.5.4.

The uncertainty on the cross section is estimated to be ± 10 %.

Table 2.5.4. The preferred values of the elastic momentum transfer cross section (σ_m) for electrons in atomic oxygen.

E [eV]	σ_m [Å^2]
0.54	2.55
2.18	3.95
3.40	4.23
4.90	4.03
8.71	5.12

References for 2.5.5.4

89Wil1 Williams, J.F., Allen, L.J.: J. Phys. B **22** (1989) 3529.

2.5.5.5 Neon

The preferred cross sections for neon are presented over the energy range 0.003 to 30 eV. The data are tabulated in Table 2.5.5 and presented graphically in two ranges, 0.003 to 10 eV in Fig. 2.5.5 and 0.003 to 30 eV in Fig. 2.5.6. The upper limit on the energy range has been limited to 30 eV as there are serious discrepancies between the available experimental and theoretical cross sections above this energy. At lower energies (< 4 eV) the preferred cross section is based on the swarm cross sections of [72Rob1, 80OMa1], together with the theoretical calculations of [90Sah1]. Between 4 and 30 eV, the preferred cross section is based on the crossed beam measurements of [84Reg1, 94Gul1], and the theoretical calculations of [89Sah1, 90Sah1].

The uncertainty is estimated to be: ± 2 % for $0.003 \le E < 1$ eV, ± 5 % for $1 \le E < 10$ eV, ± 8 % for $E \ge 10$ eV. The best estimate scattering length for neon is considered to be 0.215 ± 0.015 a_0 and is based on the values of [80OMa1, 85McE1, 89Buc1, 90Sah1, 94Gul1].

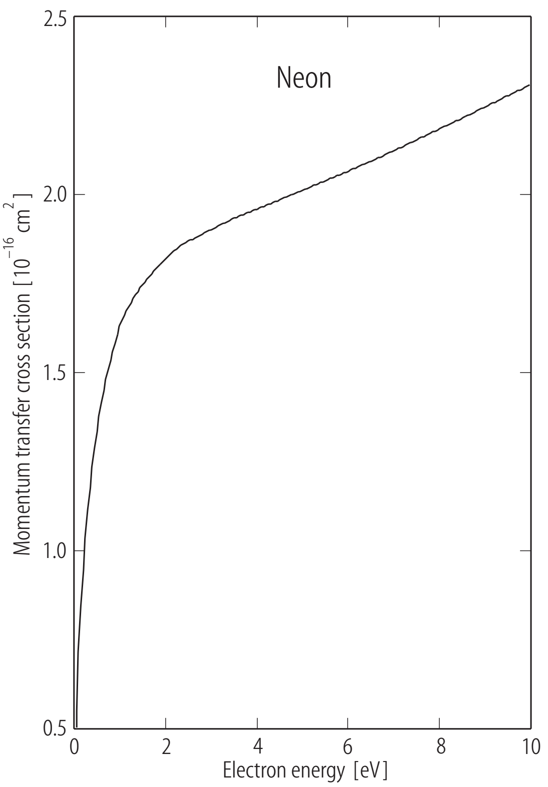

Fig. 2.5.5. Preferred values of σ_m for neon over the range 0.003 to 10 eV.

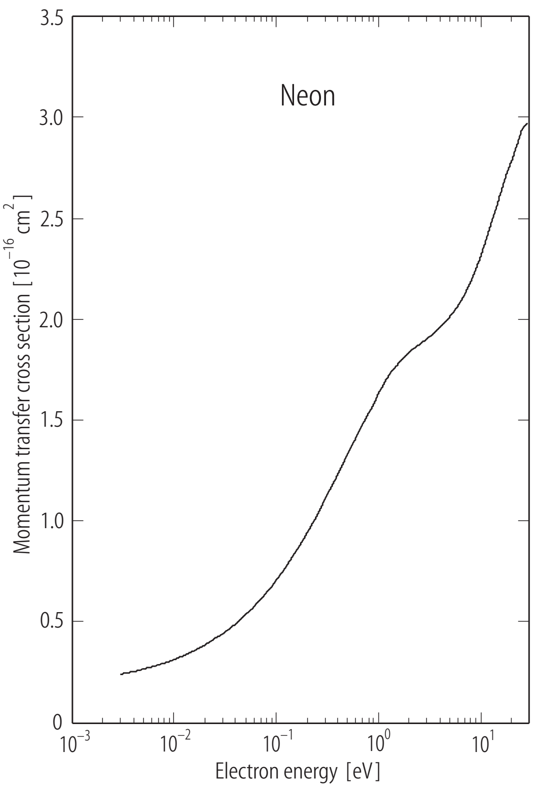

Fig. 2.5.6. Preferred values of σ_m for neon over the range 0.003 to 30 eV.

Table 2.5.5. The preferred values of the elastic momentum transfer cross section (σ_m) for electrons in neon.

E [eV]	σ_m [Å^2]	E [eV]	σ_m [Å^2]	E [eV]	σ_m [Å^2]
0.000	0.163	0.07	0.611	1.5	1.75
0.003	0.241	0.08	0.645	1.8	1.80
0.004	0.254	0.09	0.675	2.0	1.82
0.005	0.266	0.10	0.707	2.5	1.86
0.006	0.277	0.12	0.762	3	1.90
0.007	0.287	0.15	0.837	4	1.96
0.008	0.296	0.18	0.901	5	2.01
0.009	0.305	0.20	0.94	6	2.07
0.010	0.314	0.25	1.03	7	2.12
0.012	0.33	0.3	1.11	8	2.19
0.015	0.352	0.4	1.23	9	2.25
0.018	0.373	0.5	1.33	10	2.31
0.020	0.386	0.6	1.41	12	2.44
0.025	0.417	0.7	1.48	15	2.59
0.03	0.442	0.8	1.53	18	2.72
0.04	0.491	0.9	1.58	20	2.78
0.05	0.535	1.0	1.62	25	2.93
0.06	0.574	1.2	1.69	30	2.98

References for 2.5.5.5

72Rob1 Robertson, A.G.: J. Phys. B **5** (1972) 648.
80OMa1 O'Malley, T.F., Crompton, R.W.: J. Phys. B **13** (1980) 3451.
84Reg1 Register, D.F., Trajmar, S.: Phys. Rev. A **29** (1984) 1785.
85McE1 McEachran, R.P., Stauffer, A.U.: Phys. Lett. A **107** (1985) 397.
89Buc1 Buckman, S.J., Mitroy, J.: J. Phys. B **22** (1989) 1365.
89Sah1 Saha, H.P.: Phys. Rev. A **39** (1989) 5048.
90Sah1 Saha, H.P.: Phys. Rev. Lett. **65** (1990) 2003.
94Gul1 Gulley, R.J., Alle, D.T., Brennan, M.J., Brunger, M.J., Buckman, S.J.: J. Phys.B **27** (1994) 2593.

2.5.5.6 Sodium

The preferred values of σ_m for sodium are based on the swarm-derived cross section of [78Nak1] and the close-coupling calculations of [71Nor1, 98Bra1]. These are given in Table 2.5.6.

No estimate of the uncertainty is provided in this case.

References for 2.5.5.6

71Nor1 Norcross, D.W.: J. Phys. B **4** (1971) 1458.
78Nak1 Nakamura, Y., Lucas, J.: J. Phys. D **11** (1978) 337.
98Bra1 Bray, I.: Private Communication 1998.

Table 2.5.6. The preferred values of the elastic momentum transfer cross section (σ_m) for electrons in sodium.

E [eV]	σ_m [Å^2]	E [eV]	σ_m [Å^2]	E [eV]	σ_m [Å^2]
0.050	290	0.25	424	3.0	19.3
0.060	389	0.30	349	4.0	9.85
0.070	504	0.40	248	5.0	5.13
0.080	643	0.50	184	6.0	4.25
0.090	736	0.60	155	7.0	3.17
0.10	786	0.70	135	8.0	2.63
0.12	794	0.80	120	9.0	2.52
0.15	736	0.90	108	10.0	2.26
0.18	643	1.0	97.8	11.0	2.08
0.20	569	2.0	39.4		

2.5.5.7 Magnesium

There has been only one measurement of σ_m for magnesium by [78Wil1] based on integrated differential scattering cross sections. These values are given in Table 2.5.7.

It is possible that the uncertainties on these values are as large as 100 %.

Table 2.5.7. The preferred values of the elastic momentum transfer cross section (σ_m) for electrons in magnesium.

E [eV]	σ_m [Å^2]
10	7.6
20	4.1
40	0.47

References for 2.5.5.7

78Wil1 Williams, W., Trajmar, S.: J. Phys. B **11** (1978) 2021.

2.5.5.8 Argon

The preferred cross sections for argon are presented over the energy range 0.012 to 10 eV. The data are tabulated in Table 2.5.8 and presented graphically in two ranges, one which emphasises the Ramsauer-Townsend minimum in Fig. 2.5.7 and the other, Fig. 2.5.8, the range 0.012 to 10 eV. The upper limit on the energy range has been limited to 10 eV as there are serious discrepancies between the available experimental and theoretical cross sections above this energy. At lower energies (< 1 eV) the preferred cross section is based on the swarm cross sections of [94Sch1, 95Pet1], together with the theoretical calculations of [97McE1]. Between 1 and 10 eV, the preferred cross section is based on the swarm measurement of [88Nak1], the crossed beam measurements of [81Sri1, 96Gib1] and the theoretical calculations of [95Sah1, 97McE1].

The uncertainty is estimated to be: ± 5 % for $0.012 \le E < 1$ eV, although in the region of the Ramsauer-Townsend minimum (0.2…0.3 eV) ± 10 % is a more realistic estimate. For $1 \le E < 10$ eV the uncertainty is estimated to be ± 10 %. The best estimate scattering length for argon is considered to be –1.452 ± 0.02 a_0 and is based on the values of [85Fer1, 89Buc1, 93Sah1, 94Sch1, 95Pet1, 97McE1].

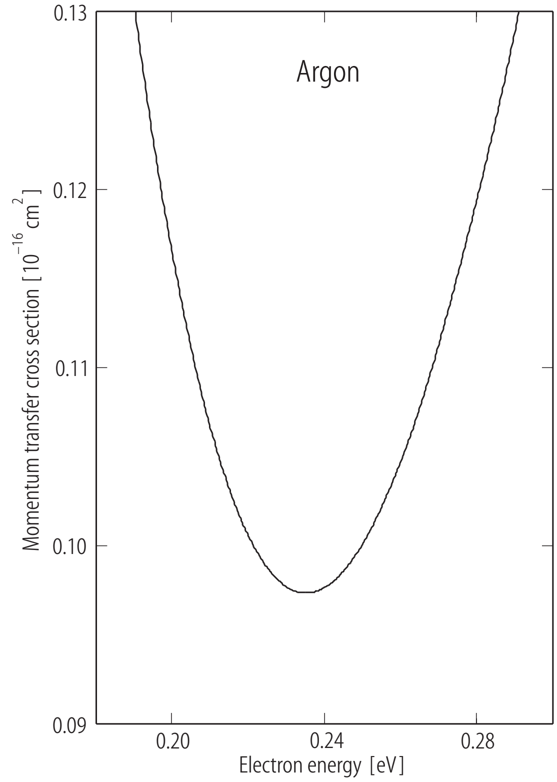

Fig. 2.5.7. Preferred values of σ_m for argon in the region of the Ramsauer-Townsend minimum.

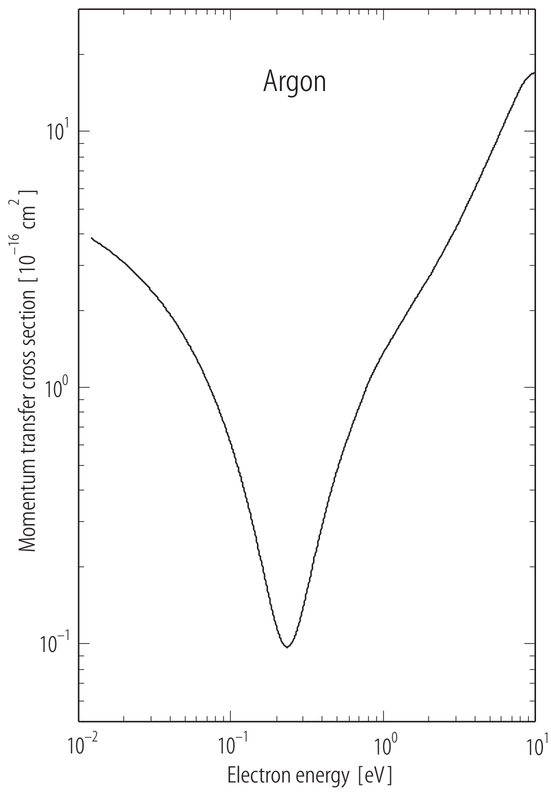

Fig. 2.5.8. Preferred values of σ_m for argon over the range 0.012 to 10 eV.

References for 2.5.5.8

81Sri1 Srivastava, S.K., Tanaka, H., Chutjian, A., Trajmar, S.: Phys. Rev. A **23** (1981) 2156.
85Fer1 Ferch, J., Granitza, B., Masche, C., Raith, W.: J. Phys. B **18** (1989) 1365.
88Nak1 Nakamura, Y., Kurachi, M.: J. Phys. D **21** (1988) 718.
89Buc1 Buckman, S.J., Mitroy, J.: J. Phys. B **22** (1989) 1365.
93Sah1 Saha, H.P.: Phys. Rev. A **48** (1993) 1163.
94Sch1 Schmidt, B., Berkhan, K., Gotz, B., Muller, M.: Phys. Scr. T **53** (1994) 30.
95Pet1 Petrovic, Z. Lj., O'Malley, T.F., Crompton, R.W.: J. Phys. B **28** (1995) 3309.
95Sah1 Private Communication, cited in [96Gib1].
96Gib1 Gibson, J.C., Gulley, R.J., Sullivan, J.P., Buckman, S.J., Chan, V., Burrow, P.D.: J. Phys. B **29** (1996) 3177.
97McE1 McEachran, R.P., Stauffer, A.D.: Aust. J. Phys. **50** (1997) 511.

Table 2.5.8. The preferred values of the elastic momentum transfer cross section (σ_m) for electrons in argon.

E [eV]	σ_m [Å^2]	E [eV]	σ_m [Å^2]	E [eV]	σ_m [Å^2]
0.012	3.86	0.17	0.174	0.60	0.664
0.015	3.53	0.18	0.150	0.65	0.756
0.018	3.24	0.19	0.131	0.70	0.847
0.020	3.08	0.20	0.117	0.80	1.05
0.025	2.71	0.21	0.107	0.90	1.21
0.03	2.41	0.22	0.101	1.0	1.36
0.04	1.93	0.23	0.0977	1.2	1.64
0.05	1.57	0.24	0.0976	1.5	2.05
0.06	1.29	0.25	0.100	1.8	2.45
0.07	1.07	0.26	0.105	2.0	2.70
0.08	0.881	0.28	0.119	2.5	3.43
0.09	0.731	0.30	0.140	3	4.20
0.10	0.607	0.32	0.165	4	6.00
0.11	0.505	0.325	0.172	5	8.01
0.12	0.420	0.35	0.209	6	10.2
0.13	0.350	0.40	0.293	7	12.6
0.14	0.292	0.45	0.384	8	14.9
0.15	0.244	0.50	0.477	9	16.4
0.16	0.205	0.55	0.571	10	17.1

2.5.5.9 Potassium

The preferred values of the elastic momentum transfer cross section (σ_m) for electrons in potassium are presented over the energy range 0.1 to 11 eV. The data, given in Table 2.5.9, are derived from theoretical calculations by [86Fab1, 98Bra1].

No estimate of the uncertainty is provided in this case.

Table 2.5.9. The preferred values of the elastic momentum transfer cross section (σ_m) for electrons in potassium.

E [eV]	σ_m [Å^2]	E [eV]	σ_m [Å^2]	E [eV]	σ_m [Å^2]
0.1	632	2.0	70.0	8.0	13.8
0.2	369	3.0	30.3	9.0	12.3
0.3	289	4.0	20.3	10.0	11.0
0.4	253	5.0	18.3	11.0	9.61
0.5	244	6.0	16.7		
1.0	182	7.0	15.4		

References for 2.5.5.9

86Fab1 Fabrikant, I.I.: J. Phys. B **19** (1986) 1527.
98Bra1 Bray, I.: Private Communication 1998.

2.5.5.10 Manganese

There has only been one determination, that of [78Wil1], of the momentum transfer cross section for manganese. This was derived from a measurement of relative angular distributions at an energy of 20 eV. The relative measurements were placed on an absolute scale using the optical oscillator normalisation technique. The value obtained was 4.2 Å^2 and no error limit is quoted.

References for 2.5.5.10

78Wil1 Williams, W., Cheeseborough, J.C., Trajmar, S.: J. Phys. B **11** (1978) 2031.

2.5.5.11 Copper

The preferred values of the elastic momentum transfer cross section (σ_m) for electrons in copper at energies between 6 and 100 eV are given in Table 2.5.10. They were derived from differential scattering measurements by [77Tra1].

The uncertainty on the cross section is estimated to be greater than ± 100 %.

Table 2.5.10. The preferred values of the elastic momentum transfer cross section (σ_m) for electrons in copper.

E [eV]	σ_m [Å^2]
6	71.1
10	38.1
20	45.9
60	7.2
100	5.7

References for 2.5.5.11

77Tra1 Trajmar, S., Williams, W., Srivastava, S.K.: J. Phys. **B** 10 (1977) 3323.

2.5.5.12 Zinc

The preferred values of the elastic momentum transfer cross section (σ_m) for electrons in zinc at energies between 2 and 30 eV are given in Table 2.5.11. These are based on three theoretical calculations contained in [94Kum1, 97McE1] which show good agreement.

No estimate of the uncertainty is provided in this case.

Table 2.5.11. The preferred values of the elastic momentum transfer cross section (σ_m) for electrons in zinc.

E [eV]	σ_m [Å^2]	E [eV]	σ_m [Å^2]	E [eV]	σ_m [Å^2]
2	51.0	6	16.6	10	7.1
3	38.3	7	13.0	15	3.5
4	28.4	8	10.8	20	2.3
5	21.8	9	8.4	30	1.5

References for 2.5.5.12

94Kum1 Kumar, P., Jain, A.K., Tripathi, A.N., Nahar, S.N.: Phys. Rev. A **49** (1994) 899.
97McE1 McEachran, R.P.: Private Communication 1997.

2.5.5.13 Krypton

The preferred elastic momentum transfer cross section for krypton is presented over the energy range 0.001 to 10 eV. The data are tabulated in Table 2.5.12 and presented graphically in two ranges, one which emphasises the Ramsauer-Townsend minimum in Fig. 2.5.9 and the other, Fig. 2.5.10, the range 0.010 to 10 eV. The upper limit on the energy range has been limited to 10 eV as there are serious discrepancies between the available experimental and theoretical cross sections above this energy. At lower energies (< 4 eV) the preferred cross section is based on the swarm cross sections of [93Bre1, 94Sch1], together with the theoretical calculation of [88McE1]. Between 4 and 10 eV, the preferred cross section is based on the swarm measurement of [89Nak1], the crossed beam measurements of [81Sri1, 88Dan1] and the theoretical calculation of [88McE1].

The uncertainty is estimated to be ± 5 % for $0.010 \le E < 1$ eV, although in the region of the Ramsauer-Townsend minimum (0.4…0.8 eV) ± 20 % is a more realistic estimate. For $1 \le E < 4$ eV the uncertainty is estimated to be ± 10 %, whilst for $E > 4$ eV, the uncertainty is no better than ± 30 %. The best estimate scattering length for krypton is considered to be $(-3.35 \pm 0.1)a_0$ and is based on the values of [88Wey1, 89Buc1, 90Mit1, 93Bre1, 94Sch1].

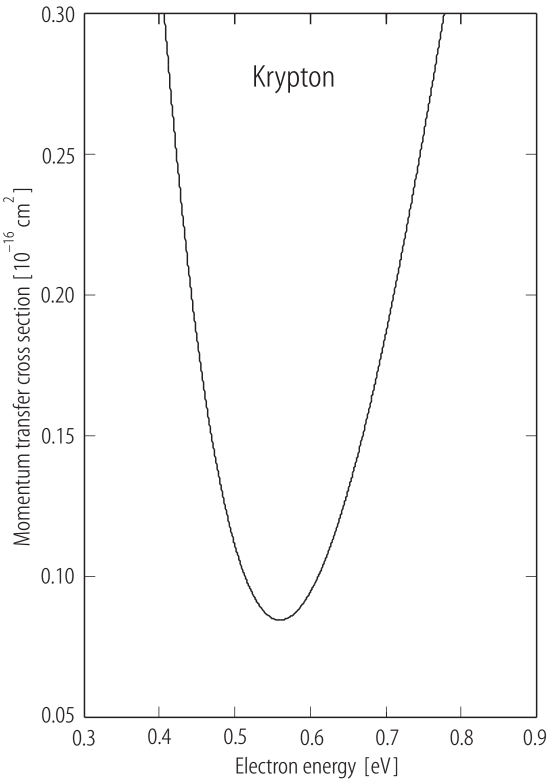

Fig. 2.5.9. Preferred values of σ_m for krypton in the region of the Ramsauer-Townsend minimum.

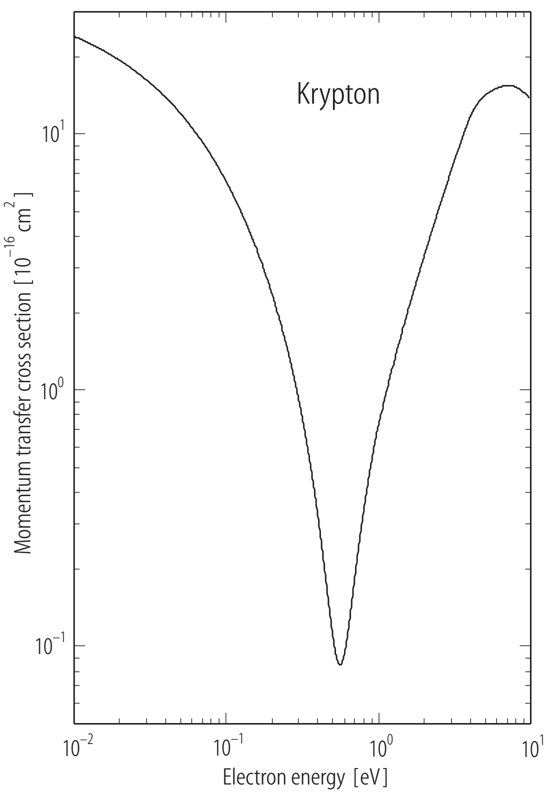

Fig. 2.5.10. Preferred values of σ_m for krypton over the range 0.01 to 10 eV.

Table 2.5.12. The preferred values of the elastic momentum transfer cross section (σ_m) for electrons in krypton.

E [eV]	σ_m [Å^2]	E [eV]	σ_m [Å^2]	E [eV]	σ_m [Å^2]
0.0001	37.4	0.510	0.102	1.10	0.929
0.001	33.1	0.515	0.0987	1.15	1.04
0.0015	32.1	0.520	0.0956	1.20	1.15
0.002	31.3	0.525	0.0929	1.25	1.26
0.0025	30.6	0.530	0.0905	1.30	1.38
0.003	30.0	0.535	0.0886	1.35	1.50
0.0035	29.4	0.540	0.0870	1.40	1.63
0.004	28.8	0.545	0.0858	1.45	1.76
0.005	27.9	0.550	0.0850	1.50	1.89
0.006	27.0	0.555	0.0845	1.55	2.02
0.007	26.2	0.560	0.0844	1.60	2.16
0.01	24.2	0.565	0.0846	1.65	2.31
0.012	23.0	0.570	0.0851	1.70	2.45
0.015	21.6	0.575	0.0860	1.75	2.60
0.017	20.6	0.580	0.0871	1.80	2.75
0.020	19.5	0.585	0.0885	1.85	2.90
0.025	17.8	0.590	0.0902	1.90	3.06
0.03	16.3	0.595	0.0922	1.95	3.22
0.035	15.1	0.60	0.0945	2.00	3.38
0.04	13.9	0.61	0.0998	2.05	3.55
0.045	13.0	0.62	0.106	2.10	3.72
0.05	12.1	0.63	0.113	2.15	3.89
0.07	9.30	0.64	0.122	2.20	4.07
0.10	6.55	0.65	0.131	2.25	4.24
0.12	5.27	0.66	0.140	2.30	4.42
0.15	3.87	0.67	0.151	2.35	4.61
0.17	3.18	0.68	0.162	2.40	4.79
0.20	2.37	0.70	0.187	2.45	4.98
0.23	1.78	0.72	0.213	2.50	5.18
0.25	1.47	0.75	0.257	2.6	5.57
0.27	1.22	0.77	0.289	2.7	5.97
0.30	0.908	0.80	0.339	3.0	7.23
0.32	0.745	0.82	0.374	3.25	8.33
0.35	0.548	0.85	0.428	3.5	9.47
0.37	0.444	0.87	0.466	4	11.7
0.40	0.321	0.90	0.525	5	14.2
0.42	0.257	0.92	0.566	6	15.1
0.45	0.184	0.95	0.629	7	15.5
0.47	0.148	0.97	0.673	8	15.3
0.50	0.111	1.00	0.729	9	14.6
0.505	0.106	1.05	0.827	10	13.7

References for 2.5.5.13

81Sri1 Srivastava, S.K., Tanaka, H., Chutjian, A., Trajmar, S.: Phys. Rev. A **23** (1981) 2156.

87Buc1 Buckman, S.J., Lohmann, B.: J. Phys. B **20** (1987) 5807.

88Dan1 Danjo, A.: J. Phys. B **21** (1988) 3759.
88McE1 McEachran, R.P., Stauffer, A.D.: Proc. Int. Symp. on Correlation and Polarisation in Electronic and Atomic Collisions, Singapore: World Scientific.
88Wey1 Weyhreter, M., Barzick, B., Mann, A., Linder, F.: Z. Phys. D **7** (1988) 333.
89Buc1 Buckman, S.J., Mitroy, J.: J. Phys. B **22** (1989) 1365.
89Nak1 Nakamura, Y.: Abstracts of 6th. Int. Swarm. Sem. (Glen Cove, NY) (1989), p1.
90Mit1 Mitroy, J.: Aust. J. Phys. **43** (1990) 19.
93Bre1 Brennan, M.J., Ness, K.F.: Aust. J. Phys. **46** (1993) 249.
94Sch1 Schmidt, B., Berkhan, K., Gotz, B., Muller, M.: Phys. Scr. T **53** (1994) 30.

2.5.5.14 Xenon

The preferred elastic momentum transfer cross section for xenon is presented over the energy range 0.005 to 10 eV. The data are tabulated in Table 2.5.13 and presented graphically in two ranges, one which emphasises the Ramsauer-Townsend minimum in Fig. 2.5.11 and the other, Fig. 2.5.12, the range 0.05 to 10 eV. The upper limit on the energy range has been limited to 10 eV as there are serious discrepancies between the available experimental and theoretical cross sections above this energy. At lower energies (< 2 eV) the preferred cross section is based on the swarm cross sections of [91Nak1, 94Sch1], the crossed beam measurements of [86Reg1, 88Wey1, 98Gib1], together with the theoretical calculation of [98Gib1]. Between 2 and 10 eV, the preferred cross section is based on the swarm measurements of [89Nak1, 94Sch1] and the crossed beam measurements of [86Reg1, 87Nis1, 98Gib1].

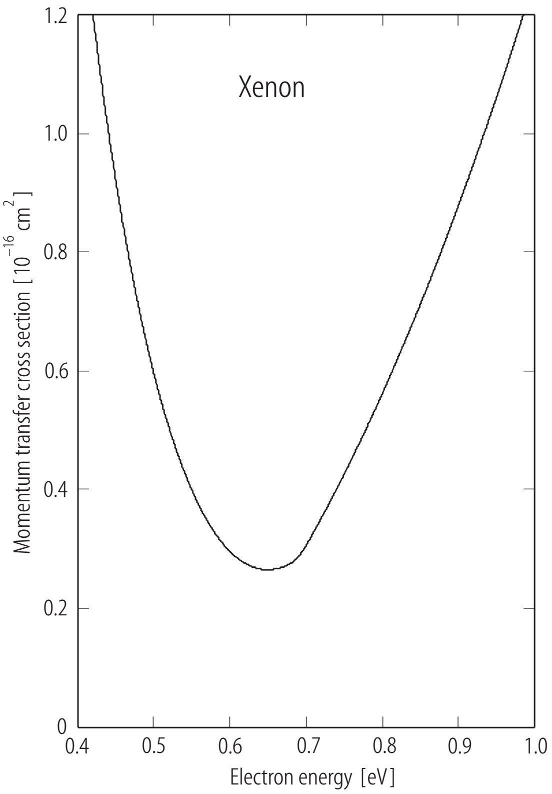

Fig. 2.5.11. Preferred values of σ_m for xenon in the region of the Ramsauer-Townsend minimum.

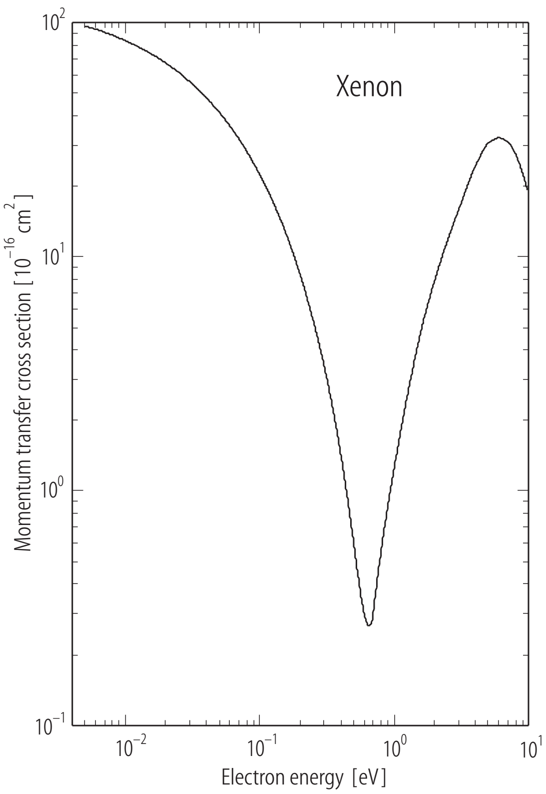

Fig. 2.5.12. Preferred values of σ_m for xenon over the range 0.01 to 10 eV.

The uncertainty is estimated to be: ± 10 % for $0.010 \le E < 1$ eV, although in the region of the Ramsauer-Townsend minimum (0.5…0.9 eV) ± 50 % is a conservative estimate. For $1 \le E < 2$ eV the uncertainty is estimated to be ± 10 %, whilst for $E > 2$ eV, the uncertainty is no better than ± 30 %. The best estimate scattering length for xenon is considered to be $(-6.3 \pm 0.3)a_0$ and is based on the values of [88Wey1, 94Sch1, 98Gib1].

Table 2.5.13. The preferred values of the elastic momentum transfer cross section (σ_m) for electrons in xenon.

E [eV]	σ_m [Å^2]	E [eV]	σ_m [Å^2]	E [eV]	σ_m [Å^2]
0.005	97.0	0.46	0.844	0.77	0.479
0.007	91.1	0.48	0.708	0.8	0.562
0.01	84.0	0.5	0.596	0.83	0.651
0.015	74.6	0.51	0.548	0.85	0.713
0.02	67.3	0.52	0.504	0.87	0.778
0.025	61.2	0.53	0.465	0.9	0.880
0.03	56.1	0.54	0.430	0.95	1.06
0.04	47.9	0.55	0.399	1	1.26
0.05	41.4	0.56	0.372	1.08	1.62
0.06	36.2	0.57	0.348	1.14	1.92
0.07	31.9	0.58	0.328	1.2	2.25
0.08	28.2	0.59	0.310	1.3	2.85
0.1	22.5	0.6	0.296	1.4	3.51
0.12	18.1	0.61	0.285	1.5	4.22
0.14	14.8	0.62	0.276	1.7	5.74
0.17	11.1	0.63	0.270	2	7.97
0.2	8.36	0.64	0.266	2.5	11.8
0.25	5.33	0.65	0.265	3	15.8
0.27	4.47	0.66	0.267	4	24.4
0.3	3.43	0.67	0.270	5	30.7
0.32	2.89	0.68	0.276	6	32.3
0.35	2.22	0.69	0.284	7	31.0
0.37	1.87	0.7	0.306	8	27.5
0.4	1.43	0.715	0.341	9	22.8
0.42	1.20	0.73	0.377	10	18.5
0.44	1.01	0.75	0.427		

References for 2.5.5.14

86Reg1 Register, D.F., Vuskovic, L., Trajmar, S.: J. Phys. B **19** (1986) 1685.

87Nis1 Nishimura, H., Matsuda, T., Danjo, A.: J.Phys. Soc. Jpn. **56** (1987) 70.

88Wey1 Weyhreter, M., Barzick, B., Mann, A., Linder, F.: Z. Phys. D **7** (1988) 333.

89Nak1 Nakamura, Y.: Abstracts of 6th Int. Swarm. Sem. (Glen Cove, N.Y.) (1989), p. 1

91Nak1 Nakamura, Y.: Joint Symp. on Electron and Ion Swarms and Low Energy Electron Scattering (Bond University) Abstracts (1991), p. 103.

94Sch1 Schmidt, B., Berkhan, K., Gotz, B., Muller, M.: Phys. Scr. T **53** (1994) 30.

98Gib1 Gibson J.C., Lun D.R., Allen, L.J., McEachran, R.P., Parcell, L.A., Buckman, S.J.: J. Phys. B **31** (1998) 3949.

2.5.5.15 Cesium

There has been a substantial amount of work, both experimental (swarm and beam) and theoretical, on low energy electron scattering from cesium. Unfortunately there is little accord for the momentum transfer cross sections derived from the various techniques (see e.g. [93Thu1]). However, the most sophisticated calculation [92Thu1] shows excellent agreement in the low energy regime with relative, angular distributions [77Geh1] and with the calculations of [72Kar1, 86Fab1].

The preferred cross sections for cesium, based on these theoretical calculations, are presented over the energy range 0.1 to 2 eV. The data are tabulated in Table 2.5.14.

No estimate of the uncertainty is provided in this case.

Table 2.5.14. The preferred values of the elastic momentum transfer cross section (σ_m) for electrons in cesium.

E [eV]	σ_m [Å^2]	E [eV]	σ_m [Å^2]
0.1	547	0.8	132
0.2	385	0.9	119
0.3	306	1.0	109
0.4	240	1.2	97.7
0.5	201	1.5	57.7
0.6	169	1.8	55.7
0.7	146	2.0	50.1

References for 2.5.5.15

72Kar1 Karule, E.M.: J. Phys. B **5** (1972) 2051.
77Geh1 Gehenn, W., Reichert, E.: J. Phys. B **10** (1977) 3105.
86Fab1 Fabrikant, I.I.: J. Phys. B **19** (1986) 1527.
92Thu1 Thumm, U., Norcross, D.W.: Phys. Rev. A **45** (1992) 6349.
93Thu1 Thumm, U., Norcross, D.W.: Phys. Rev. A **47** (1993) 305.

2.5.5.16 Barium

There have been two experimental measurements of σ_m in barium by [78Jen1, 94Wan1], both based on elastic differential scattering data at energies from 15 to 100 eV. These measurements differ significantly at their lowest common energy and they both vary substantially from recent calculated cross sections. The preferred cross section, based on these experimental values and the theoretical calculations of [94Kum1, 94Szm1], are given in Table 2.5.15.

The uncertainty on the cross section is estimated to be greater than ± 100 %.

Table 2.5.15. The preferred values of the elastic momentum transfer cross section (σ_m) for electrons in barium.

E [eV]	σ_m [Å^2]
15	4.5
20	4.0
30	3.4
40	3.0
60	2.5
80	2.3
100	2.0

References for 2.5.5.16

78Jen1 Jensen, S., Register, D., Trajmar, S.: J. Phys. B **11** (1978) 2367.
94Kum1 Kumar, P., Jaim, A.K., Tripathi, A.N., Nahar, S.N.: Z. Phys. D **30** (1994) 149.
94Szm1 Szmytkowski, R., Sienkiewicz, J.E.: Phys. Rev. A **50** (1994) 4007.
94Wan1 Wang, S., Trajmar, S., Zetner, P.W.: J. Phys. B **27** (1994) 1613.

2.5.5.17 Mercury

There have been several experimentally derived elastic momentum transfer cross sections for mercury. At low energies (<10 eV) these are all based on transport coefficient data, principally drift velocity measurements. At higher energies, there also exists a σ_m based on differential scattering measurements. The preferred values in the lower energy range were chosen on the basis of the accuracy of the drift velocity measurements of [91Eng1] in Hg vapour-gas mixtures. At higher energies, the preferred values are based on the experimental cross sections of [93Pan1] and the calculations of [87McE1, 87Hab1]. The preferred values are given in Table 2.5.16 and shown in Fig. 2.5.13.

The uncertainty is estimated to be: ± 10 % for 0.010 ≤ E < 2 eV and ± 30 % for higher energies.

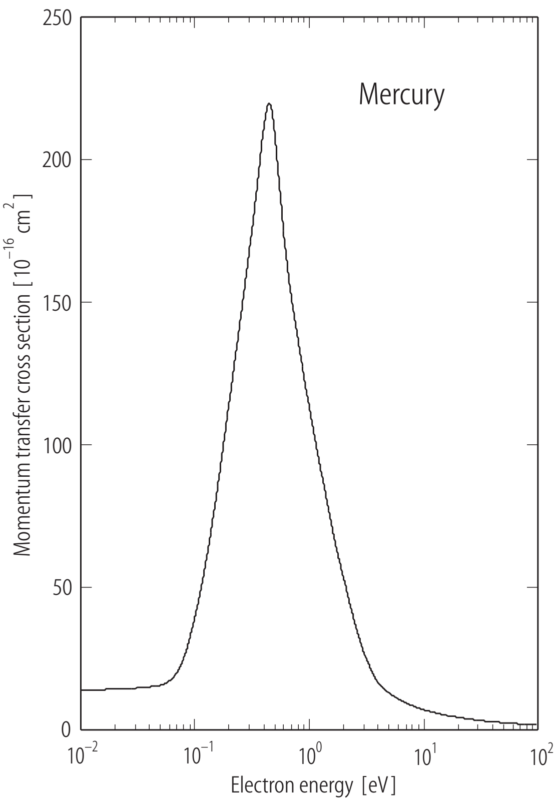

Fig. 2.5.13. Preferred values of σ_m for mercury.

Table 2.5.16. The preferred values of the elastic momentum transfer cross section (σ_m) for electrons in mercury.

E [eV]	σ_m [Å^2]	E [eV]	σ_m [Å^2]	E [eV]	σ_m [Å^2]
0.005	13.8	0.28	159	1.8	60.5
0.01	13.9	0.3	168	2	53.0
0.015	14.0	0.32	177	2.5	37.5
0.02	14.1	0.34	186	3	27.0
0.03	14.5	0.36	195	4	16.5
0.04	14.9	0.38	204	5	12.7
0.05	15.5	0.39	208	6	10.7
0.06	17.0	0.4	211	7	9.19
0.07	20.0	0.41	214	8	8.31
0.08	25.1	0.42	217	9	7.39
0.09	31.9	0.43	219	10	6.91
0.1	39.4	0.44	220	12	6.04
0.12	54.9	0.46	219	15	5.11
0.13	62.9	0.48	215	18	4.54
0.14	71.0	0.5	209	20	4.24
0.15	78.9	0.55	190	25	3.65
0.16	86.5	0.6	174	30	3.19
0.17	94.2	0.65	161	40	2.7
0.18	102	0.7	151	50	2.36
0.19	109	0.75	143	60	2.09
0.2	115	0.8	137	70	1.89
0.21	121	0.9	124	80	1.74
0.22	127	1	113	90	1.66
0.23	133	1.2	95.5	100	1.55
0.24	139	1.4	82.0		
0.26	149	1.6	70.0		

References for 2.5.5.17

87Hab1 Haberland, R., Fritsche, L.: J. Phys. B **20** (1987) 121.
87McE1 McEachran, R.P., Stauffer, A.D.: J. Phys. B **20** (1987) 5517.
91Eng1 England, J.P., Elford, M.T.: Aust. J. Phys. **44** (1991) 647.
93Pan1 Panajotovic, R., Pejcev, V., Konstantinovic, M., Filipovic, D., Bocvarski, V., Marinkovic, B.: J. Phys. B **26** (1993) 1005.