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# Electron scattering from Kr: I. Differential cross section for elastic scattering

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**Abstract.** Differential cross sections have been measured for elastic scattering of electrons from Kr. Measurements have been performed at impact energies of 5, 7.5, 10, 15, 20, 30, 40, 50, 60, 70, 80, 90, 100, 150 and 200 eV in the angular range from 10 to 125°. Absolute values of the differential cross section have been obtained by means of the relative flow method. Integral and momentum transfer cross sections have been derived from the measured data by extrapolating to 0 and 180° scattering angles. Comparison was made between the present results and those from other experiments and theoretical calculations.

## 1. Introduction

Studies of collisions of electrons with rare-gas atoms have been of great interest since the 1920s. Early measurements revealed pronounced minima in the total cross sections for electrons colliding with heavy rare-gas atoms at energies of around 0.5 eV (Townsend and Bailey 1922, Ramsauer 1923, Ramsauer and Kollath 1929). Recently, interest in electron impact studies of rare gases has been increased with the development of rare-gas halide high-power lasers. Hence, absolute values of various electron scattering cross sections are needed for either theoretical models or practical applications. However, only a limited amount of work has been done with the aim of obtaining absolute differential cross sections for either elastic scattering or inelastic scattering from Kr. In addition, there are considerable disagreements in the previous experimental results for the elastic differential cross sections of Kr at intermediate electron energies.

Several investigations have been made of the total cross sections for electron-krypton collisions (Wagenaar and de Heer 1980, 1985, Dababneh *et al* 1980, 1982) and on momentum transfer cross sections (Frost and Phelps 1964). Measurements of the relative elastic differential cross sections have been made by Mehr (1967), Lewis *et al* (1974), Heindorff *et al* (1976) and Zhou Qing *et al* (1982). Absolute values of the elastic differential cross sections for Kr have been reported by Williams and Crowe (1975), Jansen and de Heer (1976) and Srivastava *et al* (1981). Very recently, Wagenaar *et al* (1986) have measured absolute differential cross sections for the elastic scattering of electrons from Kr at small angles (<10°) in the energy range from 20 to 100 eV. A survey of previous experimental and theoretical work is given in a report by Bransden and McDowell (1978). An analysis and evaluation of total excitation, ionisation and scattering cross sections for Kr has been made by de Heer *et al* (1979).

Theoretical calculations for Kr have been carried out in an optical potential model by McCarthy *et al* (1977) who gave results for differential cross sections and spin polarisations, and by Sin Fai Lam (1982) who used a relativistic approximation to calculate elastic phaseshifts and cross sections. Elastic scattering phaseshifts and differential cross sections have been calculated by McEachran and Stauffer (1984) with an adiabatic exchange method including only the dipole part of the polarisation potential. Very recently, differential cross sections and polarisations for elastic scattering have been calculated by Haberland *et al* (1986) with a Kohn-Sham-type one-particle theory.

As a first step in a systematic study of electron-krypton collisions, we have measured the differential cross sections for elastic scattering. Absolute values of the differential cross section have been obtained with the relative flow method in the energy range from 5 to 200 eV and in the angular range from 10 to 125°.

## 2. Experimental apparatus and procedures

The electron impact spectrometer and the experimental procedures used in the present measurements have been described previously (Nishimura *et al* 1985). The Kr beam effused through a capillary array and was crossed at right angles by an electron beam from an energy selector. The scattered electrons were energy analysed and detected by a channel electron multiplier. The energy resolution of the spectrometer was about 60 meV full width at half maximum and the angular resolution was about ±2°. The true zero scattering angle was determined from the symmetry of scattering around the nominal zero degree angle. The electron impact energy scale was calibrated by observing the 19.35 eV resonance of He at 90° scattering angle.

For the determination of the absolute scale of the elastic differential cross sections, the relative flow method was adopted (Srivastava *et al* 1975, Nishimura *et al* 1985). The intensity of electrons elastically scattered from Kr was measured and immediately followed by the measurements of the scattered electron intensity from He under the same experimental conditions. Thus the intensity ratio of these two atomic beams was decided at each impact energy as a function of scattering angle. Then the absolute value of the elastic differential cross sections for Kr was determined from the ratio by multiplying by the absolute differential cross section of He (Register *et al* 1980). The pressure behind the capillary array was adjusted to reproduce as closely as possible the flux distribution of both gases (Trajmar and Register 1983).

Errors in the determination of the elastic differential cross sections are attributed to uncertainties in the measurement of the differential cross section ratio, $\sigma(\mathrm{Kr})/\sigma(\mathrm{He})$ and the errors associated with the standard cross section of He, $\sigma(\mathrm{He})$. In the determination of the ratio, $\sigma(\mathrm{Kr})/\sigma(\mathrm{He})$, the major error comes from the uncertainty in the measurement of the scattering angle. This error increases for those angles where the differential cross section varies rapidly with the scattering angles as is the case with small-angle data and the data near minima. The estimated error is about 15% in these angular regions and becomes smaller at the scattering angles where the angular distribution is flat. It is estimated that the overall error in the measurement of the ratio, $\sigma(\mathrm{Kr})/\sigma(\mathrm{He})$, is about 17%, which is the square root of the sum of squares of the error of 15% in scattering angle measurements, 5% in pressure and another 5% in electron beam current measurements. Taking into account the 5-10% error in the value of $\sigma(\mathrm{He})$ (Register *et al* 1980), the total error in the present differential cross section is estimated to be about 20%. For the integral and momentum transfer cross sections, an additional error is involved, which comes from the uncertainty in extrapolation of the measured differential cross sections to 0 and 180° scattering angles. The estimated error in this procedure is about 15%.

## 3. Results and discussion

### 3.1. *Differential cross section for elastic scattering*

Using the method described in the preceding section, the normalised absolute differential cross sections for elastic scattering were obtained in the electron impact energy range from 5 to 200 eV, and in the angular range from 10 to 125°. The present results are summarised in table 1. Typical angular distributions at 10, 20 and 100 eV impact energies are shown in figures 1, 2 and 3. In the present angular distributions, two minima are found between 10 and 125° except at impact energies of 30, 40 and 50 eV, where the second minimum is out of the range of observational angles. Above 30 eV, the positions of these minima shift systematically toward smaller scattering angles with the increase of impact energy.

In figure 1, the present results at 10 eV impact energy are compared with the measurements of Srivastava *et al* (1981) and the theoretical calculations of McEachran and Stauffer (1984). There is good agreement in the shape of the angular distributions between the present results and those of Srivastava *et al.* However, in magnitude, the present results are higher than the latter by a factor of about 1.5. Substantial differences are observed between the present angular distribution and the theoretical calculations of McEachran and Stauffer.

The angular distribution at 20 eV impact energy is shown in figure 2 together with the experimental results of Williams and Crowe (1975), and Srivastava *et al.* Also shown are the calculations of McCarthy *et al* (1977) and McEachran and Stauffer. There has been extensive discussion on the descrepancies found in the experimental differential cross sections at 20 eV (Srivastava *et al* 1981). Srivastava *et al* found considerably lower values than those of Williams and Crowe especially in the scattering angles below 70°. The present results agree well with the data of Williams and Crowe in the entire region of scattering angles investigated. The calculations of McCarthy *et al* successfully predict the present measurements.

At 100 eV impact energy the present results, shown in figure 3, agree well within error limits with the experimental results of Srivastava *et al* and Jansen and de Heer. The data of Williams and Crowe are higher than our results at the forward scattering angles below 30° and at the second maximum around 60–70°, while better agreement is observed in the backward scattering. The theoretical results of McCarthy *et al* reproduce the present measurements well except for the angular behaviour at small scattering angles up to the first minimum, where their calculations give a steeper angular distribution than the experimental results.

The present results agree, within experimental error limits, with the previous measurements of Srivastava *et al* with exceptions at 10 and 20 eV impact energies, where our results are considerably higher. The previous results by Jansen and de Heer, and Williams and Crowe are, in general, higher than the present data, though excellent agreement is observed between the present data and those of Williams and Crowe at 20 eV. The calculations of McCarthy *et al* repr.oproduce the present results well except

**Table 1.** Differential cross section for the elastic scattering (in units of $10^{-16}$ cm$^2$ sr$^{-1}$). $\sigma_I$ and $\sigma_M$ represent the integral and momentum transfer cross sections (in units of $10^{-16}$ cm$^2$). The estimated errors are 20% for differential cross sections, and 25% for integral and momentum transfer cross sections.

| Scattering angle (deg) | Incident electron energy (eV) 5.0 | 7.5 | 10 | 15 | 20 | 30 | 40 | 50 |
|---|---|---|---|---|---|---|---|---|
| 10 | — | — | 13.6 | 17.0 | 18.2 | 19.0 | 19.6 | 19.1 |
| 15 | — | — | 11.6 | 14.7 | 15.0 | 13.4 | 13.8 | 13.2 |
| 20 | 1.7 | 6.4 | 9.8 | 11.8 | 12.0 | 9.6 | 9.0 | 7.6 |
| 25 | 1.5 | 5.0 | 7.6 | 9.2 | 9.7 | 6.6 | 5.8 | 4.5 |
| 30 | 1.3 | 4.0 | 6.6 | 7.0 | 7.3 | 4.2 | 3.5 | 2.5 |
| 35 | 1.2 | 3.1 | 5.4 | 5.5 | 5.1 | 2.7 | 1.9 | 1.3 |
| 40 | 1.2 | 2.5 | 4.4 | 4.6 | 3.9 | 1.6 | 0.90 | 0.54 |
| 45 | 1.3 | 2.1 | 3.2 | 3.3 | 2.7 | 0.85 | 0.41 | 0.19 |
| 50 | 1.4 | 1.9 | 2.8 | 2.5 | 1.7 | 0.46 | 0.17 | 0.058 |
| 55 | 1.6 | 1.9 | 2.3 | 1.7 | 0.92 | 0.22 | 0.065 | 0.048 |
| 60 | 1.8 | 2.0 | 1.9 | 1.2 | 0.54 | 0.10 | 0.050 | 0.12 |
| 65 | 2.0 | 2.0 | 1.6 | 0.86 | 0.37 | 0.057 | 0.081 | 0.16 |
| 70 | 2.1 | 2.0 | 1.6 | 0.64 | 0.21 | 0.078 | 0.11 | 0.21 |
| 75 | 2.1 | 2.0 | 1.8 | 0.45 | 0.17 | 0.11 | 0.14 | 0.21 |
| 80 | 2.0 | 2.0 | 1.6 | 0.39 | 0.20 | 0.17 | 0.16 | 0.20 |
| 85 | 1.8 | 1.7 | 1.4 | 0.46 | 0.24 | 0.19 | 0.16 | 0.20 |
| 90 | 1.5 | 1.4 | 1.2 | 0.45 | 0.30 | 0.21 | 0.17 | 0.17 |
| 95 | 1.2 | 1.0 | 1.1 | 0.43 | 0.33 | 0.23 | 0.16 | 0.15 |
| 100 | 0.88 | 0.72 | 0.79 | 0.42 | 0.36 | 0.23 | 0.15 | 0.11 |
| 105 | 0.56 | 0.38 | 0.54 | 0.40 | 0.40 | 0.21 | 0.12 | 0.076 |
| 110 | 0.27 | 0.16 | 0.30 | 0.32 | 0.42 | 0.19 | 0.099 | 0.044 |
| 115 | 0.13 | 0.070 | 0.18 | 0.30 | 0.36 | 0.16 | 0.073 | 0.034 |
| 120 | 0.096 | 0.16 | 0.38 | 0.29 | 0.36 | 0.14 | 0.054 | 0.019 |
| 125 | 0.26 | 0.36 | 0.72 | 0.33 | 0.35 | 0.099 | 0.033 | 0.0099 |
| $\sigma_I$ | 17.2 | 26.0 | 30.3 | 23.0 | 19.6 | 12.7 | 11.3 | 10.1 |
| $\sigma_M$ | 16.0 | 22.6 | 22.2 | 9.8 | 6.7 | 2.4 | 1.6 | 1.5 |

| Scattering angle (deg) | Incident electron energy (eV) 60 | 70 | 80 | 90 | 100 | 150 | 200 |
|---|---|---|---|---|---|---|---|
| 10 | 18.9 | 16.0 | 13.0 | 11.5 | 10.2 | 7.0 | 5.4 |
| 15 | 12.5 | 8.8 | 8.0 | 6.0 | 6.0 | 3.3 | 2.6 |
| 20 | 6.9 | 4.4 | 4.0 | 3.0 | 3.0 | 1.4 | 1.1 |
| 25 | 3.6 | 2.4 | 1.8 | 1.6 | 1.4 | 0.54 | 0.37 |
| 30 | 1.8 | 1.2 | 0.78 | 0.73 | 0.62 | 0.21 | 0.19 |
| 35 | 0.82 | 0.53 | 0.23 | 0.25 | 0.22 | 0.088 | 0.13 |
| 40 | 0.35 | 0.15 | 0.074 | 0.050 | 0.040 | 0.072 | 0.12 |
| 45 | 0.080 | 0.030 | 0.025 | 0.032 | 0.045 | 0.10 | 0.13 |
| 50 | 0.037 | 0.042 | 0.056 | 0.084 | 0.11 | 0.13 | 0.14 |
| 55 | 0.084 | 0.10 | 0.13 | 0.16 | 0.17 | 0.16 | 0.14 |
| 60 | 0.16 | 0.15 | 0.23 | 0.23 | 0.20 | 0.16 | 0.11 |
| 65 | 0.23 | 0.18 | 0.25 | 0.25 | 0.22 | 0.13 | 0.090 |
| 70 | 0.28 | 0.20 | 0.24 | 0.25 | 0.21 | 0.094 | 0.050 |
| 75 | 0.27 | 0.20 | 0.21 | 0.21 | 0.16 | 0.058 | 0.022 |
| 80 | 0.25 | 0.17 | 0.16 | 0.15 | 0.10 | 0.023 | 0.0037 |
| 85 | 0.19 | 0.13 | 0.093 | 0.094 | 0.060 | 0.0054 | 0.0028 |
| 90 | 0.13 | 0.070 | 0.054 | 0.051 | 0.029 | 0.0047 | 0.019 |
| 95 | 0.080 | 0.040 | 0.020 | 0.023 | 0.012 | 0.019 | 0.050 |
| 100 | 0.041 | 0.017 | 0.011 | 0.012 | 0.021 | 0.050 | 0.093 |
| 105 | 0.019 | 0.0040 | 0.010 | 0.026 | 0.047 | 0.080 | 0.12 |
| 110 | 0.0062 | 0.0036 | 0.018 | 0.048 | 0.070 | 0.11 | 0.15 |
| 115 | 0.0017 | 0.0094 | 0.031 | 0.066 | 0.088 | 0.12 | 0.15 |
| 120 | 0.0021 | 0.017 | 0.040 | 0.082 | 0.11 | 0.12 | 0.13 |
| 125 | 0.0034 | 0.022 | 0.043 | 0.090 | 0.10 | 0.11 | 0.11 |
| $\sigma_I$ | 9.0 | 6.9 | 5.7 | 5.3 | 4.7 | 3.1 | 2.7 |
| $\sigma_M$ | 1.1 | 0.86 | 0.89 | 1.04 | 0.98 | 0.90 | 0.94 |

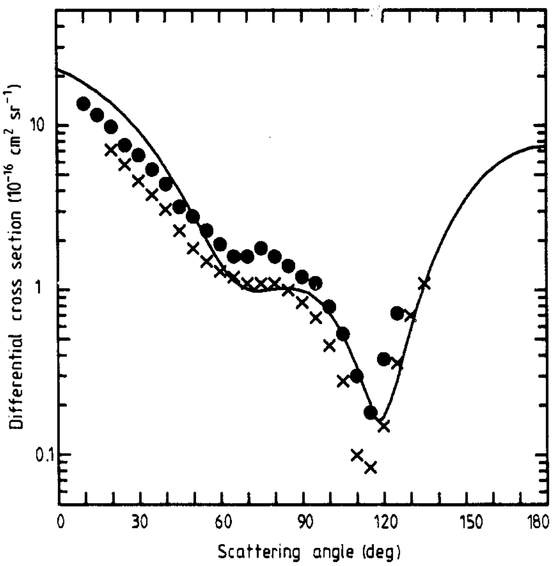


**Figure 1.** Differential cross sections for the elastic scattering of 10 eV electrons from Kr. Measurements: ●, present results; ×, Srivastava *et al* (1981). Calculations: ——, McEachran and Stauffer (1984).

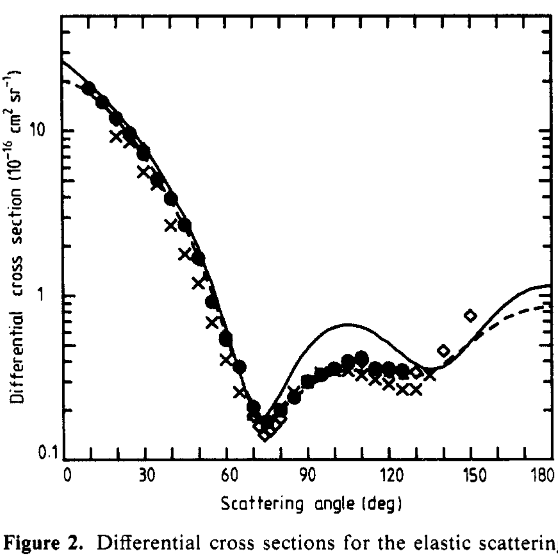


**Figure 2.** Differential cross sections for the elastic scattering of 20 eV electrons from Kr. Measurements: ●, present results; ×, Srivastava *et al* (1981); ◇, Williams and Crowe (1975). Calculations: - - -, McCarthy *et al* (1977); ——, McEachran and Stauffer (1984).

for small differences at high impact energies ($\geqslant$50 eV). The theoretical results of McEachran and Stauffer give higher cross sections at small scattering angles at low impact energies below 10 eV, and at above 30 eV their calculations are consistently higher than the present results. Recent calculations of Haberland *et al* (not shown in the figures) give different angular distributions at 10 eV impact energy where the first

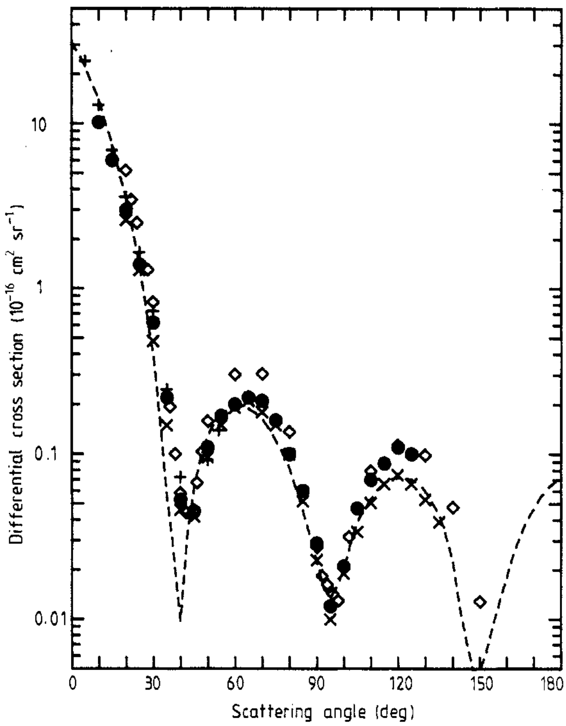


**Figure 3.** Differential cross sections for the elastic scattering of 100 eV electrons from Kr. Measurements: ●, present results; ×, Srivastava *et al* (1981); ◇, Williams and Crowe (1975); +, Jansen and de Heer (1976). Calculations: - - -, McCarthy *et al* (1977).

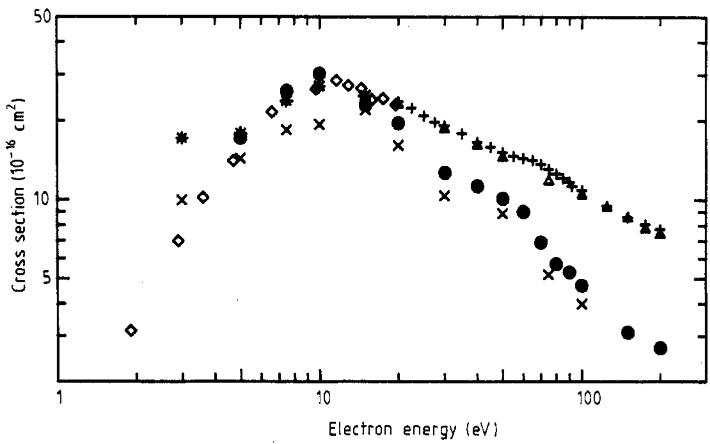


**Figure 4.** Integral cross sections for elastic scattering of electrons by Kr compared with other elastic and total cross sections. Elastic scattering: present results, ●; Srivastava *et al* (1981), × (from He normalisation) and * (from phaseshift analysis). Total scattering: Dababneh *et al* (1980), ◇ (at energies >20 eV their data are not plotted in the figure); Dababneh *et al* (1982), △; Wagenaar and de Heer (1985), +.

shallow minimum around 70° is missing. At 20 eV impact energy, their calculations predict the present results within the experimental error limits, while at high impact energies their results are significantly higher than the present measurements.

### 3.2. *Integral and momentum transfer cross sections*

In the present experiments, the measurements were made in the angular range from 10 to 125°. To obtain the integral and momentum transfer cross sections, the differential cross sections have to be extrapolated to experimentally inaccessible angles. In the present measurements, the real phaseshift method was used just for the purposes of the data fitting and extrapolation. The details are discussed elsewhere (Register *et al* 1980, Nishimura *et al* 1986). The integral and momentum transfer cross sections are derived by integrating the data through the scattering angle after the extrapolation. They are also recorded in table 1 as $\sigma_I$ and $\sigma_M$. In figure 4, the present integral cross sections are compared with the measurements of Srivastava *et al* (1981). They have presented the integral and momentum transfer cross sections for elastic scattering in two ways; (i) from phaseshift analysis (<15 eV), and (ii) from He normalisation (3-100 eV). The present results are in good agreement with their data from phaseshift analysis. However, their results from He normalisation are considerably lower than our values especially at impact energies below 30 eV except for a better agreement at 15 eV. Excellent agreement is observed between the present results and the total cross sections of Dababneh *et al*, and Wagenaar and de Heer at impact energies below 20 eV where the inelastic processes are less important. Momentum transfer cross sections in the present measurements agree well with the results of Srivastava *et al* from phaseshift analysis at impact energies below 10 eV and those from He normalisation above 15 eV except for their smaller cross section at 20 eV.

## References

Bransden B H and McDowell M R C 1978 *Phys. Rep.* **46** 249
Dababneh M S, Hsieh Y-F, Kauppila W E, Pol V and Stein T S 1982 *Phys. Rev.* A **26** 1252
Dababneh M S, Kauppila W E, Dowing J P, Laperriere F, Pol V, Smart J H and Stein T S 1980 *Phys. Rev.* A **22** 1872
de Heer F J, Jansen R H J and van der Kaay W 1979 *J. Phys. B: At. Mol. Phys.* **12** 979
Frost L S and Phelps A V 1964 *Phys. Rev.* **136** A1538
Haberland R, Fritsche L and Noffke J 1986 *Phys. Rev.* A **33** 2305
Heindorff T, Höfft J and Dabkiewicz P 1976 *J. Phys. B: At. Mol. Phys.* **9** 89
Jansen R H J and de Heer F J 1976 *J. Phys. B: At. Mol. Phys.* **9** 213
Lewis B R, McCarthy I E, Teubner P J O and Weigold E 1974 *J. Phys. B: At. Mol. Phys.* **7** 2549
McCarthy I E, Noble C J, Phillips B A and Turnbull A D 1977 *Phys. Rev.* A **15** 2173
McEachran R P and Stauffer A D 1984 *J. Phys. B: At. Mol. Phys.* **17** 2507
Mehr J 1967 *Z. Phys.* **198** 345
Nishimura H, Danjo A and Sugahara H 1985 *J. Phys. Soc. Japan* **54** 1757
Nishimura H, Matsuda T and Danjo A 1986 *J. Phys. Soc. Japan* **56** 70.
Ramsauer C 1923 *Ann. Phys., Lpz.* **72** 345
Ramsauer C and Kollath R 1929 *Ann. Phys., Lpz.* **3** 536
Register D F, Trajmar S and Srivastava S K 1980 *Phys. Rev.* A **21** 1134.
Sin Fai Lam L T 1982 *J. Phys. B: At. Mol. Phys.* **15** 119
Srivastava S K, Chutjian A and Trajmar S 1975 *J. Chem. Phys.* **63** 2659
Srivastava S K, Tanaka H, Chutjian A and Trajmar S 1981 *Phys. Rev.* A **23** 2156
Townsend J S and Bailey V A 1922 *Phil. Mag.* **43** 593

Trajmar S and Register D F 1983 *Electron–Molecule Collisions* ed I Shimamura and K Takayanagi (New York: Plenum)
Wagenaar R W, de Boer A, van Tubergen T, Los J and de Heer F J 1986 *J. Phys. B: At. Mol. Phys.* **19** 3121
Wagenaar R W and de Heer F J 1980 *J. Phys. B: At. Mol. Phys.* **13** 3855
—— 1985 *J. Phys. B: At. Mol. Phys.* **18** 2021
Williams J F and Crowe A 1975 *J. Phys. B: At. Mol. Phys.* **8** 2233
Zhou Qing, Beerlage M J M and van der Wiel M J 1982 *Physica* **113C** 225