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Absolute total cross section measurements for intermediate energy electron scattering: III. Ne and Ar

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Abstract. Absolute total cross section measurements are presented for e^--Ne and e^--Ar scattering. The covered energy range spans from 100 to 3000 eV. The overall systematic uncertainty was ±2.4%, the random uncertainty was ±1.5% and the angular resolution error was less than 0.5%. A comparison with existing experimental and theoretical data is given. This comparison suggests that the semi-empirical data of de Heer *et al* for Ne are possibly overestimated by 5% at 100 eV.

1. Introduction

Renewed interest in atomic physics has triggered an increasing number of theoretical and experimental papers in the field of electron-atom and electron-molecule collisions. Total cross sections have been measured in the last ten years for energies from a few tenths of an eV to a few thousand eV in noble gases and some small molecules.

The experimental work up to 1970 has been reviewed by Bederson and Kieffer (1971) and up to 1977 by Brandsen and McDowell (1978). Our present knowledge for noble gases can be reconstructed from partial summaries and from references contained in the papers of de Heer *et al* (1979), Wagenaar and de Heer (1980), Kauppila *et al* (1981) and Nickel *et al* (1985). The theoretical work in the same field has been reviewed by Bransden and McDowell (1977) for intermediate energies.

This paper presents the measured cross sections of Ne and Ar in the energy range from 100 to 3000 eV. It is a continuation of the work performed in our laboratory for He (Dalba *et al* 1979, 1981), O_2, N_2 and NO (Dalba *et al* 1980) and H_2O (Zecca *et al* 1987).

2. Experimental set-up

The apparatus has been extensively described in our previous paper (see Dalba *et al* 1981). We report here only the main features and the improvements which were made in the apparatus and in the experimental procedure before these measurements.

We used a Ramsauer-type spectrometer with an electron orbit radius of 200 mm. Five apertures were installed in the 180° magnetic sector to obtain the beam forming and selection. A modification of the scattering chamber was introduced with respect

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to the original Ramsauer design. An additional aperture divides the scattering chamber in two parts. The first part constitutes the gas cell and the second one is a gridded structure, open for gas pumping and electrically opaque for scattered electrons. The purpose of this geometry is to improve the angular resolution of the measurements. The length of the electron trajectories in the gas cell was 140.2 mm. The circular optic bench was built of AISI 304 stainless steel as in the previous version; the apertures and their holders were built of a non-magnetic copper–nickel alloy (ARCAP-France).

Two different sets of slits were used: the first one labelled 'low-energy' was used from 100 to 361 eV; the 'high-energy' set was used from 256 eV to 3 keV. The low-energy set was designed to achieve an angular acceptance of 3.4×10^{-4} sr (1.6×10^{-4} sr for the high-energy set). These two numbers were evaluated as the solid angle subtended by the scattering chamber exit aperture from the centre of the gas cell. With the low-energy apertures no electrons scattered from the beam axis at angles larger than 0.89° (cut-off angle; 0.60° for the high-energy apertures) can reach the detector. The dimensions of the apertures are given in table 1 for both sets.

Table 1. Dimensions (mm) of the slits for the two sets used (see also Dalba *et al* 1981).

		Low-energy set		High-energy set	
Position	Slit no	Width	Height	Width	Height
Anode	1	2	2.5	0.8	1.6
Beam selection	2	2.8	2.4	1.4	1.7
	3	2	2.25	0.8	1.3
	4	2	2	0.8	1.0
Scattering chamber	5	2.6	2.3	1.0	1.2
	6	3.6	3.3	2.3	1.8
	7	3.4	4.4	2.7	2.5
Collector	8	3.7	4.7	2.9	2.8

Simultaneous measurements of both the collector (I_c) and the scattering chamber (I_s) currents are essential in the Ramsauer technique. The sum I_c+I_s equals the total current entering the scattering cell at any given pressure. Therefore if $I_c/(I_c+I_s)$ is used instead of I_c in de Beer's attenuation law, the measured cross sections will be insensitive to beam fluctuations during the measurements.

The maximum sensitivity to the scattering process is obtained when the scattering chamber current at zero pressure is zero. This condition is difficult to fulfil since small misalignments due to mechanics or to stray fields cause a partial interception of the beam even at zero pressure. This would not affect the measurements if the interception were constant with respect to time and energy. Since this is not the real case, it is good practice to use a high I_c/I_s ratio at zero pressure. The present measurements were performed with a ratio larger than 10 at 100 eV to about 30 above 200 eV. At energies below 100 eV the magnetic field inhomogeneity and the residual magnetisation of the parts distort the beam and lower the ratio. Detected current stability is also impaired. For these reasons, results for energies below 100 eV are not presented.

The highest pressures of the target gas in the scattering chamber were chosen to obtain a beam attenuation of less then three. The pressure was measured with an MKS

Baratron meter (type 94 A-H1). The head temperature was stabilised at 19 °C. As in the previous measurements, a proportional temperature control was found to perform better than the MKS temperature controller (type 1090-1). In fact, this unit has some hysteresis, leading to a temperature 'sawtooth', 0.5 °C peak-to-peak. This results in a similar waveform for the zero and pressure readings of the capacitance head. A proportional temperature control with 0.1 °C stability avoids this effect.

The gas-chamber temperature was free running between 17 and 21 °C. The small temperature difference with respect to the capacitance head allowed us to ignore the thermal transpiration correction of the cross sections.

3. Experimental procedure

The experiment was controlled by a microcomputer. Beam tuning was manually performed to obtain a high I_c/I_s ratio. It was achieved by fine changes in the Earth's magnetic-field compensation. The computer program was then charged to perform measurements at several successive energies. At each energy I_c and I_s pairs were measured at six or seven increasing pressures in the gas chamber. It should be mentioned that the zero of the Baratron meter was read twice: before and after each measurement. The pressure readings were then corrected assuming a linear zero drift during the measurement.

The attenuation law for the Ramsauer technique is

$$I_{ci}/(I_{ci}+I_{si}) = I_{cj}/(I_{cj}+I_{sj}) \exp[-\sigma l(N_i - N_j)]$$

where σ is the total cross section, l is the length of the electron trajectories in the gas cell, N is the gas density and i and j correspond to two different pressures.

The cross section in a run was computed as the slope of the $\ln[I_c/(I_c+I_s)]$ line against pressure. Four runs or more were performed at each energy. More measurements were done to reduce the statistical error at low energies and for certain points, such as 500 and 1000 eV. The final values of the cross sections as reported in the following are the averages of all the values obtained at each energy.

4. Error evaluation

Both I_c and I_s currents were measured by the same instrument (Keithley model 417 current amplifier). The error introduced was limited to the non-linearity error. It was evaluated to be less than 1.5%.

The calibration accuracy of the capacitance manometer was assumed to be 1.0%. The pressure readings were compensated for the capacitance head temperature coefficient with the MKS model 170M-35 compensation unit. The compensated error was not greater than 0.2%, so the error left by this source was negligible.

The errors due to the reference pressure and to the constant background pressure in the second part of the scattering chamber, following the formula for the attenuation law, do not influence the cross section values.

Since the gas-chamber temperature was read only at the beginning of an energy sweep, its drift introduced an error. This was always lower than 0.3%. According to the latest works on cross sections (see Wagenaar and de Heer (1985) and Nickel *et al* (1985)), the formula for thermal transpiration should include some coefficient which depends on the vacuum fitting geometry. Since to date there is no codified procedure

to calculate this coefficient, no thermal transpiration correction was applied to the measured values. This neglect is in part justified since the direct application of the Knudsen formula (see Knudsen 1910) to our measurements always gives an error of less than 0.3%.

The uncertainty in the length of the interaction chamber was ±0.3 mm and this results in an error in the cross section of less than 0.2%.

The intrinsic characteristics of the computer hardware and software did not allow us to measure the energy to better than 1%. The cross section values given in the tables and in the figures were calculated by linear interpolation of neighbouring points. This procedure introduces an additional error which was evaluated to be less than 1%, the reasoning being that no sharp structure in the cross section is present in the vicinity of the points.

The energy scale was corrected for the known contact potential from the cathode to the apparatus (1.5 ± 0.5 V). The uncertainty in this quantity results in an error in the cross section of less than 0.5%.

The end effect at the entrance and exit apertures of the gas chamber following the theory of Mathur *et al* (1975) is negligible in our geometry. Experimental checks of the theory were made by Dalba *et al* (1979) and by Wagenaar and de Heer (1985).

A systematic energy-dependent error lowering the measured cross section is introduced by the finite angular resolution of the apparatus. This error was evaluated for our geometry using the experimental differential elastic cross sections of Wagenaar *et al* (1986) at 100 eV and those of Jansen *et al* (1976) from 200 to 3000 eV. The calculated angular resolution errors are 0.04% at 100 eV, 0.08% at 500 eV, 0.11% at 1000 eV and 0.27% at 3000 eV for neon. For argon these values are 0.07%, 0.16%, 0.25% and 0.46% at the same energies. The contribution of inelastic scattering to the angular resolution error was not calculated. It is believed to be smaller than the elastic part due to the energy discrimination of the apparatus. These evaluations were confirmed by the use of the two different sets of apertures: points between 256 and 361 eV were measured with both sets and the results were well within the statistical noise. A few points at energies between 2000 and 3000 eV were remeasured with the low-energy slit set. The results confirmed that the angular resolution error was smaller than 1.5% even at 3000 eV. The values for cross sections presented in this paper were not corrected for these angular resolution errors.

The overall systematic error computed as the quadratic sum of the above listed errors is equal to 2.4%. The statistical error in the whole energy range is less than 1.5%.

The gas purity was 99.99% for neon and 99.9985% for argon. The main contaminants as given by the analysis of the supplier were $O_2 < 3$ PPM V, $H_2O < 3$ PPM V, $He < 80$ PPM V, $N_2 < 15$ PPM V in neon and $O_2 < 3$ PPM V, $H_2O < 5$ PPM V and $N_2 < 5$ PPM V in argon.

5. Results and discussion

The present total absolute cross sections for e^--Ne and e^--Ar scattering are given in table 2.

The present measurements for Ne are compared with previous reuslts in figures 1(*a*) and 2(*a*). Figure 1(*a*) shows the cross section as a function of the square root of the electron energy. The full curves are selected results of four theoretical groups. Dewangan and Walters (1977) used a distorted-wave second Born approximation to

Table 2. Total absolute cross sections (10^{-20} m^2).

Energy (eV)	Neon	Argon
100.00	3.001	8.831
110.25	2.918	8.110
121.00	2.858	7.806
132.25	2.688	7.526
144.00	2.593	7.173
169.00	2.457	6.461
196.00	2.244	5.988
225.00	2.094	5.599
256.00	1.998	5.262
289.00	1.855	4.875
324.00	1.763	4.550
361.00	1.658	
400.00	1.559	4.059
484.00		3.626
500.00	1.378	3.574
576.00	1.272	3.230
700.00	1.105	2.897
784.00	1.032	2.681
900.00	0.941	2.413
1000.00	0.851	2.269
1156.00	0.790	2.049
1296.00	0.726	1.874
1444.00	0.661	1.742
1600.00		1.596
1764.00	0.568	1.485
2000.00	0.501	1.362
2304.00	0.459	1.213
2704.00	0.392	1.066
3000.00	0.357	0.981

calculate the elastic scattering. Applying the optical theorem they give the neon total cross sections in the energy range 100–3000 eV. Their calculated values are some 20% higher than the present measurements at 200 eV; the discrepancy decreases to 10% between 400 and 1000 eV, increasing again to 15% at 3000 eV.

Byron and Joachain (1977) calculated the total Ne cross sections by the application of the optical theorem formalism to the eikonal-Born series method. This gives cross section values which are similar to those obtained by Dewangan and Walters (1977).

Figure 1(*a*) also shows the calculations of Thirumalai and Truhlar (1982) performed with a matrix effective potential (MEP) model. The agreement of their results with the present measurements is very good in the overlap range from 150 to 700 eV. The agreement with the theoretical values obtained by Staszewska *et al* (1983) is also very good. This paper gives several successive models based on a dispersion equation approach. Figure 1(*a*) shows the results of the last model which includes the static exchange, polarisation and absorption.

Figure 2(*a*) gives a somewhat unconventional comparison of the present results with the previous experimental measurements. Total cross section values at 100 eV are about ten times greater than at 3000 eV but, on the other hand, the newest measurements differ from each other by not more than 5%. These two facts render a presentation like figure 1(*a*) of little use. Figure 2(*a*) was obtained using the following

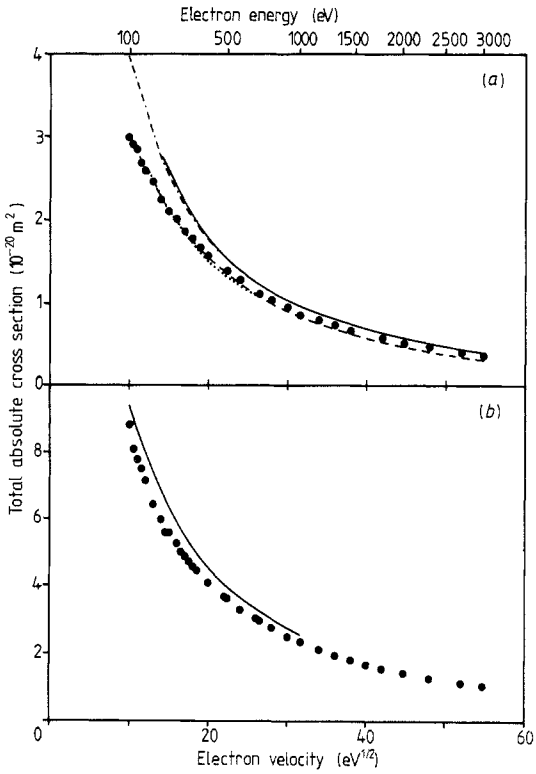

Figure 1. Total absolute cross sections (present experimental results and theoretical calculations) for (*a*) electron-neon and (*b*) electron-argon scattering. (*a*) ●, present experiment; ——, Dewangan and Walters DWSBA (1977); – · – · –, Byron and Joachain EBS (1977); · · · ·, Thirumalai and Truhlar MEP (1982); – – –, Staszewska *et al* DEAPA (1983). (*b*): ●, present experiment; ——, Joachain *et al* OM II (1977).

procedure: the semi-empirical data of de Heer *et al* (1979) were fitted with a sixth-order polynomial for the double logarithmic dependence of the cross section on the energy; the resulting coefficients are (in order of ascending power) −7.242 59, 11.614 59, −4.471 39, −1.070 98, 1.192 485, −0.306 71, 0.026 64 for Ne, and 0.673 24, 0.758 06, −0.253 55, −0.105 97, 0.047 59, −0.005 22, −0.000 06 for Ar. This best fit function was represented in figure 2(*a*) by the broken horizontal line at zero discrepancy. All the experimental data were plotted on this graph as their percentage difference from the value of this function: data higher than the semi-empirical values of de Heer *et al* (1979) were plotted with a positive discrepancy value.

The choice of the semi-empirical data as a reference is an arbitrary one that the authors have made.

The presentation of figure 2(*a*) allows us to see discrepancies and agreements between different measurements. It is easily seen that the measurements of Wagenaar and de Heer (1980) are generally higher than our measurements, the maximum discrepancy being 5% at 256 eV. The agreement with the measurements of Nickel *et al* (1985) is much better—less than 1%. The measurements of Kauppila *et al* (1981) are slightly lower than ours, with a maximum discrepancy of 4% near 500 eV. The measurements of Garcia *et al* (1986) are some 4% higher than ours in the overlap

range from 700 to 3000 eV. Our measurements are within ±5% of the semi-empirical data.

Figure 2(*a*) allows us to detect a possible fault in the semi-empirical evaluations of de Heer *et al* (1979). It is clear from the figure that all the existing measurements are in good agreement for energies around 100 eV. In addition, if a curve is drawn through each set of measurements, the slope of such a curve at 100 eV is positive for all authors. This could be interpreted as an indication that the semi-empirical data are overestimated at 100 eV. The correction needed could be 5%.

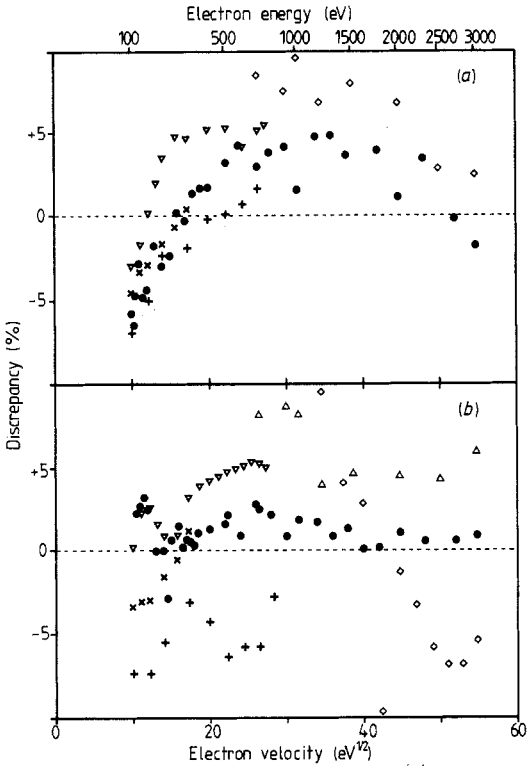

Figure 2. Experimental results: discrepancy from a fit to the semi-empirical data of de Heer *et al* (1979). See text. (*a*) e^--Ne: ●, present experiment; ×, Nickel *et al* (1985); ▽, Wagenaar and de Heer (1980); +, Kauppila *et al* (1981); ◇, Garcia *et al* (1986). (*b*) e^--Ar: as in figure 2(*a*) except: ◇, Nogueira *et al* (1982); △, Garcia *et al* (1986).

Figure 1(*b*) shows the comparison of our measurements for argon with theoretical values obtained by Joachain *et al* (1975) with an optical model and by Joachain *et al* (1977) with an improved potential, modified for the absorption part. The theoretical data are about 4% higher than the experimental ones in the entire range.

Figure 2(*b*) is again a comparison between experimental data from different laboratories. The reference horizontal line was obtained in the same way as for neon. The coefficients of the sixth-degree polynomial fitting best on a log-log scale to the semi-empirical data of de Heer *et al* (1979) have already been given. No special conclusions can be drawn for argon. It can be noticed that all the measurements are again in a ±5% band except for the data of Nogueira *et al* (1982) which are presented

in this figure only for selected points. We stress also the close agreement of our present measurements with the semi-empirical data.

Some general features are common to figures 2(*a*) and 2(*b*): the measurements of Wagenaar and de Heer (1980) are generally higher than ours, the values of Kauppila *et al* (1981) are generally lower and the best agreement is found with Nickel *et al* (1985). The recent measurements of Garcia *et al* (1986) are about 5% higher than the present ones.

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