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Total cross sections for electron scattering from Ne, Ar and Kr in the energy range 700–6000 eV

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Abstract. Total cross sections for electron scattering from Ne, Ar and Kr in the impact energy range 700-6000 eV have been measured. The experimental method has been based on the measurement of the attenuation of a linear electron beam. The results have been compared with available theoretical, semi-empirical and experimental total cross sections. No previous data have been found in the literature for impact energies above 3000 eV.

1. Introduction

Electron scattering by noble gases has been the subject of a large number of experimental and theoretical studies. Early experiments on total cross sections were carried out at low electron energies (<100 eV) largely using the Ramsauer technique (Ramsauer 1921a, b). Bederson and Kieffer (1971) have summarised the results of experiments performed using this technique. Later measurements have been made up to higher energies by studying the attenuation of a linear electron beam in the gas. Blaauw *et al* (1980) and Wagenaar and de Heer (1980) have measured total cross sections for electrons scattered from noble gases up to 750 eV impact energy. Kauppila *et al* (1981) have performed cross section measurements for electrons as well as for positrons at energies below 800 eV. Recently, very accurate total cross sections for noble gases at low and intermediate impact energies have been measured by Jones and Bonham (1982), Jost *et al* (1983), Wagenaar and de Heer (1985) and Nickel *et al* (1985). Accurate total cross section measurements across a broader energy range are needed to check the validity of theoretical approximations as well as the sum rule (Bransden and McDowell 1969) based on the forward dispersion relations (Gerjuoy and Krall 1960). However, to our knowledge there are no experimental data in the literature for energies above 800 eV, except for the work of Dalba *et al* (1979) on He in the energy range 100-1400 eV and the work of Nogueira *et al* (1982) on Ar in the range 500-3000 eV. The lack of total cross section measurements at high energies (1000 eV) has prompted this work.

In the present work, total cross sections for Ne, Ar and Kr have been measured in the energy range 700-6000 eV by a transmission beam technique. As mentioned by several authors (e.g. Blaauw *et al* 1980, Floeder *et al* 1985), the electrons inelastically scattered in the forward direction can give rise to important experimental errors in the attenuation measurements. In order to avoid this effect in the present work, an electrostatic energy analyser has been used.

Experimental results have been compared with the predictions of the Born-Bethe approximation and with the theoretical calculations of Dewangan and Walters (1977), Byron and Joachain (1977) and Joachain *et al* (1977). These authors used their calculations on elastic scattering to obtain total cross sections by means of the optical theorem (Massey and Burhop 1969). Moreover, the semi-empirical total cross sections obtained by de Heer *et al* (1979) for noble gases in the energy range 20-3000 eV have been compared with the results of the present work in the overlapping region.

2. Experimental set-up

A sketch of the experimental arrangement is given in figure 1. The electron gun consists of a tungsten filament, an extractive electrode and collimating electrostatic lenses. The pressure in the gun was maintained lower than 10^{-6} Torr. The collision chamber was limited by two apertures of 2 mm diameter separated by a length L that was varied from 10 to 30 cm, according to the experimental requirements. The typical beam intensity in the scattering chamber was 10^{-9} A. The light intensity produced by the electron beam in the entrance of the collision chamber was measured by a photon counting method, using a filter monochromator with 50 Å resolution and a 56 AVP photomultiplier. These light intensity measurements were very useful for beam intensity normalisation as well as for pressure calibration checking.

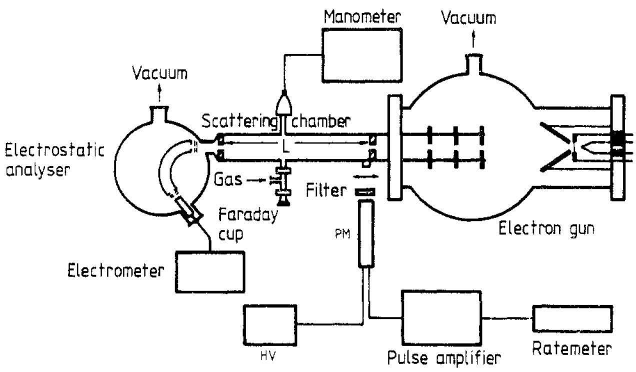

Figure 1. Schematic diagram of the experimental arrangement.

In order to discriminate the inelastically scattered electrons, a Comstock AC-901 double focusing electrostatic analyser was used. The entrance and exit apertures of the analyser consisted of 0.7 and 0.5 mm holes separated by 7 mm, providing an energy resolution of 0.4%. The transmitted electrons were collected on a Faraday cup and the intensity was measured with a Keithley 610C electrometer. The Faraday cup and the energy analyser were maintained at a pressure lower than 10^{-6} Torr.

3. Procedure

The method is based on the measurement of the electron beam attenuation in the scattering chamber. The attenuation follows the well known law

$$I = I_0 \exp(-NL\sigma_T)$$

where I_0 is the intensity of the primary electron beam, I is the attenuated beam intensity, N is the atomic density and σ_T is the total scattering cross section. N is obtained from the measurement of pressure and temperature in the gas cell. Special care was taken in the accurate determination of gas pressure, which in this work ranged between 1 and 30 mTorr. A Thermovac TM 202 thermal conductivity manometer, previously calibrated against a Kammerer mercury manometer, was used. It was ensured that pressure gradients did not contribute to the experimental errors by measuring the pressure at several points along the cell. In order to achieve good accuracy even at pressures below 10 mTorr, the dependence of the light intensity in the entrance of the scattering chamber on the gas pressure was studied. As mentioned above, a filter monochromator with 50 Å resolution was used to isolate non-self-absorbed lines (i.e. transitions in which the lower level has a very low population). For these spectral lines, resonant trapping is negligible; therefore the light intensity must be proportional to gas pressure. For high pressures (>10 mTorr) an excellent linear dependence of light intensity on calibrated pressure was found, as expected. An improvement in the calibration accuracy at lower pressures was achieved by linear extrapolation on the light intensity against pressure plot.

To measure accurately the attenuation of the electron beam it is necessary to discriminate the forward inelastically scattered electrons. As mentioned above, an energy analyser was used to eliminate the contribution from inelastic scattering. The energy spectrum of the electrons reaching the analyser was studied. A typical result for 4000 eV electrons on Kr is shown in figure 2. The full curve represents the energy spectrum in the absence of gas in the chamber. The broken curve shows the spectral shape when the gas pressure in the chamber is 10 mTorr. By subtracting the latter from the former the spectrum of electrons inelastically scattered in the forward direction is obtained (chain curve). As seen in figure 2, by biasing the energy analyser

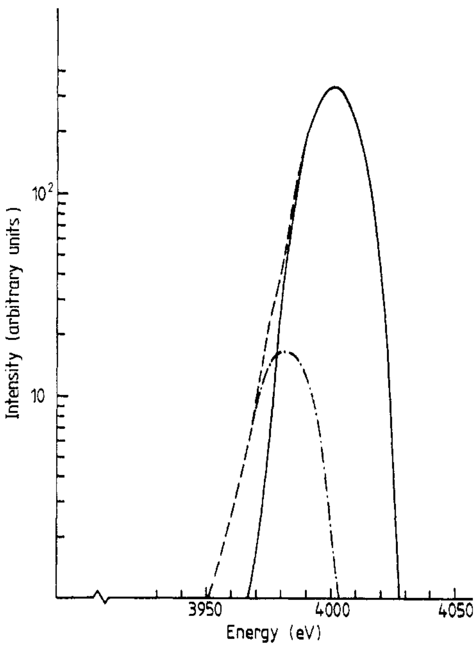

Figure 2. Logarithmic plot of the electron energy spectrum. ——, energy spectrum in the absence of gas in the chamber; - - -, energy spectrum with 10 mTorr of Kr in the chamber; - · -, energy spectrum of the electrons inelastically scattered in the forward direction.

appropriately on the high-energy side it was possible to carry out accurate measurements of electron beam attenuation without the aforementioned systematic error.

Elastically scattered electrons are not discriminated by the analyser. However, this error contribution can be neglected if a sufficiently low angular resolution is used. In the present work the solid angle subtended by the entrance aperture of the analyser as seen from the centre of the gas chamber was typically of the order of 10^{-5} sr. By extrapolating experimental (Jansen *et al* 1976, Jansen and de Heer 1976) and theoretical (McCarthy *et al* 1977) data on elastic differential cross sections for very low angles to 0°, it can be shown that under our experimental conditions the error due to forward elastic scattering is negligible compared with other experimental uncertainties.

A typical logarithmic plot of transmitted electron beam intensity against pressure is shown in figure 3. The experimental points lie on a straight line whose slope gives the total cross section. Measurements were performed for incident electron beam currents from 10^{-11} to 10^{-9} A. In this range, no dependence of total cross section upon current was found. In order to check that our measured length L corresponds to the actual absorption length, measurements of total cross section were carried out using several collision chamber lengths ranging from 10 to 30 cm. Cross section results were found to be independent of L.

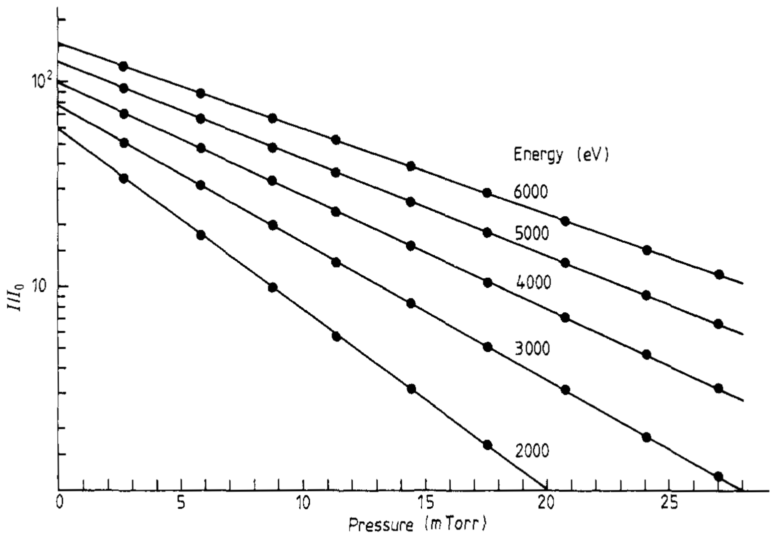

Figure 3. Electron beam intensity plotted against pressure of Kr for energies from 2000 to 6000 eV.

4. Results and discussion

Tables 1, 2 and 3 show the experimental results of total cross sections for electron scattering on Ne, Ar and Kr respectively in the impact energy 700–6000 eV. Estimated experimental errors are 6% and are mainly due to the uncertainty in the determination of the pressure.

Table 1. Total cross sections (in a_0^2) for electron–neon scattering.

	Experimental			Semi-empirical	Theoretical	
E (eV)	Present work	Wagenaar and de Heer (1980)	Kauppila *et al* (1981)	de Heer *et al* (1979)	Dewangan and Walters (1977)	Byron and Joachin (1977)
700	4.16	4.03	3.90	3.884	4.37	4.40
800	3.86					
900	3.47					
1000	3.28			2.941	3.39	
1200	2.80					
1500	2.39					
2000	1.89			1.778	2.00	
2500	1.53					
3000	1.33			1.297	1.43	
3500	1.14					
4000	1.07					
4500	0.96					
5000	0.83					
5500	0.76					
6000	0.73					

Table 2. Total cross sections (in a_0^2) for electron–argon scattering.

	Experimental				Semi-empirical	Theoretical Joachain *et al* (1977)	
E (eV)	Present work	Wagenaar and de Heer (1980)	Kauppila *et al* (1981)	Nogueira *et al* (1982)	de Heer *et al* (1979)	I	II
700	10.92	10.62	9.52	11.5		11.0	
800	10.18		8.98	10.8		10.1	10.0
900	9.29			10.1			
1000	8.61			9.50	7.96	8.64	8.65
1200	7.29			7.68			
1500	6.25			6.21			
2000	5.03			4.75	4.82		
2500	4.21			3.79			
3000	3.68			3.29	3.47		
3500	3.25						
4000	2.86						
4500	2.61						
5000	2.36						
5500	2.20						
6000	2.00						

Wagenaar and de Heer (1980) and Kauppila *et al* (1981) have carried out an extensive experimental investigation of total cross sections at impact energies lower than 800 eV. The results of these authors have been compared with those of the present work in the overlapping energy range. As seen from tables 1, 2 and 3, the measurements of Wagenaar and de Heer (1980) for Ne, Ar and Kr at 700 eV energy agree with ours. There is agreement with the results of Kauppila *et al* (1981), within the experimental

Table 3. Total cross sections (in a_0^2) for electron-krypton scattering.

	Experimental		
E (eV)	Present work	Wagenaar and de Heer (1980)	Semi-empirical de Heer *et al* (1979)
700	14.9	14.29	
800	14.0		
900	13.0		
1000	11.9		10.89
1200	10.6		
1500	9.46		
2000	8.18		6.828
2500	7.25		
3000	6.25		5.416
3500	5.75		
4000	5.21		
4500	4.82		
5000	4.39		
5500	4.18		
6000	3.89		

errors, on the value of the total cross section for Ne at 700 eV impact energy. However, their measurements for Ar at 700 and 800 eV are about 13% lower than our results.

Semi-empirical values obtained for energies below 3000 eV by de Heer *et al* (1979) has also been compared with our measurements. As can be seen from tables 1 and 2, semi-empirical cross sections for Ne and Ar are in good agreement with our results, but the present total cross sections for Kr (table 3) above 1000 eV are higher than the semi-empirical values. Nogueira *et al* (1982) have measured total cross sections on Ar in the energy range 500-3000 eV. In their experimental set-up the detector did not discriminate the small-angle inelastically scattered electrons. Nevertheless, they have corrected their experimental cross sections using theoretical Born-Bethe differential inelastic cross sections. These corrected values are also included in table 2 for comparison.

Experimental cross sections have, where possible, been compared with theoretical predictions. In the Born approximation the dependence of the elastic cross section σ_{el} on incident electron energy E_0 can be written as (Inokuti and McDowell 1974)

$$\frac{E_0}{R}\frac{\sigma_{el}}{a_0^2}=\pi\left(A+B\frac{R}{E_0}+\ldots\right) \tag{1}$$

where R is the Rydberg constant and a_0 the Bohr radius. Inokuti and McDowell (1974) have calculated the values of the constants A and B for Ne. On the other hand, the total cross section for inelastic scattering σ_{inel} is given, according to the Born-Bethe approximation, by (Inokuti 1971)

$$\frac{E_0}{R}\frac{\sigma_{inel}}{a_0^2}=4\pi\left[M_{tot}^2\ln\left(4C_{tot}\frac{E_0}{R}\right)+\gamma_{tot}\frac{R}{E_0}+\ldots\right] \tag{2}$$

where the constants M_{tot}^2, C_{tot} and γ_{tot} have been given for all atoms from H to Sr by Inokuti *et al* (1975, 1981). By adding equations (1) and (2), the total cross section for Ne in the Born-Bethe approximation has been obtained. In figure 4, $E_0\sigma_T R^{-1}a_0^{-2}$ is

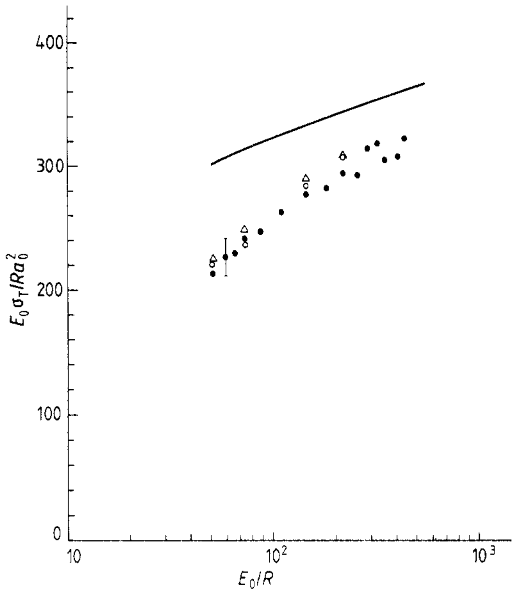

Figure 4. $E_0\sigma_T R^{-1}a_0^{-2}$ plotted against E_0R^{-1} for Ne. ——, Born σ_{el} plus Born–Bethe σ_{inel}; ○, semi-empirical σ_{el} (de Heer *et al* 1979) plus Born–Bethe σ_{inel}; △, DWSBA σ_{el} (Dewangan and Walters 1977) plus Born–Bethe σ_{inel}; ●, present work: the experimental errors are 6%.

plotted against $\ln(E_0R^{-1})$. As can be seen, the experimental values of this work give total cross sections lower than those deduced from the Born approximation. It has been pointed out (de Heer *et al* 1979) that the Born approximation overestimates the elastic cross sections even at 3000 eV impact energy, in agreement with the present result. Total cross sections (open triangles) obtained by adding theoretical values of σ_{el} calculated by means of the distorted-wave second Born approximation (DWSBA) (Dewangan and Walters 1977) and the Born–Bethe inelastic cross sections are also plotted in figure 4. The open circles represent total cross sections obtained by adding semi-empirical elastic cross sections of de Heer *et al* (1979) and the Born–Bethe inelastic cross sections. As can be seen from the figure, both results are in agreement with the experimental cross sections of this work in the overlapping region.

Similarly, our experimental results are compared in figures 5 and 6 with total cross sections obtained using the Born–Bethe values of σ_{inel} and the semi-empirical elastic cross sections (de Heer *et al* 1979). In addition, σ_T values obtained by adding the Born–Bethe σ_{inel} and the results of σ_{el} calculated by means of the optical model for Ar (Joachain *et al* 1977) and by the static potential for Kr (Fink and Yates 1970) are plotted in these figures. As figures 5 and 6 show, if one takes into account the experimental errors the measurements of the present work agree with total cross sections based on the Born-Bethe approximation for σ_{inel}.

On the other hand, the agreement between the present measurements and the total cross sections obtained by applying the optical theorem on calculations of elastic scattering is significant. The theoretical total cross sections obtained by Dewangan and Walters (1977) for Ne using the DWSBA (distorted-wave second Born approximation) method, shown in table 1, agree with the present experimental results. The calculation at 700 eV of Byron and Joachain (1977), based on the optical model, is also in agreement. Joachain *et al* (1977) have carried out calculations for Ar over the energy range 100–1000 eV by employing two optical model methods (labelled by them as methods I and II). As can be seen from table 2, the agreement with the measurements of the present work is excellent.

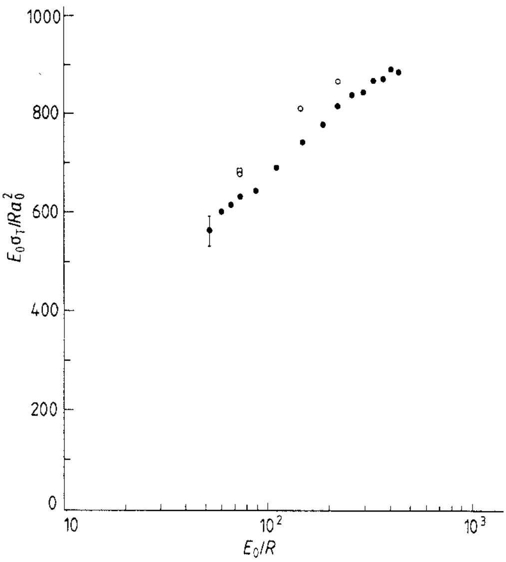

Figure 5. As figure 4 but for Ar. □, optical model σ_{el} (Joachain *et al* 1977) plus Born-Bethe σ_{inel}; other symbols as in figure 4.

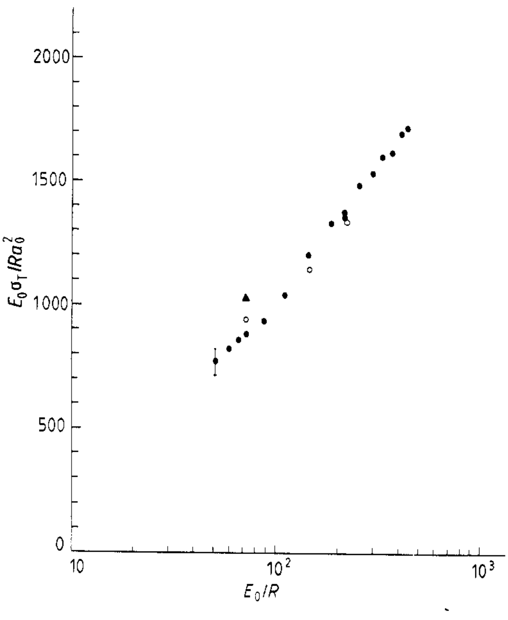

Figure 6. As figure 4 but for Kr. ▲, static-potential σ_{el} (Fink and Yates 1970) plus Born-Bethe σ_{inel}; other symbols as in figure 4.

In summary, total cross sections for electron scattering by Ne, Ar and Kr have been measured over the energy range 700-6000 eV. Measurements obtained for energies below 3000 eV are in general in good agreement with previous experimental and semi-empirical results. Total cross sections obtained by adding Born-Bethe values for σ_{inel} and elaborate determinations of σ_{el} give account of the present experimental results. Independent calculations based on the optical theorem are also in agreement with our measurements. Nevertheless, accurate experimental and theoretical data over a broader range for σ_{el} would be very useful for obtaining inelastic cross sections from the total ones, allowing comparison with the corresponding Born–Bethe values. Likewise, optical theorem calculations of total cross sections at higher energies are necessary.

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