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Total cross sections for electron scattering from Ne, Ar, Kr and Xe

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Abstract. Total cross sections have been measured for electron scattering on Ne, Ar, Kr and Xe in the impact energy range between 25 and 750 eV. The method used has been introduced by Blaauw *et al* for the same measurement with He and N_2 as targets. It is a linearisation of the Ramsauer-type experiment, which enables good angular and energy resolution; the accuracy in the total cross sections obtained is better than 5%. Substantial differences are found with experimental data of other groups, which can often be attributed to shortcomings in their experimental set-up. The best agreement is obtained with the recent data of Kauppila, Stein and co-workers. Above 100 eV our Ne and Ar data can be compared with theoretical calculations, of which the optical model results of Joachain *et al* rapidly converge to the present ones. Good agreement is also found with the semi-empirical total cross sections of de Heer *et al.*

1. Introduction

Recently Blaauw *et al* (1980, to be referred as I) have reported their total cross section measurements for electrons incident on He and N_2. The present article describes the continuation of this work for other targets, namely Ne, Ar, Kr and Xe. Our results for these targets have previously been published in a FOM-report (Wagenaar 1978) and by Blaauw (1979), but those data are superseded by the present ones, which are two percent higher at most. This is due to a new evaluation of the gas pressure measurement, as discussed in I and indicated in § 2.

We shall only give a brief description of our experimental set-up which has already been discussed elsewhere (an extensive account is given in Blaauw (1979), see also I and Wagenaar (1978)). Our method is basically a linearisation of the Ramsauer (1921) technique, without the use of a magnetic field. An electron gun produces a highly parallel beam with impact energies variable between 25 and 750 eV and a thermal energy spread of 0·4 eV. This beam is led through a collision chamber of length 42 mm and diameter 80 mm, having entrance and exit orifices of 1 mm diameter. The detection takes place in a retarding field analyser (RFA, aperture 1 mm internal diameter) at 100 mm behind the centre of the collision chamber or by a Faraday cup (FC2, aperture 8 mm internal diameter) just in front of this analyser. This corresponds to solid angles of $7{\cdot}85\times10^{-5}$ sr and $7{\cdot}5\times10^{-3}$ sr respectively, with respect to the centre of the collision chamber. To control the variation of the electron beam properties during the measurements another Faraday cup can be moved downwards just in front of the collision chamber, intercepting the primary beam.

The experimental procedure is based on the relation between the beam attenuation and the total cross section σ_{tot}, which is given by

$$I_2/I_1 = \exp\left(-NL\sigma_{tot} + N(l\Delta\Omega)_{eff}\frac{d\sigma}{d\Omega}(\theta = 0)\right). \quad (1)$$

Here I_2/I_1 is the ratio of the beam intensities in the collectors behind and in front of the collision chamber. On the right-hand side of equation (1) we have the usual Lambert–Beer law, supplemented with a second term to correct for small-angle scattering into the collector (RFA or FC2). L is the length over which absorption takes place and N is the corresponding gas density. The total cross section is represented by σ_{tot}, whereas $d\sigma(\theta = 0)/d\Omega$ refers to elastic scattering into the solid angle of the RFA or to inelastic plus elastic scattering into the solid angle of FC2. The second term contains the effective product $(l\Delta\Omega)_{eff}$, which is the value of the integral:

$$(l\Delta\Omega)_{eff} = \int_0^L dx\ \Omega(x) \quad (2)$$

where $\Omega(x)$ is the solid angle subtended by the detector as seen by a scattering event taking place at position x on the beam axis.

In many previous experiments, as reviewed by Bederson and Kieffer (1971), lack of sufficient attention to angular resolution has led to signals in the detector which were too large, in particular at the higher impact energies where the scattering is peaked more in the forward direction. This resulted in total cross sections which were too low. Therefore it is important to repeat these measurements under better experimental conditions. Such improvements are present in our work, that of Kauppila *et al* (1977), of Kennerly and Bonham (1978) and of Dalba *et al* (1979). Up till now of these groups only Kauppila co-workers (see also Dababneh *et al* 1980) have obtained data for Ne, Ar, Kr and Xe.

2. Experimental procedure

Referring to equation (1), the reliability of our experimental procedure is determined by the accuracy with which L and N are known and also by how small the correction term can be kept relative to the first absorption term.

By comparing absorption measurements performed with two different collision chamber lengths, we could not detect a significant deviation of the absorption length L from the geometrical length of the collision chamber due to a possible streaming out effect of the gas. The largest difference between corresponding measurements with the two cells was found to be 0·5%, which we assign as the (pessimistic) error estimation for L (see I, § 3.1).

The gas density in equation (1) has been derived from the measurement of the gas pressure by means of a baratron manometer, which was kept at an elevated temperature of 322 K. Consequently by thermal transpiration there exists a small pressure drop over the tube which connects the baratron with the collision chamber at low pressures. Following the suggestion of Edmonds and Hobson (1965), that the magnitude of this drop can be dependent on the particular experimental arrangement, we measured this effect for the various gases under study (see I, § 3.1). For typical pressures in the range we have measured, i.e. from 0·1 to 1·5 Pa, the pressure in the baratron sensing head appeared to be 2% higher than the actual pressure in the collision cell. This value is significantly smaller than the Knudsen limit (which amounts in this case 4%), but is certainly not negligible. This is the reason why the present data are 2% higher than those given by Wagenaar (1978) and Blaauw (1979), where we neglected the thermal transpiration correction.

The second term in the exponent on the right-hand side of equation (1) is related to forward elastic and inelastic scattering as explained in § 1 and has to be kept small with respect to the first term in the exponent. For intermediate and high electron energies (i.e. $\geqslant 35$ eV) we used the retarding field analyser with its small solid angle; at low energies (i.e. $\leqslant 40$ eV) FC2 was used with its relatively large solid angle, because under vacuum conditions in the collision chamber we were not able to tune the primary beam completely into the 1 mm internal diameter entrance aperture of the analyser at these energies. Fortunately, the scattering pattern turns out to be such that in both modes of operation the second term is relatively small. In the case of measurements with the RFA at high energies, this can be demonstrated with a qualitative estimate of the magnitude of the correction term using data on the elastic differential cross section $(\mathrm{d}\sigma/\mathrm{d}\Omega)_{\mathrm{el}}$. These cross sections at zero angle can be obtained by extrapolating the optical model calculations of Joachain *et al* (1977) and of McCarthy *et al* (1977). The results of this procedure in the case of argon are given in table 1, where we derive a maximum relative contribution of 0·05%. However, at lower energies such an estimate is very difficult to perform, especially for small-angle inelastic scattering, so the magnitude of the correction term in the case of measurements with FC2 as the detector had to be investigated experimentally. Over a suitable energy range we measured the attenuated beam intensity at each data point with the RFA as well as with FC2. It was shown that both modes yielded the same results within the statistical errors of 1% for all the noble gases under study when $E \leqslant 35$ eV. Consequently, below this energy we may safely neglect the correction term even if we use FC2.

The energy of the electron beam was calibrated (see I) by measuring the position of the 19·3 eV resonance in electron–helium scattering.

The independence of σ_{tot} of the gas pressure and beam current was established.

Table 1. The energy dependence of the correction term with the RFA for Ar.

Energy (eV)	σ_{tot}† (a_0^2)	$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}(\theta \simeq 0)_{\mathrm{elastic}}$ (a_0^2 sr^{-1})	Correction (relative) $\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\Delta\Omega/\sigma_{\mathrm{tot}}$ (%)
100	29·6	≃90	0·02
200	21·3	≃85	0·03
300	17·5	≃80	0·04
400	14·9	≃75	0·05

† See table 4.

3. Error discussion

The measurements are subject to the same error sources as mentioned in I. We therefore confine ourselves here with presenting a table in which the errors are summarised as a function of impact energy for each gas separately (see table 2).

Table 2. Survey of the experimental errors

Gas	Energy (eV)	Statistical errors	Systematical errors a	b	c	d	Total error
Neon	⩽100	1·0	0·5	1·0	0·7	0·2	3·4
	⩾100	1·0		0·5	1·5	0·0	3·5
Argon	⩽100	1·0	0·5	2·5	0·4	0·5	4·9
	⩾100	1·0		1·5	1·0	0·3	4·3
Krypton	⩽100	1·0	0.5	2·5	0·4	0·4	4·8
	⩾100	1·0		1·5	1·0	0·3	4·3
Xenon	⩽100	1·0	0·5	2·5	0·4	0·5	4·9
	⩾100	1·0		2·0	0·8	0·0	4·3

[a] From the uncertainty of the absorption length.
[b] From the uncertainty of the calibration of the manometer.
[c] From the uncertainty of the linearity of the current meter.
[d] From the uncertainty of the energy definition.
All errors are percentage errors.

4. Results and discussion

4.1. General

In this section we compare our results of total cross section measurements with those of other groups. Except Kauppila *et al* (1977, 1980), all the experimental groups used the Ramsauer technique where the electron beam is energy selected with the aid of a magnetic field perpendicular to the orbit plane. However, it is difficult to control the spatial extension of the electron beam in such an arrangement, so that an unknown fraction of scattered particles may be registered in the detector (see the considerations of Bederson and Kieffer (1971)). Especially at high impact energies this 'scattering-in' effect can cause a considerable reduction in the measured total cross section. It has been noted (Brüche 1927) that Brode's (1925) modification of the Ramsauer apparatus even leads to an amplification of this effect. Kauppila *et al* (1977) removed this basic shortcoming for the greater part by introducing a curved magnetic field parallel (instead of perpendicular) to the electron orbit as a coarse energy selector together with a retarding field element in front of their channeltron. In this way they discriminated against all inelastically scattered electrons, but the 'scattering-in' contribution of electrons which were elastically scattered over small angles could not be completely eliminated. A useful feature of their well defined experimental parameters is that it enabled them to assess the magnitude of this effect in their final results.

Further comparison of our data is possible with the semi-empirical ones of de Heer *et al* (1979) which were obtained by summation of (mostly experimental) cross sections for elastic scattering, ionisation and excitation.

As far as theory is concerned, comparison is made with the optical model (OM) calculations of Byron and Joachain (1977) and of Joachain *et al* (1977) for Ne and Ar respectively. For Ne we also consider the first Born results of Inokuti and McDowell (1974), obtained by the addition of elastic and inelastic cross sections, and the distorted-wave second Born approximation (DWSBA) calculations of Dewangen and Walters (1977).

The data for the different noble-gas atoms are presented in tables 3–5 and figures 1–4 of the next sections.

4.2. e^-–Ne

Comparing our results in table 3 and figure 1 with those of other experiments, large deviations are found from the old data of Ramsauer (1921), Brüche *et al* (1927) and

Table 3. Total cross sections for electron–neon scattering in units of a_0^2.

	Experiment						Semi-empirical	Theory		
								First Born	DWSBA	OM
E(eV)	This work	K	SN	N	Bru	R	H	IMcD	DW	BJ
20			12·91		12·26	12·8	12·30			
22·5	13·62	13·2			11·77					
25	13·70			11·6	12·48	13·2				
27·5	13·73				12·31					
30	13·72	13·3		11·9	12·29	12·4	12·07			
35	13·62			11·7	12·23					
40	13·44			11·5	11·16	10·5	12·06			
45	13·25			11·4	11·06					
50	13·06	12·7		11·2		11·6	12·67			
55	12·92			11·0						
60	12·73			10·7			12·64			
65	12·52									
70	12·32			10·2			12·52			
75	12·12	11·7								
80	11·90			9·9			12·28			
90	11·47			9·6			12·00			
100	11·03	10·6		9·4			11·66	29·5		14·2
125	10·17									
150	9·50	9·02		8·0			9·25			
175	8·94									
200	8·45	7·98		7·0			7·98	16·8	9·77	9·64
250	7·56									
300	6·80	6·38		5·4			6·62	11·9	7·63	7·53
350	6·23									
400	5·76	5·47		4·5			5·51	9·27	6·35	6·29
450	5·36									
500	5·02	4·78					4·77	7·57	5·47	5·45
550	4·67									
600	4·42	4·27								
650	4·20									
700	4·03	3·90					3·88	5·66	4·37	4·40
750	3·86									

K, Kauppila *et al* (1980).
SN, Salop and Nakano (1970).
N, Normand (1930).
Bru, Brüche (1927).
R, Ramsauer (1921).
H, de Heer *et al* (1979).
IMcD, Inokuti and McDowell (1974).
DW, Dewangen and Walters (1977).
BJ, Byron and Joachain (1977).

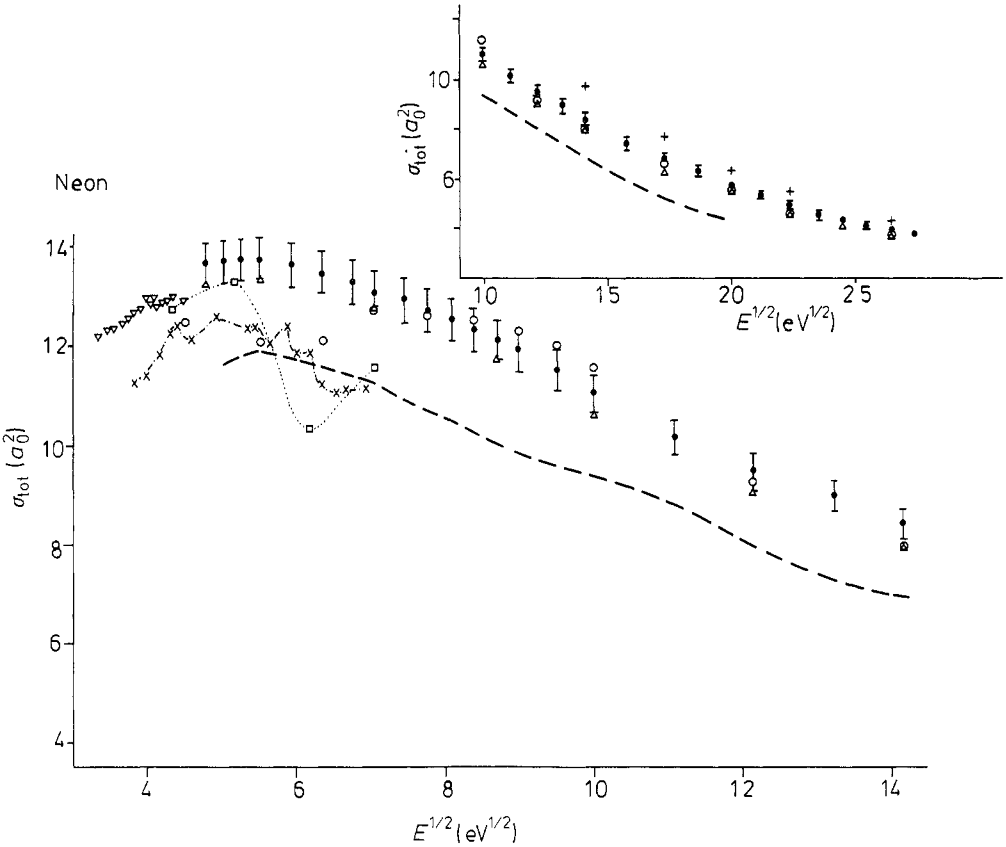

Figure 1. Total cross section for electron–neon scattering. ⧲, this experiment; △, Kauppila *et al* (1980); ○, semi-empirical, de Heer *et al* (1979); ▽, Salop and Nakano (1970); – – –, Normand (1930); ×–·–×, Brüche (1927); ···□····, Ramsauer (1921); +, DWSBA, Dewangen and Walters (1977); OM, Byron and Joachain (1977).

Normand (1930). These all indicate bad screening against small-angle scattering. A good fit to the low-energy data of Salop and Nakano (1970) confirms the reliability of their carefully modified Ramsauer-type apparatus. The data of Kauppila *et al* (1980) are slightly lower than ours, with an average of 3% below 100 eV and of 5% above 100 eV. As mentioned earlier, the cause of this deviation must be found in their incomplete screening against elastically scattered electrons. From the ratio of the magnetic field strengths in and behind the scattering chamber and the condition of 80% transmission of their retarding field, Kauppila *et al* (1980) calculated the maximum angle over which electrons could be scattered elastically and still be collected in the channeltron cone to be 7°. Using the optical model (OM) calculations of Byron and Joachain (1977) for the differential elastic cross sections, they estimated their measured total cross sections to be an average of 5% too low in the energy range from 100 to 500 eV. It will be clear that this correction makes their data agree with ours perfectly.

With respect to theory we see that the first Born approximation does not yet hold in our energy range. Although the DWSBA and OM results are almost equal to each other, they are still too large with respect to the experimental data.

4.3. e^-–Ar

The results are given in table 4 and figure 2. All the experiments, except that of Aberth *et al* (1964), have yielded systematically lower values. At the lower energies ($\leqslant 30$ eV) the data of Kauppila *et al* (1980), Ramsauer (1921, 1923) and Brüche *et al* (1927) come close to each other, whereas a rather large deviation (up to 19% at 20 eV) is found with

Table 4. Total cross sections for electron–argon scattering in units of a_0^2.

	Experiment									Semi-empirical	Theory	
											J	
E(eV)	This work	K	GB	A	N	Bru	Bro	R (1923)	R (1921)	H	I	II
15	82·76	77·0	68·06	98·0		73·14		78·67	77·87			
17·5	79·42		60·60			64·64		71·35	73·13			
20	73·70	61·9	50·06	83·5	48·7	59·68	35·5	63·02	66·82	78·27		
22·5	67·02				46·6	52·47	34·3					
25	60·52			78·5	44·4	49·09	33·0	47·71	48·82			
27·5	54·95					47·31						
30	50·72	46·2			38·6	45·26	28·6	41·82	44·13	58·32		
35	46·41				35·8	40·22	26·6	37·61	42·72			
40	53·40				32·8	36·35	25·3			45·57		
45	39·92				31·0	34·84	23·7					
50	37·30	35·5			28·7		21·9			39·82		
55	35·53				28·3		20·8					
60	34·55				27·7		19·7	23·45		36·60		
65	34·10											
70	33·23				24·2		18·3			34·66		
75	32·49	29·9										
80	31·80				24·2		17·6			32·15		
90	30·62				23·2		17·0			30·49		
100	29·60	27·4			22·7		16·2	18·03		29·56	31·5	33·3
125	27·35				18·9		14·6					
150	25·13	22·7			18·1		12·6			24·75		
175	23·03				16·6		11·1					
200	21·33	20·0			16·1		9·7			21·36	22·6	23·0
250	18·92				14·4		7·9					
300	17·47	16·4			12·9		6·7			16·81	18·3	18·2
350	16·09				12·1							
400	14·91	13·7			10·9					14·27	15·6	15·4
450	13·92											
500	13·08	11·7								12·51	13·7	13·4
550	12·35											
600	11·71	10·5										
650	11·15											
700	10·62	9·52										
750	10·13											

Symbols have the same meaning as in table 3, in addition:
GB, Golden and Bandel (1966).
A, Aberth *et al* (1964).
Bro, Brode (1925).
R, Ramsauer (1921, 1923).
J, Joachin *et al* (1977), optical model.

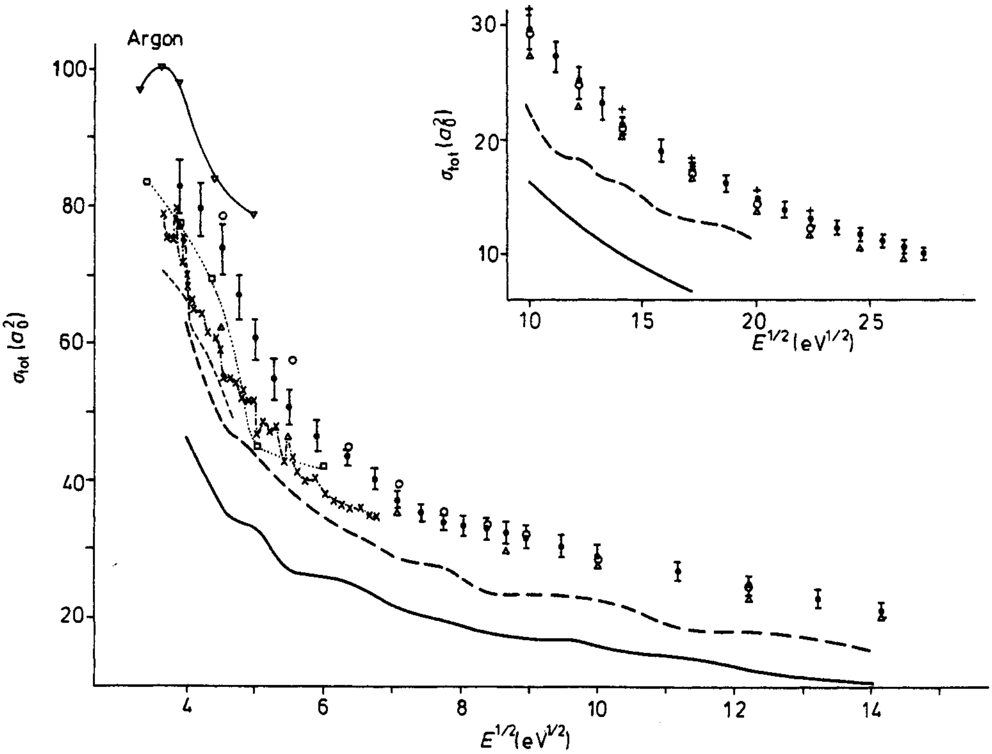

Figure 2. Total cross section for electron–argon scattering. Φ, this experiment; $\triangle$, Kauppila *et al* (1980); $\bigcirc$, semi-empirical, de Heer *et al* (1979); – – –, Golden and Bandel (1966); ∇, Aberth *et al* (1964); – – –, Normand (1930); × – · – ×, Brüche (1927); ———, Brode (1925); · · · $\square$ · · ·, Ramsauer (1921); +, OM, Joachain *et al* (1977).

our results. With increasing impact energy this deviation from Kauppila *et al* (1980) becomes smaller, reaches a minimum of 6% near 50 eV, but becomes systematically larger again (up to 12%) at the higher impact energies. Accounting for the 'scattering-in' contribution, which Kauppila *et al* (1980) estimate (using the same procedure as sketched in § 4.2) to be about 9% between 100 and 800 eV, brings their data into good agreement with ours in the high-energy range. The remark of Aberth *et al* (1964) that in their crossed-beam recoil experiment electrons can be reflected back into the scattering region, causing their data to be 10–20% too high, is confirmed by our measurements. Above 75 eV the semi-empirical data of de Heer *et al* (1979) are in good agreement with ours, better than 5%, but at low energies ($\leqslant$50 eV) the difference is larger.

The OM cross sections of Joachain *et al* (1977), as far as series I is concerned, come close to our data.

4.4. e^-–Kr and e^-–Xe

For electrons incident on Kr and Xe our total cross sections are in reasonable agreement with the semi-empirical data of de Heer *et al* (1979) above 100 eV. For Kr the difference varies from 2% at 100 eV to 7% at 500 eV, whereas for Xe it goes from 14%

Table 5. Total cross sections for electron–krypton and electron–xenon scattering in units of a_0^2.

	Kr				Xe			
	Experiment			Semi-empirical	Experiment			Semi-empirical
E(eV)	This work	D	R	H	This work	D	R	H
15		91·9	94·2			126·8	109	
17·5		86·8	87·4		137·3	123·9		
20		81·1	80·4	78·57	133·0	119·6		110·2
22·5	87·16	75·6			123·5	110·9		
25	81·28	71·8			110·1	96·1	74·3	
27·5	76·50	68·47			94·73	81·5		
30	72·63	66·70	54·5	62·22	79·85	71·99	114·3	
35	66·94	61·36	49·3		64·95	59·81		
40	62·99	58·85		53·28	58·62	53·45		
45	59·90	53·96			55·64	50·74		
50	56·71	53·03		48·72	53·10	46·81		
55	54·27				50·27			
60	52·33				48·25		34·0	36·85
65	50·56		29·0		46·90			
70	48·76				46·19			
75	46·85				45·92			
80	45·04				45·63			
85	43·39				45·15			
90	41·83				44·63			
95	40·38				44·07			
100	39·04	37·02	22·2	38·25	43·51			38·10
125	33·92				41·44			
150	30·68			31·01	39·40			35·51
175	28·88				37·61			
200	27·68			26·06	36·02			34·24
250	25·32				33·27			
300	22·81			21·77	30·95			27·80
350	20·80				28·93			
400	19·25			18·69	27·32			25·56
450	18·12				25·83			
500	17·12			16·06	24·53			22·36
550	16·26				23·40			
600	15·54				22·38			
650	14·90				21·45			
700	14·29				20·56			18·40
750	13·67				19·68			

Symbols have the same meaning as in tables 3 and 4, in addition:
D, Dababneh *et al* (1980).
R, Ramsauer (1923).

at 100 eV down to 10% at 500 eV; at lower energies these differences are larger. As suggested by de Heer *et al* (1979), it would be useful to have a second set of experimental data to compare with in the energy range from about 20 to 100 eV. Dababneh *et al* (1980) extended the work of Kauppila *et al* (1978, 1980) on total

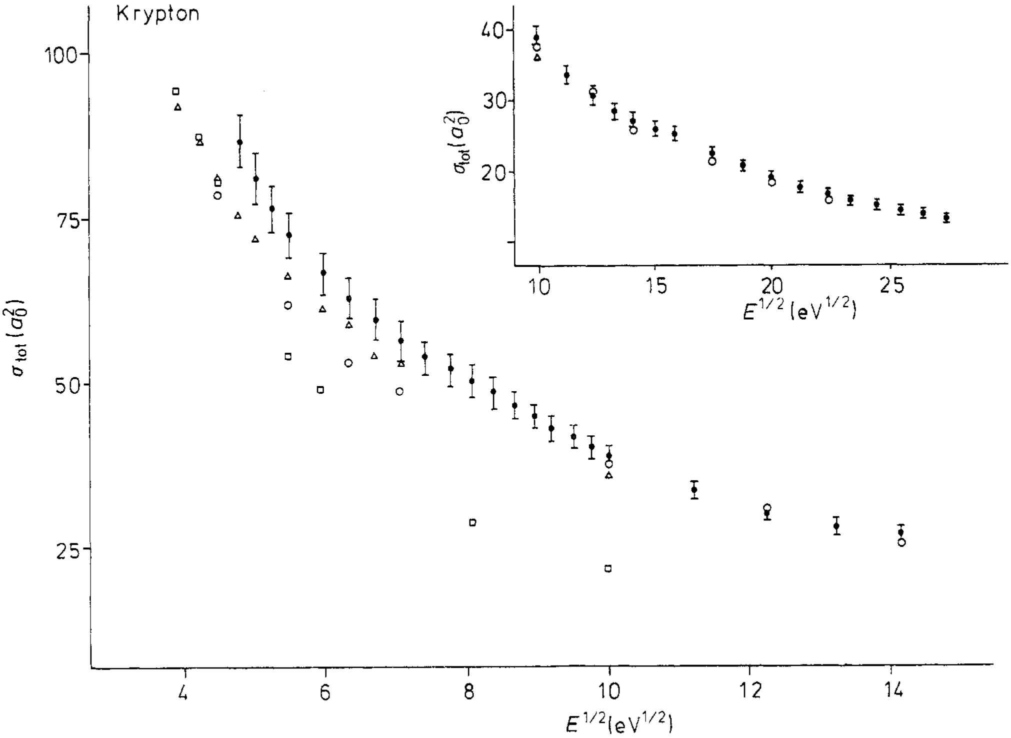

Figure 3. Total cross section of electron–krypton scattering. ⧳, this experiment; △, Dababneh *et al* (1980); ○, semi-empirical, de Heer *et al* (1979); □, Ramsauer (1923).

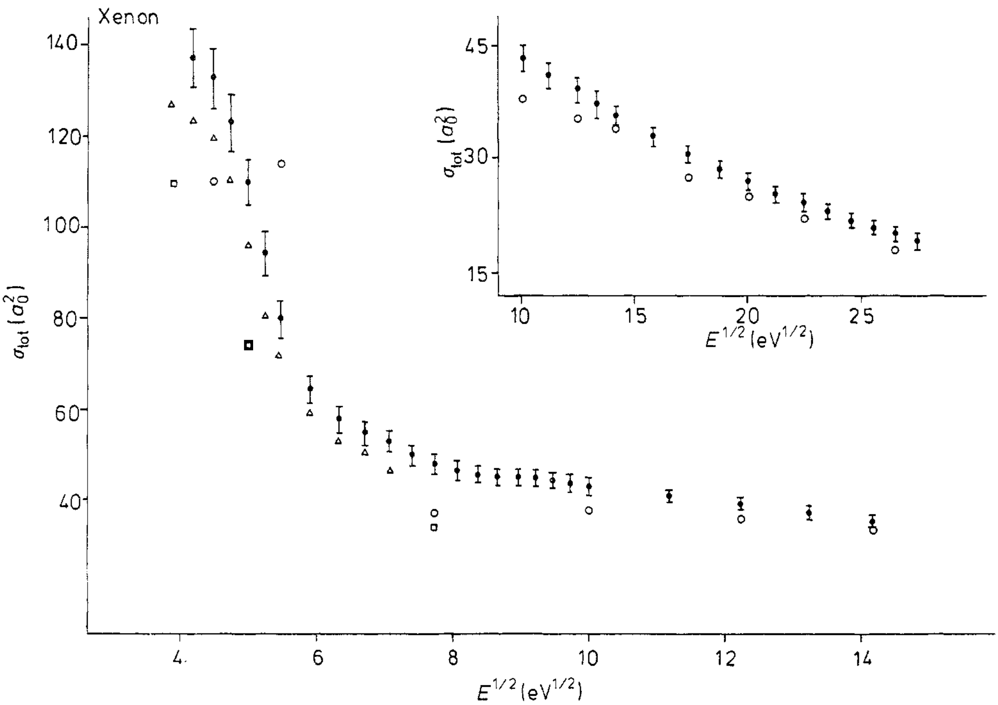

Figure 4. Total cross section of electron–xenon scattering. ⧳, this experiment; △, Dababneh *et al* (1980); ○, semi-empirical, de Heer *et al* (1979); □, Ramsauer (1923).

scattering of positrons and electrons to Kr and Xe in the low- and intermediate-energy ranges (i.e. from 0·35–100 eV and from 0·35–50 eV for Kr and Xe respectively). They adjusted the electron beam transmission in such a way that discrimination against all elastically scattered electrons over angles larger than 5° was established. Comparison with our data shows that their results are lower everywhere, for Kr 15% at 22·5 eV to 7% at 50 eV, whereas for Xe the differences have a nearly constant value of 12%. The energy range over which they measured is too small to reveal a systematically increasing deviation at high energies between the two data series due to an incomplete screening against small-angle scattering. However, even in this intermediate-energy range Dababneh *et al* (1980) could estimate with the OM calculations of McCarthy *et al* (1977) that their Kr results are too small by 2% at 20 eV to about 7% at 100 eV and their Xe results by 3% at 20 eV to about 5% at 50 eV. Correcting for this effect makes their Kr data agree very well with ours at higher energies, but in the case of Xe a substantial difference of about 8% remains. For the large difference at low energies between the two Kr data sets we could not find a satisfactory explanation. In this case it is worth mentioning that the data of Dababneh *et al* (1980) are closer to the semi-empirical ones of de Heer *et al* (1979) than our present data and also close to Ramsauer (1923) at the lowest energies. This would suggest that our data are somewhat too high at low energies ($\leqslant$50 eV).

5. Conclusions

Total cross section measurements have been presented for electron scattering from Ne, Ar, Kr and Xe, claiming an accuracy better than 5%, performed under very well defined conditions of angular and energy resolution. For all four gases our apparatus yielded systematically higher data than previous results; the explanation must be found in a more complete compensation for forward scattering in our set-up than achieved by others. Indeed, good agreement is found with the recent data of Kauppila and co-workers if their suggested correction for this effect is taken into account. The semi-empirical data of de Heer *et al* (1979) agree, in general, with ours within the combined error limits. Only in the case of Kr and Xe at low energies (i.e. $\leqslant$50 eV) our data shows a substantially larger deviation from de Heer *et al* and Dababneh *et al* than expected from the forward scattering contribution and admitted by the combined errors.

In the case of Ar there is good agreement with the optical model calculations of Joachain *et al* (1977). For Ne both the optical model cross sections of Byron and Joachain (1977) and the second Born distorted-wave cross sections of Dewangen and Walters (1977) converge to our experimental data near 500 eV.

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