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Absolute total cross section measurements for intermediate energy electron scattering II. N_2, O_2 and NO†

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Abstract. Total absolute cross section measurements are presented for electrons scattered by O_2, N_2 and NO molecules. The energy range covered spans from 100 to 1600 eV. Neglecting the systematic error introduced by the finite angular resolution of the apparatus, the experimental accuracy has been estimated to be $\pm 2{\cdot}5\%$. This systematic effect could necessitate an upward correction of as much as 13% at 1000 eV in N_2. No similar evaluation was possible for O_2 and NO. A comparison is given for N_2 with existing measurements. The agreement is reasonable. The results for O_2 are compatible with the existing data in the low-energy range. No comparison was possible for NO.

1. Introduction

This work is part of a research programme which aims to measure total absolute cross sections for electron scattering on atoms and molecules. Two different sets of apparatus are used in the 0·2 to 100 eV and 100 to 1600 eV energy ranges.

The need for such measurements was stressed by several authors (Bederson and Kieffer 1971, Burke and Williams 1977, Golden *et al* 1971) both in connection with application problems (plasma physics, data collection for fusion research) and with the progress of theoretical calculations of total and differential, elastic and inelastic cross sections. In addition, cross section data for N_2 and O_2 can be useful in the study of some atmospheric phenomena such as the aurora and the airglow (Phelps 1972).

In a preceding paper (Dalba *et al* 1979), cross section data for e^-–He scattering in the 100 to 1600 eV energy range were presented. Those results are in satisfactory agreement with the latest measurements (Jost and Möllenkamp 1977, Blaauw *et al* 1980) in the range of overlap (100 to 750 eV): the discrepancies are within the combined experimental error.

The authors consider the He measurements to be a reliability test for their apparatus, the most probable source of discrepancy with other measurements possibly being the lack of congruence of the capacitive manometers calibration.

Finally, it is possible that the measurements of Dalba *et al* (1979) are affected at the higher energies by an error due to the finite angular resolution of the apparatus. It was not possible to evaluate this error because of the lack of experimental and theoretical differential electron–helium cross section data in this energy range.

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For the three gases of the present work, a number of elastic (Bromberg 1970, 1974, Jansen *et al* 1976, Dubois and Rudd 1976) and inelastic cross section measurements (Rapp and Englander Golden 1965, Wakiya 1978) exist.

Total cross section measurements exist only for N_2 in the energy range below 750 eV (Blaauw *et al* 1977, 1980). Differential measurements for N_2 were published by Peixoto and Nogueira (1976) at 500 and 1000 eV.

2. Experimental procedure

In this work an attenuation technique has been used in which both the current of the electrons transmitted through the gas (I_c) and the current of the electrons scattered into the 'gas chamber' (I_s) were measured.

The apparatus has a Ramsauer-type configuration and has been described elsewhere (Dalba *et al* 1979); we only recall here that the radius of the electron orbit is 200 mm, the length of the gas chamber is 147·7 mm, the angular resolution of the apparatus (as defined by Kusch 1964) is 0·7° and the energy resolution is $E/\Delta E \simeq 100$.

A single measurement run, at a fixed energy, consisted of measuring five to eight different values of gas pressure and the corresponding pairs of current I_c and I_s.

The experimental cross section was evaluated from the formula

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

where l is the gas chamber length, N is the gas density, obtained from the pressure and temperature measurements, and the indices i, j label the values corresponding to two contiguous pressures. With n pressures, $(n-1)$ values of the cross section were computed for a single run. The average of these $(n-1)$ values was assumed to be the best determination of the cross section for that run.

The pressure in the gas chamber was changed by a factor of 10 in a single run. Typical values ranging from 1×10^{-4} to 1×10^{-2} Torr were used in different runs. The maximum pressure was chosen so as to maintain the beam attenuation ratio $(I_{c,max}/I_{c,min})$ below 2·5, in order to keep the probability of double scattering events very low.

The cross section data presented in this work are average values over a number of runs varying from two to four. The standard deviations of these averages are about 1·5% for N_2, 2% for O_2 and 2·5% for NO. These figures are to be considered as the random uncertainties of our measurements (the error on relative measurements). The differences between these three figures reflect the consequences that the different activity of the three gases on the cathode has on the measurement performance.

Differential pumping in the selection region and the use of a diverter valve (Basta *et al* 1976) to keep the background pressure of the target gas constant proved to be indispensable tools for these gases.

3. Accuracy evaluation

The main sources of systematic error have been examined in detail in a previous paper (Dalba *et al* 1979); since that analysis was independent of the type of target gas, we shall summarise the main results here.

The accuracy on the pressure measurements is of fundamental importance: the error on the cross section is due mainly to the calibration of the instrument (an MKS Baratron capacitance meter, type 94 AH-1). Because of the larger cross section of these gases, smaller pressures were used than in the measurements on helium. The accuracy claimed by the manometer manufacturer is still better than 1% at the lowest pressure used. Nevertheless, at these pressures the zero drift of the manometer is more important. The authors believe that a ±1·5% figure can be assumed as a realistic estimate of the pressure measurement accuracy.

Table 1. Total scattering cross sections (in units of a_0^2).

		N_2		O_2	NO
$\sqrt{E}$	E(eV)	Present	Blaauw *et al* (1980)	Present	Blaauw *et al* (1980)
10	100		32·07	30·63	
11	121	32·08		28·53	30·25
	125		29·16		
12	144	29·35		26·93	29·34
	150		26·74		
13	169			25·05	25·81
	175		24·69		
14	196	24·90		22·77	23·99
	200		22·92		
15	225		21·38	21·22	21·77
	250		20·22		
16	256	20·93		19·68	20·81
	275		19·10		
17	289			18·36	18·89
	300		18·14		
18	324	18·22		17·36	18·22
	325		17·30		
	350		16·53		
19	361			16·04	
	375		15·86		
20	400	15·78	15·25	15·05	15·19
	450		14·15		
22	484	13·65		13·15	13·51
	500		13·19		
	550		12·26		
24	576	12·12		11·72	12·04
	600		11·39		
	650		10·60		
26	676	10·67		10·32	10·33
	700		9·89		
	750		9·37		
28	784	9·35		9·21	9·47
30	900	8·32		8·34	8·35
32	1024	7·57		7·44	7·57
34	1156	6·81		6·76	6·88
36	1296	6·15		6·12	6·03
38	1444	5·58		5·55	5·63
40	1600	5·06		5·11	

Care was taken to have the capacitance head temperature tracking the gas chamber temperature in order to reduce thermal transpiration. Good accuracy is also necessary in the measurement of the interaction length: by means of a direct measurement with helium (Dalba *et al* 1979), it has been possible to establish that the influence of the end effects on the cross section does not exceed the statistical uncertainty of those measurements, namely 1·5%.

The geometrical spread of the electron trajectories and the measurement error of the gas chamber length cause uncertainties in the cross section of the order of 0·4% and 0·2%, respectively. The error in the cross section due to the non-linearity of the electrometer measuring the currents I_c and I_s has been evaluated to be 0·6%.

The errors in the measurements of temperature and accelerating voltage affect the cross section with uncertainties of 0·3 and 0·2%, respectively. Standard precautions were taken in order to avoid sample gas contamination. The certified purity was 99·999% for N_2, 99·995% for O_2 and 99·9% for NO. In view of the sufficiently low ultimate pressure of the vacuum system (1×10^{-8} Torr), the error due to the background gas was considered negligible.

By summing the various errors quadratically, an overall error of less than 2·5% is obtained (error in absolute measurements).

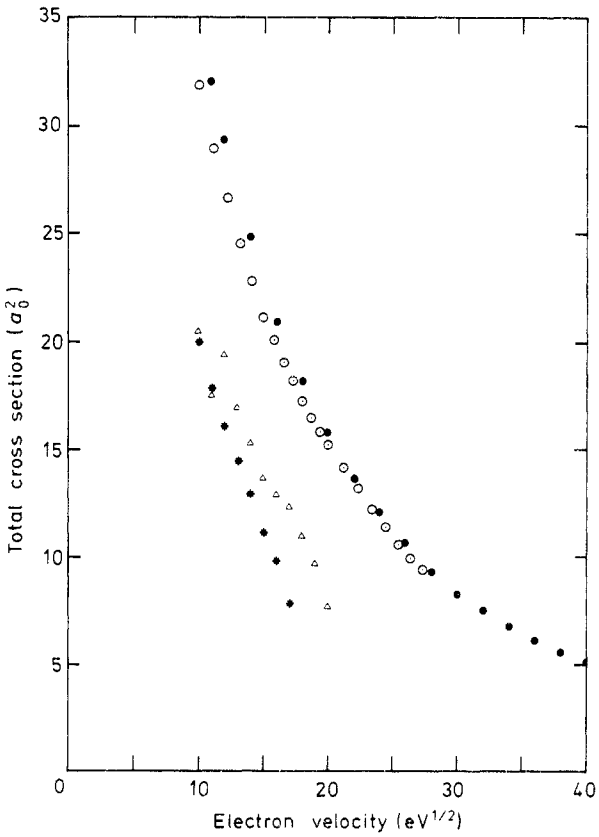

Figure 1. e^-–N_2 total cross section as a function of electron velocity. ●, present experiment; ○, Blaauw *et al* (1980); *, Brode (1925); △, Normand (1930). (The data of Blaauw *et al*, Brode and Normand are shown only for the range of overlap with our measurements.)

In the foregoing analysis, the error due to the finite angular resolution of the apparatus has not been discussed. An evaluation has been attempted using the experimental data on differential cross sections at our disposal. By extrapolating to zero angle the absolute measurements of elastic cross section performed by Bromberg (1970, 1974) on N_2 and O_2 at 300, 400 and 500 eV, and by Dubois and Rudd (1976) on N_2 at 800 eV, we have estimated that the error in the elastic part due to the finite angular resolution is less than 0·5% for those energies. A rough extrapolation to zero angle of the measurement of total differential cross section of Peixoto and Nogueira (1976) in N_2 suggests an error in our measurements due to the finite angular resolution of less than 5% at 500 eV, and less than 13% at 1000 eV.

4. Experimental results

4.1. Nitrogen

The total cross section measurements of Brode (1925) and Normand (1930) had for a long time been the only available data above 100 eV electron energy. Then, in 1977, de Heer's group performed at FOM precise measurements in the energy range 15 to 750 eV using a linear apparatus (Blaauw *et al* 1977, 1980).

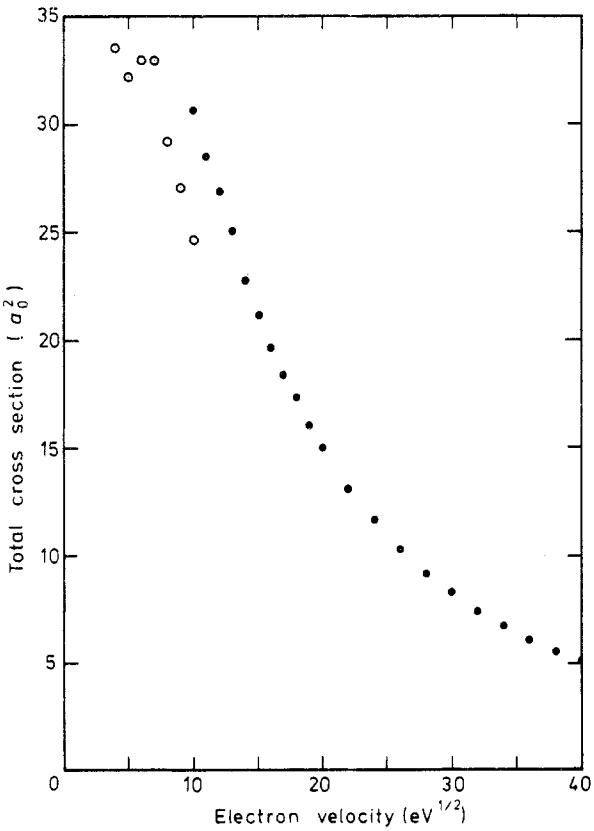

Figure 2. e^-–O_2 total cross section as a function of electron velocity. ●, present experiment; ○, Sunshine *et al* (1966).

The results of our measurements are shown in table 1 and in figure 1, where a comparison is also made with the results of previous measurements. Our values are everywhere higher than those of Blaauw *et al* (1980): about 10% at 100 eV and 2·5% at 750 eV. The data of Brode and Normand are about 50% lower than ours. The fact that the discrepancy with the measurements of Blaauw *et al* (1980) decreases with energy (see figure 1) could be interpreted with a systematic disagreement of the order of 10% superimposed on an energy-dependent error due to the lower angular resolution of our apparatus. Using this hypothesis, the angular resolution error could be of the order of 0 to 1% at 100 eV and 7 to 8% at 750 eV. This seems to agree with the figures calculated from the differential data of Peixoto and Nogueira (1976).

The 10% discrepancy is difficult to explain on the basis of the characteristics of the two sets of apparatus. Such a discrepancy is outside the combined errors. Possible sources of such an error are the decalibration of the capacitance meters or impurities in the gas sample.

The results for O_2 (see figure 3) suggest that a contamination from this gas (air leak) could not explain the discrepancy.

4.2. Oxygen

The results of our measurements are shown in table 1 and figure 2. A comparison has

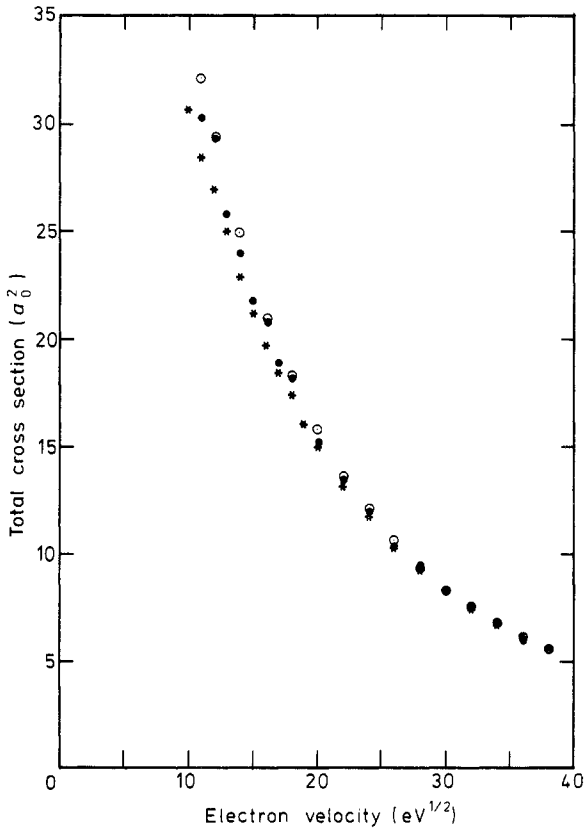

Figure 3. e^-–N_2 (○), e^-–O_2 (*) and e^-–NO (●) total cross sections as a function of electron velocity.

been possible only with the measurements of Sunshine *et al* (1966): at 100 eV electron energy, which is the only value of overlap, the cross section of Sunshine *et al* is about 20% lower than ours.

The absolute error quoted by Sunshine *et al* is 20%, so that their results do not conflict with ours. The angular resolution error for electron–oxygen scattering was not evaluated due to the lack of inelastic angular cross section data. The only guess which can be made is to assume that this error has the same value as for nitrogen.

4.3. Nitrogen monoxide

The results of our measurements are shown in table 1 and figure 3. A few points show relatively large fluctuations, to be ascribed to the greater instability of the apparatus due to the high activity of NO on the cathode. The angular resolution error was not evaluated for NO.

In figure 3 a comparison is also made between the results for N_2, O_2 and NO. The cross sections are very close at the highest energies. Then they depart from each other toward lower energies. At 121 eV the total cross section for NO is about 6% lower than for N_2 and 6% higher than that for O_2.

References

Basta M, Lazzizzera I and Zecca A 1976 *J. Phys. E: Sci. Instrum.* **9** 6
Bederson B and Kieffer L J 1971 *Rev. Mod. Phys.* **43** 601
Blaauw H J, de Heer F J, Wagenaar R W and Barends D H 1977 *J. Phys. B: Atom. Molec. Phys.* **10** L299
Blaauw H J, Wagenaar R W, Barends D H and de Heer F J 1980 *J. Phys. B: Atom. Molec. Phys.* **13** 359
Brode R B 1925 *Phys. Rev.* **25** 636
Bromberg J P 1970 *J. Chem. Phys.* **52** 1243
—— 1974 *J. Chem. Phys.* **60** 1717
Burke P G and Williams J F 1977 *Phys. Rep.* **34** 324
Dalba G, Fornasini P, Lazzizzera I, Ranieri G and Zecca A 1979 *J. Phys. B: Atom. Molec. Phys.* **12** 3787
Dubois R D and Rudd M E 1976 *J. Phys. B: Atom. Molec. Phys.* **9** 2657
Golden D E, Lane N F, Temkin A and Gerjouy E 1971 *Rev. Mod. Phys.* **43** 642
Jansen R H J, de Heer F J, Luyken H J, Van Wingerden B and Blaauw H J 1976 *J. Phys. B: Atom. Molec. Phys.* **9** 185
Jost K and Möllenkamp R 1977 *Proc. 10th Int. Conf. on Physics of Electronic and Atomic Collisions* (Paris: Commissariat à l'Energie Atomique) Abstracts p 394
Kusch P 1964 *J. Chem. Phys.* **40** 1
Normand C E 1930 *Phys. Rev.* **35** 1217
Peixoto E M A and Nogueira I C 1976 *Phys. Rev.* A **13** 1352
Phelps A V 1972 *Ann. Geophys.* **28** 611
Rapp D and Englander Golden P 1965 *J. Chem. Phys.* **43** 1464
Sunshine G, Aubrey B B and Bederson B 1966 *Phys. Rev.* **154** 1
Wakiya K 1978 *J. Phys. B: Atom. Molec. Phys.* **11** 3913