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Low energy electron scattering in H_2, N_2 and O_2

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Abstract. Electron beam transmission experiments have been performed, in the energy range 10 meV to 175 meV, with a magnetically collimated electron beam formed in a synchrotron radiation photoionization source using SuperACO, LURE. The apparatus has been calibrated with He and absolute backward scattering cross sections have been measured for the target gases H_2, N_2 and O_2. A relationship, involving s and p partial waves, has been established between the backward scattering cross sections (σ_B) and the momentum transfer cross sections (σ_M). This has been used to check the accuracy of experimental data and the consistency of values of σ_B, σ_M and total scattering cross sections. Experimental data and theory for H_2 are in good agreement, whereas for N_2 experimental values of σ_B and σ_M conflict below 80 meV and agreement with theories is mixed. For O_2, discrepancies are greater than for N_2 both in experimental data and between theory and experiment, which may differ by up to a factor of 5 for the total scattering cross section at the lowest energies.

1. Introduction

Electron collisions with H_2, N_2, O_2 and He at very low energy are of considerable interest and have been the subject of intensive theoretical and experimental study in recent years. The most recent theoretical work, at low energy, is that of Nesbet *et al* (1986), Gibson and Morrison (1984), and Schneider and Collins (1983) for H_2, Gillan *et al* (1988) and Morrison *et al* (1987) for N_2, Noble and Burke (1992) for O_2, and Saha (1993) and Plenkiewicz *et al* (1990) for He. The most recent experimental investigations are those of Subramanian and Kumar (1989) and Brunger *et al* (1991) for H_2, Sohn *et al* (1986) for N_2, Ziesel *et al* (1993) for O_2 (hereafter referred to as paper I), and Buckman and Lohmann (1986) for He. In the present work, beam–gas cell scattering experiments have been performed to measure absolute values of the backward scattering cross sections for H_2, N_2 and O_2 as a function of electron energy in the energy range of 10 meV to 175 meV. Low energy electron scattering cross sections are very sensitive to the formulation of long range polarization and exchange and these data provide a stringent test for present and future scattering calculations in this energy regime. Data for H_2, N_2 and O_2 also have important applications in modelling astrophysical plasmas,

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planetary atmospheres and RF plasmas used in device technology (e.g. Dalgarno and Layzer 1987, Wayne 1991, May *et al* 1993).

Experimentally this low energy range has been very little investigated in beam experiments. There exists however a substantial literature for swarm experiments involving measurements of momentum transfer cross sections, covering this energy range, whose results are summarized in Shimamura (1989). Transmission experiments below 100 meV are restricted to the results of Ferch *et al* (1980) for H_2, involving time-of-flight experiments down to 20 meV, and paper I for O_2 down to 12 meV. In the latter work, no attempt was made to measure absolute cross sections. The only other beam experiment probing this energy range is that of Randell *et al* (1993), involving electron scattering in chlorofluorocarbons.

In section 2 experimental details are given, and in section 3, calibration of our data with He is described. In section 4, expressions are developed which relate backward scattering, σ_B, momentum transfer, σ_M, and total scattering cross sections, σ_T. Using data for He, these expressions enable the accuracy of our experimental data for σ_B and consistency of values of σ_B, σ_M and σ_T to be established. This analysis also forms a basis for discussion of data for H_2, N_2 and O_2. In section 5 experimental data are presented for these gases and in section 6 comparisons are made with theory and with experimental cross sections for momentum transfer and total scattering.

2. Experiment

A detailed description of the apparatus may be found in Field *et al* (1984), with further modifications described in paper I. Very briefly, monochromatized synchrotron radiation was used, on line SA61 at the SuperACO storage ring at LURE, Université Paris-Sud, to form photoelectrons by ionization of Ar at a threshold of 786.5 Å. The energy resolution of the electron beam is equal to that of the photon beam and was set in the present experiment to 7.5 meV FWHM, a somewhat lower resolution than in paper I and in Randell *et al* (1993), since sharp structure was not sought here. The radiation intensity was lower by a factor of >10 compared with our earlier work, and higher electron currents and improved signal-to-noise were obtained by using a degraded energy resolution.

The electron beam was collimated using a 20 G axial magnetic field. Cross sections were measured through attenuation of the incident beam and were evaluated in the standard way through

$$\sigma = \ln(I_0/I)/Nz \qquad (1)$$

where I_0 and I are the unattenuated and attenuated electron currents respectively, N is the gas density and z is the path length of electrons through the gas. Since scattering takes place in the presence of an axial magnetic field, electrons which are forward scattered remain collimated along the direction of the incident beam. For example, electrons with a transverse energy of 100 meV move in a spiral path with a radius of 0.6 mm. Since the exit aperture of the scattering cell was 4 mm, only those electrons which are scattered into the backward hemisphere are removed from the incident beam and are recorded as scattered, noting that back-scattered electrons are lost in the system in a manner which is energy independent. Cross sections for backward scattering, σ_B, are therefore measured in this experiment. We ensure that purely σ_B is measured up to any chosen collision energy, V_R, by setting the potential on an element, R, downstream of the collision chamber to a voltage equivalent to this chosen energy. This element functions as follows: electrons traversing the collision chamber, with initial kinetic energy $<V_R$, encounter an attractive field due to the element R, irrespective of any scattering and therefore all forward scattered electrons are recorded as unscattered up to energy V_R, as required. We note that, for electrons with initial energy $>V_R$, the field between the collision chamber and the element R becomes repulsive. Thus electrons with an initial energy $>V_R$, scattered into the forward hemisphere, may have insufficient axial energy to overcome the resulting barrier and some unknown proportion of the total cross section, depending on the angular variation of scattering at the appropriate energy, would be recorded. Throughout these experiments $V_R = 175$ mV and backward scattering cross sections are therefore reported for energies $\leqslant\sim 175$ meV. The absolute energy scale was calibrated through repeated measurements of the series of resonances around 2.3 eV in N_2 (Kennerly 1980, Rohr 1977). Agreement between the potentials used and the true energy, so far as it may be determined on this basis, was generally better than 10 meV. Since the lowest energies used cannot be less than a few meV, the absolute energy scale in the present data is accurate to $\pm\sim 5$ meV.

An important modification to the apparatus has been the introduction of absolute pressure measurement in the collision chamber. Pressures were recorded using a Baratron M127A, absolute accuracy better than 0.2%. Excellent linearity of $\ln(I_0/I)$ against

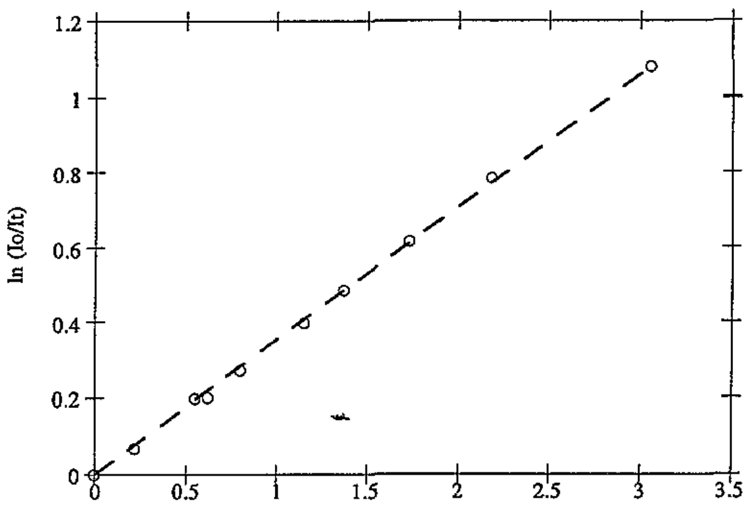

Figure 1. The linear relationship between ln(incident/transmitted current), $\ln(I_0/I)$, and pressure in the collision chamber in mTorr (1 mTorr $\sim$0.133 Pa), measured for electron scattering in N_2 at a collision energy of 2.219 eV.

pressure was found up to several mTorr, as shown in figure 1 for N_2, at an incident energy of 2.219 eV, up to an attenuation of $\sim$60%. Extreme caution must however be exercised in measuring cross sections at very low energies. For example, for H_2, we have found that the maximum attenuation permissible to avoid multiple scattering is $\leqslant$10%. Attenuation of 3% was typically used for He calibration experiments. We have checked that derived cross sections are pressure independent, for a range of attenuation between 2% to 10% for each gas. Pressure measurement enables the determination of absolute cross sections for electron scattering. The apparatus was not however originally designed for accurate cross section measurements and the product of target and scattering path length, Nz, was poorly known. We have therefore calibrated the instrument using helium as the target gas, as we describe in section 3. In this connection, the effective increase in path length due to the spiral nature of the electron path is negligibly small over the range of energies used here, since electron trajectory studies show that the initial transverse energy of the photoelectrons must be <1 meV for acceptance into the lens, directly beyond the photoionization chamber.

An experimental problem in transmission experiments is that I_0 and I cannot be simultaneously monitored. Systematic errors may therefore enter into individual cross section measurements. To alleviate this problem, experiments were performed as follows. For a fixed electron kinetic energy, I_0 was recorded, integrating for 50 seconds, target gas was then introduced, and I recorded for a further 50 seconds. This process was repeated 5 or more times, and a final I_0 recorded. The time at which each recording of I_0 and I started was also recorded. Using suitable linear interpolation, these data yielded a set of 5 or more cross sections, whose average value was adopted as the cross section. Measurements of the random fluctuations in I and I_0 show that these introduce a random error into the observations of ±1%.

3. Calibration with He

The instrument has been calibrated for the measurement of absolute cross sections against theoretical He cross sections of Saha (1993). Comparison between different theoretical values of the total scattering cross section at selected energies ⩽175 meV, shows that agreement is better than ~3% in all cases (Saha 1993, Plenkiewicz *et al* 1990, Barzick 1981). We adopt the values in Saha (1993) throughout. Calculated momentum transfer cross sections and experimental values agree to within better than 3% in all cases (Shimamura 1989, Crompton *et al* 1970). In the present case the variation of the *backward* scattering cross section, σ_B, rather than the total cross section, σ_T, has been measured. Scattering by He is weakly anisotropic between 10 meV and 175 meV and we use the angular dependence of the scattering given in Saha (1993) at 10 meV, 100 meV and 136 meV to take account of this. Using atomic units, for which the wavevector $k=(2E)^{1/2}$, the backward scattering cross section is related to the phase-shifts η_l by

$$\sigma_B=(4\pi/k^2)[\tfrac{1}{2}(\sin^2\eta_0+3\sin^2\eta_1+5\sin^2\eta_2)-\tfrac{3}{2}\sin^2\eta_0\sin^2\eta_1 -\tfrac{3}{8}\sin 2\eta_0\sin 2\eta_1-\tfrac{15}{8}\sin^2\eta_1\sin^2\eta_2-\tfrac{15}{32}\sin 2\eta_1\sin^2\eta_2]. \quad (2)$$

Using values of η_0, η_1, η_2 for 136 meV given in Saha (1993), $\sigma_B/\sigma_T=0.536$. Data in figures 1 and 2 of Saha show that at 10 meV and 100 meV, σ_B/σ_T is respectively 0.510 and 0.528.

In figure 2 we show the theoretical total scattering cross sections of Saha (1993) with our estimates of the total scattering cross sections, obtained from the present experimental values of σ_B and the known anisotropy. Our experimental values of σ_B have been calibrated to theoretical values using an effective collision length, z, of 3.9 cm, using the pressure as measured. Also shown are the calibrated backward scattering cross sections. An important point is that, within experimental error, total cross sections deduced from our backward-scattering cross sections fit the theoretical values of Saha (1993) with a single energy independent scaling factor. Errors shown in the data in

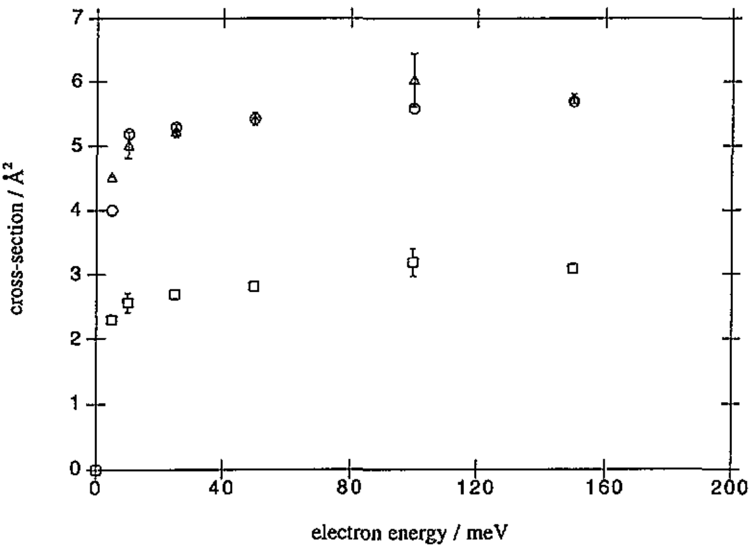

Figure 2. Calibration with helium: □, backward scattering cross sections, σ_B, obtained using a collision path length of 3.9 cm (see section 3), as a function of electron kinetic energy; △, total scattering cross sections derived from values of σ_B, taking account of the anisotropy of He scattering; ○, theoretical values of the total scattering cross section taken from Saha (1993).

figure 2 are discussed in section 4. The data point at 5 meV in figure 2 may show some systematic error, since this energy lies below the energy resolution in the primary electron beam.

4. Relationship between backward scattering and momentum transfer cross sections

We show in this section how momentum transfer cross sections, σ_M, and backward scattering cross sections, σ_B, may be used to estimate total scattering cross sections, σ_T, at low energy. This provides a means of estimating the accuracy of our experimental data and supplies a useful check on the consistency of our data with experimental momentum transfer and total scattering cross sections and theoretical cross sections. The contribution to the scattering of $l \geqslant 2$ is assumed to be negligible. In support of this assumption, Saha (1993) finds that the contribution of $l = 1$ to the total scattering cross section is ~40 times greater than that of $l = 2$, at an energy of 136 meV. Expressions derived apply to the energy range between zero and a few hundred meV, and exclude resonances and inelastic scattering. Ignoring all terms involving η_2, and writing all expressions in terms of $\sin^2$(phaseshift), equation (2) becomes

$$\sigma_B = (4\pi/k^2)\{\tfrac{1}{2}(\sin^2\eta_0 + 3\sin^2\eta_1) - \tfrac{3}{2}\sin^2\eta_0\sin^2\eta_1 - \tfrac{3}{2}[\sin^2\eta_0\sin^2\eta_1(1-\sin^2\eta_0)(1-\sin^2\eta_1)]^{1/2}\} \tag{3}$$

and the momentum transfer cross section may be expressed as

$$\sigma_M = (4\pi/k^2)\{\sin^2\eta_0(1-\sin^2\eta_1) + \sin^2\eta_1(1-\sin^2\eta_0) + 2\sin^2\eta_1 - 2[\sin^2\eta_0\sin^2\eta_1(1-\sin^2\eta_0)(1-\sin^2\eta_1)]^{1/2}\} \tag{4}$$

leading to a simple relationship between η_0 and η_1

$$\sin^2 \eta_1 = \frac{1}{3}\left[\frac{k^2}{\pi}\left(\tfrac{3}{4}\sigma_M - \sigma_B\right) - \sin^2 \eta_0\right] \tag{5}$$

and a cubic equation for η_0 of the form

$$3\alpha^2 - 2\alpha^3 - 3\alpha\mu + 3\alpha^2\mu + \mu^2 - \alpha\mu^2 - 2\alpha^2\phi - 2\mu\phi + 2\alpha\mu\phi + \phi^2 = 0 \tag{6}$$

where $\alpha = \sin^2 \eta_0$, $\mu = (k^2/\pi)(\frac{3}{4}\sigma_M - \sigma_B)$ and $\phi = (k^2/2\pi)\sigma_B$. Inserting experimental values of backward scattering and momentum transfer cross sections therefore yields η_0 and η_1. The total scattering cross section may then be calculated from $\sigma_T = (4\pi/k^2)(\sin^2 \eta_0 + 3\sin^2 \eta_1)$. The above analysis does not yield the sign of the phase-shift; for He we have adopted the signs given in Saha (1993).

We first apply this analysis to He, to estimate the accuracy of our data for σ_B by testing for consistency between these data and experimental values of σ_M (Crompton *et al* 1970, Shimamura 1989) and theoretical values of σ_T for helium (Saha 1993). To proceed, we make the assumption that values of σ_M and σ_T are exact by comparison with values of σ_B. The error associated with measured helium backward scattering cross sections may then be estimated by examining the sensitivity of values of σ_T, calculated using equations (5) and (6), to variations in the value of σ_B. Results of this

Table 1. Helium: calibrated backward scattering cross sections, σ_B, momentum transfer cross sections, σ_M (Crompton *et al* 1970, Shimamura 1989), total scattering cross sections, σ_T, calculated from equations (5) and (6) and theoretical values of σ_T (Saha 1993).

Electron energy/meV	$\sigma_B/\text{Å}^2$	$\sigma_M/\text{Å}^2$	$\sigma_T/\text{Å}^2$ Calculated	$\sigma_T/\text{Å}^2$ Saha (1993)
10	2.56 ± 0.10	5.28	5.59 ± 0.40	5.19
25	2.69 ± 0.05	5.41	5.47 ± 0.21	5.29
50	2.81 ± 0.06	5.62	5.62 ± 0.21	5.42
100	3.19 ± 0.16	5.86	4.73 ± 1.1	5.58
136	3.11 ± 0.03	6.09	5.67 ± 0.13	5.66
150	3.08 ± 0.03	6.04	5.79 ± 0.18	5.69

analysis are given in table 1, showing experimental values of σ_B and σ_M, values of σ_T calculated from equations (5) and (6) and theoretical values of σ_T (Saha 1993). Errors in σ_B have been estimated to satisfy the requirement that σ_T (calculated) and σ_T (theoretical) agree within experimental error. We also note that the calculated value of σ_T at 150 meV (=5.79 Å^2) agrees closely with the value of 5.73 Å^2 measured at this energy by Buckman and Lohmann (1986). A χ^2 test, using data in the last two columns of table 1, shows that there is 98% probability that σ_B, σ_M and σ_T form a consistent set of data. Table 1 shows that absolute values of σ_B are measured with an accuracy of ±5%. The accuracy of values of σ_B, but not the consistency of σ_B, σ_M and σ_T, may also be estimated by combining the known anisotropy of He scattering (see section 3) with values of σ_B and comparing directly with theoretical values of σ_T. This analysis also yields an error of ±5%.

With respect to estimation of phaseshifts using equations (5) and (6), values of η_1 are very sensitive to values of the cross sections adopted. For example a variation of 1% in a cross section may typically change the calculated value of η_1 by more than 10^{-3} rad, noting that typical values of η_1 may lie around a few times 10^{-3} rad. In general it is therefore only possible to obtain trends in η_1 with electron energy, given

Table 2. Helium: values of the $l=0$ and 1 phaseshifts, η_0 and η_1, obtained from equations (5) and (6) using calibrated values of σ_B and values of σ_M from Crompton *et al* (1970). The figures in brackets are the theoretical phaseshifts of Saha (1993), for an electron energy of 136 meV.

Electron energy/meV	$\sigma_B/Å^2$	$\sigma_M/Å^2$	η_0 (rad)	η_1 (rad)
25	2.69	5.41	3.0881	0.000 208
136	3.11	6.09	3.0126	0.002 05
			(3.0145)	(0.003 054)

the errors in experimental data. Examples of results of calculations are shown in table 2 for electron energies of 25 meV and 136 meV, the latter for direct comparison with phaseshifts quoted in Saha (1993) (noting that η_2 is also quoted in Saha (1993)). As expected, η_1 at 25 meV is significantly lower than at 136 meV. Equations (5) and (6) may also be used to check for consistency of experimental values of σ_B and σ_M through the condition that η_1 must be real. This aspect is used extensively in section 6.

5. Backward scattering cross sections for hydrogen, nitrogen and oxygen: experimental data

Calibrated backward scattering cross sections are shown in figures 3, 4 and 5 for H_2, N_2 and O_2 respectively. The electron energy values for the H_2 and N_2 results are the values of the controlling potential in the apparatus. In the O_2 results, the doublet resonance, associated with electron attachment into the fourth vibrationally excited state of O_2^-, may be seen, centred on 91 ± 5 meV (Land and Raith 1974). This provides an internal energy calibration for the O_2 data, and reveals a displacement of 10 meV from the value given by potentials in the apparatus. Values of electron energy have

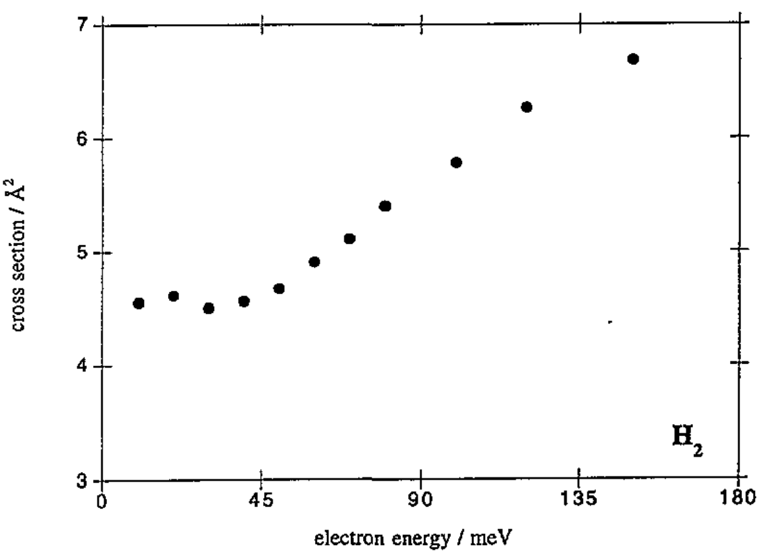

Figure 3. Hydrogen: backward scattering cross sections, σ_B, as a function of electron kinetic energy. Absolute accuracy of the cross sections is ±5% and random error is ±1%.

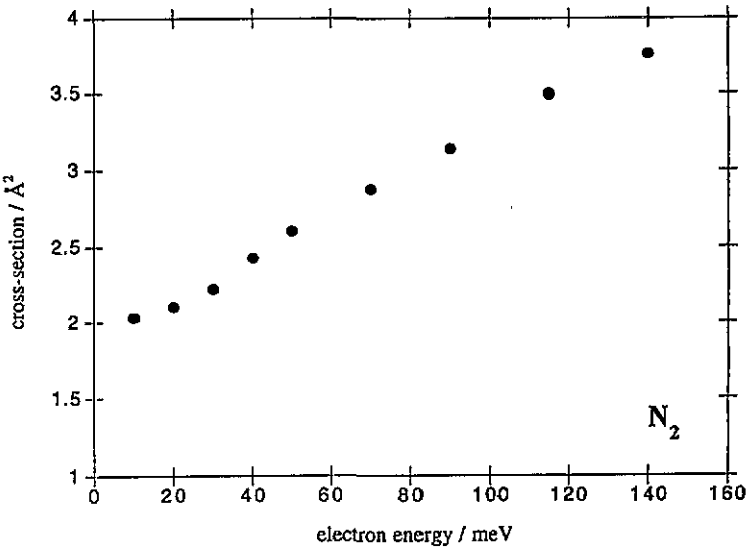

Figure 4. Nitrogen: backward scattering cross sections, σ_B, as a function of electron kinetic energy.

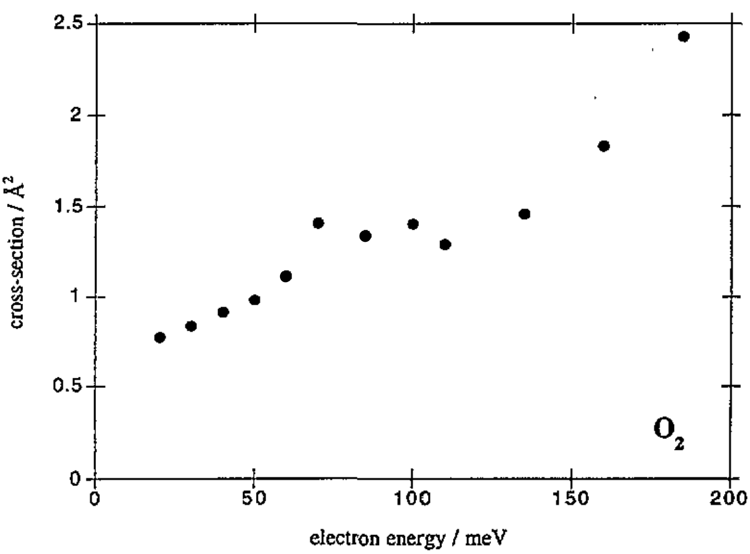

Figure 5. Oxygen: backward scattering cross sections, σ_B, as a function of electron kinetic energy.

been corrected accordingly. Energy displacements are known to be gas dependent and it would not be appropriate to use the O_2 value for the H_2 and N_2 data. Cross sections for backward scattering at zero energy, estimated by extrapolation, are 4.52 Å^2 for H_2, 1.99 Å^2 for N_2 and 0.72 Å^2 for O_2, giving scattering lengths of 0.85 Å for H_2, 0.56 Å for N_2 and 0.34 Å for O_2, where the scattering lengths are recorded as positive since Ramsauer–Townsend minima are not present (see section 6).

The O_2 data may be compared with those in paper I, which extended to 12 meV. The form of the variation of the backward scattering cross section with energy is very similar to that found in paper I, with the cross section rising through a factor of ~ 2 between 25 and 100 meV in paper I, and a factor of ~ 1.75 in the present work. The present data should be regarded as more accurate, in addition to providing absolute values of σ_B. All three sets of data in figures 3, 4 and 5 show the characteristic that the backward scattering cross section drops increasingly slowly with decreasing electron energy below ~ 50 meV. This behaviour is especially clear for H_2, for which, within experimental error, σ_B remains constant below 50 meV (figure 3). This feature of the data is not predicted by any simple theory, as we see in section 6.

6. Discussion of results

The scattering lengths given above may be used in conjunction with modified effective range theory (MERT; O'Malley 1963) to predict the variation of the backward scattering cross section with electron energy, ignoring inelastic scattering and resonances (in O_2). MERT was derived on the basis that the interaction of the electron and the target may be represented by a polarization potential of the simple form

$$V(r) = -\alpha_d/2r^4. \tag{7}$$

The variation of the backward-scattering cross section with electron energy for pure s-wave scattering has no adjustable parameters and follows the relationship

$$\sigma_B = 2\pi A^2 + \tfrac{4}{3}\pi^2 A\alpha_d k + \tfrac{2}{9}\pi^3\alpha_d^2 k^2 + \tfrac{16}{3}\pi\alpha_d A^2 k^2 \ln k \ldots \tag{8}$$

expressed in au, where A is the scattering length and α_d the polarizability of the target, noting that s-wave scattering dominates for energies of interest here. Equation (8) contains the dominant terms dictating the variation of σ_B with electron energy over the energy range considered here. Inserting appropriate values, it is however evident that the form predicted by equation (8) is not obeyed. The variation of σ_B with energy according to equation (8) follows a curve which predicts a much more gentle rise in σ_B, with increasing electron energy, than is observed. Equation (8) also predicts that the cross section should rise increasingly less steeply with increasing energy, in conflict with observations. These features are illustrated for N_2 in figure 6. The potential in equation (7) is in fact only appropriate for a spherical target at asymptotically long range. Essentially our results corroborate the results of numerous theoretical investigations, reviewed in Gillan *et al* (1988), that the variation of the electron scattering cross section is sensitive to the form of the polarization interaction and a sophisticated treatment of the interaction is necessary.

A MERT fit of the O_2 data, presented in paper I, was performed using the scattering length as a variable parameter, in the absence of an experimental value. It was found that the form of the variation of σ_B with energy could be treated as representative of a very shallow low energy Ramsauer–Townsend minimum. The absolute values of the backward scattering cross sections reported here show that this analysis is incorrect, since measured cross sections differ by more than a factor of 2 from cross sections derived on the basis of the analysis in paper I. O_2 therefore does not show a low energy Ramsauer–Townsend minimum.

Before discussing specific molecules, we note that the contribution of rotationally inelastic backward-scattering collisions to σ_B for H_2 lies between zero and <0.05 Å^2

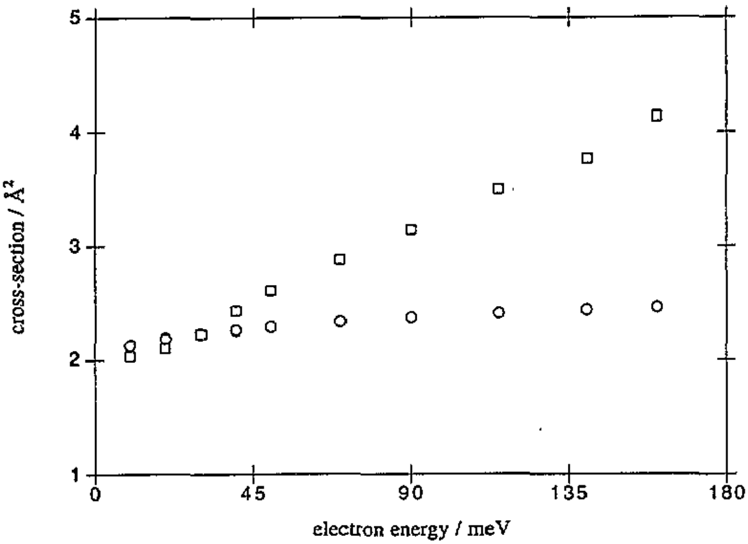

Figure 6. Nitrogen: □, backward scattering cross sections, σ_B, as a function of electron kinetic energy compared with the predictions (●) of equation (8) based upon a pure s-wave MERT analysis using the experimental value of the scattering length.

(England *et al* 1988 and references therein, Ficocelli Varracchio and Lamanna 1984, Morrison *et al* 1984, Shimamura 1989), for N_2 is <0.06 Å^2 (Shimamura 1989, Saha 1988, Morrison *et al* 1987) and for O_2 is <0.01 to 0.005 Å^2, using $Q=-1.0$ au for N_2 and -0.3 au for O_2 (Itikawa *et al* 1989), noting that $J=7$ and 8 are the most populated target states for N_2 and O_2 respectively. For H_2, the threshold energy for rotationally inelastic collisions is 45 meV, whereas for N_2 and O_2 rotational excitation can take place throughout the energy range of the experiments.

6.1. Hydrogen

At zero energy, $\sigma_B=\frac{1}{2}\sigma_M$ and the value quoted in England *et al* (1988) for σ_M yields $\sigma_B=3.18$ Å^2 at zero energy, 40% below our present result. Our data are not consistent with the rapid fall in cross section reported in England *et al* for momentum transfer in the very low energy regime. In table 3 we show momentum transfer cross sections from England *et al*, measured backward scattering cross sections, total scattering cross sections calculated on the basis of σ_M and σ_B, and experimental total cross sections estimated from the curve shown in Ferch *et al*. In order to achieve consistency with present values of σ_B, values of σ_M need to be 10% to 15% higher at 10 and 20 meV than those quoted in England *et al*. Alternatively our data must be 10% to 15% lower in this energy range, an error inconsistent with the analysis of the He data presented in section 4. We therefore suggest that the swarm data of England *et al* for H_2 may be systematically too low close to zero energy.

The last two rows of table 3 show the sensitivity of the data to small experimental errors. Thus data at 150 and 180 meV are in much better agreement with those of Ferch *et al*, if values of σ_M are increased by 4%. Calculated values of σ_T and those of Ferch *et al* are shown in figure 7, noting that our values effectively agree with those of Ferch *et al* if we introduce an experimental error in the determination of σ_B of no more than 2.5%. This error is within that which we attribute to our data, as discussed

Table 3. Hydrogen: backward scattering cross sections, σ_B, momentum transfer cross sections, σ_M (England *et al* 1988), and total scattering cross sections, σ_T, calculated from equations (5) and (6). The final column shows experimental values of σ_T taken from Ferch *et al* (1980).

Electron energy/meV	$\sigma_B/\text{Å}^2$	$\sigma_M/\text{Å}^2$	$\sigma_T/\text{Å}^2$	$\sigma_T/\text{Å}^2$ (Ferch *et al*)
10	4.56	7.26	†	—
20	4.62	7.95	†	7.5
30	4.51	8.45	7.24	7.9
40	4.57	8.91	8.44	8.1
50	4.68	9.22	8.94	8.3
60	4.91	9.50	8.84	8.6
70	5.11	9.79	8.89	8.7
100	5.40	10.44	9.70	9.2
120	5.78	10.77	8.97	9.4
150	6.27	11.33	8.64	9.7
180	6.69	11.69	7.68	10.0
150	6.27	11.78‡	10.18	9.7
180	6.69	12.16‡	9.46	10.0

† Consistent value not found.
‡ Values of σ_M have been arbitrarily increased by 4% to obtain the calculated value of σ_T shown.

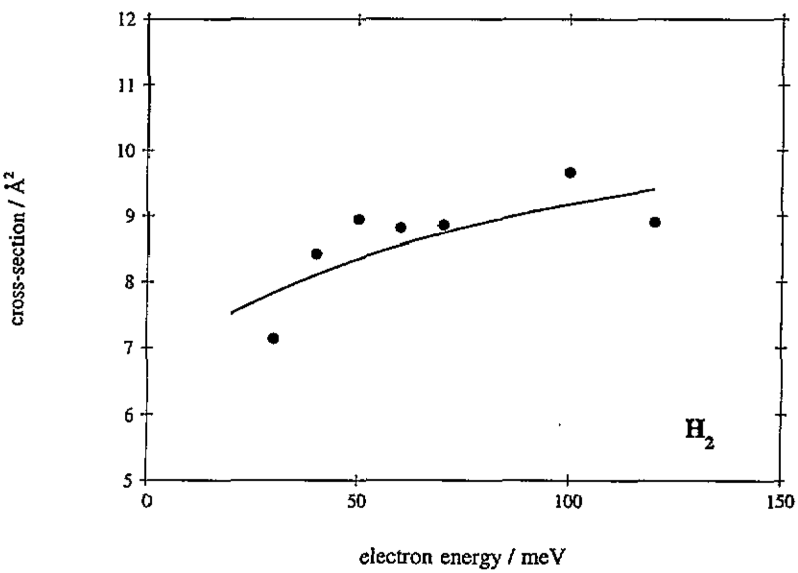

Figure 7. Hydrogen: the full curve represents data of Ferch *et al* (1980) (column 5, table 3) for the total scattering cross section and (●) represent results of calculations of the total scattering cross section (column 4, table 3), obtained using experimental values of backward and momentum transfer cross sections in equations (5) and (6).

in section 4, noting also that discrepancies between values shown in figure 7 may be attributed to errors in all three quantities σ_T, σ_M and σ_B.

With respect to theoretical calculations of the total scattering cross section, results in Gibson and Morrison (1984) and Schneider and Collins (1983) are in excellent agreement, to ~2%, with experimental data of Ferch *et al*, and therefore also with the present backward scattering cross section data. Nesbet *et al* (1986) quote a value of the total scattering cross section of 10.59 Å^2 at 136 meV, 10% greater than the experimental value in Ferch *et al* (1980).

6.2. Nitrogen

The zero energy momentum transfer cross section is given in Shimamura (1989) as 1.10 Å^2, whereas our measurements indicate a value of $2\times\sigma_B=3.98$ Å^2. The discrepancy between swarm values of σ_T and present values of σ_B continues up to 80 meV. Only at 80 meV are consistent values of σ_M and σ_B obtained. At 100 meV, using $\sigma_M=5.95$ Å^2 (Shimamura 1989) and our experimental value of $\sigma_B=3.29$ Å^2 (interpolated between 90 and 115 meV), σ_T is found from equation (5) and (6) to be 4.55 Å^2, in good agreement with the value of 4.44 Å^2 reported in Sohn *et al* (1986). The relative size of σ_B and σ_T indicates strong backward scattering at 100 meV, as Sohn *et al* measured. We find a correspondingly large value of $\eta_1=|0.010|$.

With respect to theoretical values of σ_T, Morrison *et al* (1987) give 4.63 Å^2 and 4.85 Å^2 at 100 meV, in agreement, within experimental error, with the present results. Gillan *et al* 1988 however give a value of 8.75 Å^2 at 100 meV in disagreement both with our values of σ_B in this energy range and also with σ_T of Sohn *et al* (1986). At energies <100 meV, Morrison *et al* (1987) diverge from the present data giving a value of ~1.4 Å^2 for $\sigma_M=\sigma_T$ at zero energy.

6.3. Oxygen

The present value of σ_B at zero energy, =0.72 Å^2, is in serious conflict with the value of $\sigma_M=0.35$ Å^2 (Shimamura 1989), which would correspond to $\sigma_B=0.175$ Å^2, noting that Itikawa *et al* (1989), in a compendium of O_2 data, do not quote σ_M below 600 meV. Values of σ_M at 20 and 50 meV, 0.99 Å^2 and 1.6 Å^2 respectively (Shimamura 1989), are also inconsistent with our values of σ_B. At a higher energy, for example of 150 meV, for which cross sections are unperturbed by the vibrational resonance around 91 meV, the value of σ_M in Shimamura (=3.1 Å^2) and our value of σ_B (=1.68 Å^2) yield $\sigma_T=$ 2.54 Å^2. Itikawa *et al* (1989) report an experimental value of $\sigma_T=3.9$ Å^2 (at 160 meV) and σ_B, σ_M and σ_T may be brought into agreement if we assume that the value of σ_M in Shimamura is 10% underestimated and ~3.55 Å^2, for which equations (5) and (6) yield $\sigma_T=3.92$ Å^2. We conclude that values of σ_M in Shimamura (1989) are seriously underestimated at very low energies.

Theoretical work on low energy electron scattering in O_2 is very limited, see Noble and Burke (1992). These authors mention the difficulties in treating the long-range polarization effects at low collision energies, noting that even at 2 eV, calculations overestimate experimental values (Shyn and Sharp 1982) by a factor of up to 2. Values of the total scattering cross section at 20 meV (say) are $\sim 2\times\sigma_B\sim 1.6$ Å^2, more than a factor of 5 below the zero energy value shown in Noble and Burke. As the authors stress, considerably more work is necessary to treat the polarization of the open shell target molecule.

7. Concluding remarks

Our results may be summarized as follows. Experimental data for cross sections for very low energy elastic scattering by H_2 are now well established with an accuracy of a few per cent, apart from underestimation by 10% to 15% of momentum transfer cross sections below 20 meV. The agreement with theory is good, indicating that the target polarization, treated non-adiabatically (see Gibson and Morrison 1984), and exchange interactions are adequately treated in this simplest of molecular systems. For N_2, there is serious disagreement between momentum transfer cross sections and the present backward scattering cross sections, up to energies of 80 meV. At 100 meV, however, there is good agreement between σ_B, σ_M and a measured total scattering cross section. Agreement with calculations of Morrison *et al* (1987) at this energy is good but becomes increasingly poor at energies below 100 meV. For O_2, the discrepancy between momentum and backward scattering cross sections is even more severe than for N_2 and we suggest that momentum transfer cross sections for O_2 given in Shimamura (1989) are seriously underestimated at low energies. Theory cannot yet confront the low energy experimental data for O_2 and requires extensive development to reproduce the present observations.

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