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Total electron scattering cross section measurments for Kr, O_2 and CO

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Abstract. Total cross sections have been measured for electron scattering on Kr, O_2 and CO in the 5-300 eV energy range utilizing a linear attenuation technique. The present results are found to be in good agreement with other experimental data for Kr and CO but deviate significantly from some of the previous measurements in the case of O_2.

1. Introduction

This paper reports measurements of the absolute total electron scattering cross sections for Kr, O_2 and CO in the electron impact energy range 5-300 eV. Total cross sections are useful for normalizing cross sections for specific excitation processes and for checking the consistency of available data.

The measurement of the total cross sections for Kr is a continuation of the previous work by Nickel *et al* (1985) on other rare gas targets (He, Ne, Ar, Xe). Previously Wagenaar and de Heer (1980) and Dababneh *et al* (1980, 1982) performed total electron scattering cross section measurements on Kr over a broad energy range. Later Jost *et al* (1983) and Wagenaar and de Heer (1985) have reported total electron scattering cross sections for Kr in the low and intermediate impact energies. Theoretical data for Kr are scarce. McCarthy *et al* (1977) performed optical model calculations for electron scattering from inert gases and reported total inelastic cross sections at energies ranging from 20 to 300 eV. Later, de Heer *et al* (1979) obtained semi-empirical total electron scattering cross sections for noble gases in the energy range 20-300 eV.

O_2 was selected for the present study because of its importance in several fields of basic and applied research. Although electron scattering by oxygen has been studied experimentally by several authors, only a limited energy range was covered in each experiment and the agreement among these measurements is not satisfactory. Early experiments on electron scattering cross sections for O_2 were carried out by Bruche (1927) and Ramsauer and Kollath (1930). Later measurements include the work carried out by Sunshine *et al* (1967) and Salop and Nakano (1970). Recently, Dalba *et al* (1980), Griffith *et al* (1982), Zecca *et al* (1986), Dababneh *et al* (1988) and Subramanian and Kumar (1990) have reported the $e^- + O_2$ total cross section measurements. Not much work has been done theoretically to compute total electron scattering cross sections for molecular oxygen. Integral elastic scattering cross sections at low energies have been calculated by Fisk (1936) using a semi-empirical two potential method.

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CO was chosen because it is important to many applications involving lasers and ionized gases. Total electron scattering cross sections for CO have been measured by Gus'kov *et al* (1978), Szmytkowski and Zubek (1978) and Hasted *et al* (1979). Recently, Kwan *et al* (1983), and Sueoka and Mori (1984) have reported total electron scattering cross sections for CO for a broad impact energy range. The availability of theoretical data for CO is very limited. Chandra (1977) reported theoretical computations of low-energy total electron scattering cross sections obtained by using the frame-transformation theory.

The present paper is part of a continuing research study which aims to measure total electron scattering cross sections for different target atoms and molecules in a broad impact energy range.

2. Experimental procedure and error estimation

2.1. Experimental procedure

The apparatus and experimental procedure used in the present measurements are basically the same as those described in a previous article (Nickel *et al* 1985) and we shall give only a brief description here. Attenuation of an electron beam through a static gas target is measured at several impact energies as a function of gas pressure. The cross sections are then deduced from these measurements by applying a Lambert-Beer type of expression. The basic elements of the linear transmission device employed for the present measurement are shown in figure 1. An electron gun with six cylindrically symmetric lens elements was employed which produced an electron beam in an energy range 5–300 eV with an energy resolution of 0.35 eV FWHM. The electron beam was directed through a scattering chamber consisting of a 14.43 cm long stainless steel tube bounded by two apertures A_2 and A_3. Gas was fed to the chamber through a leak valve and pressure in the chamber was monitored by an MKS Baratron capacitance manometer. A calibrated thermistor was used to monitor the temperature of the scattering cell. The detection of the transmitted electron current took place in a gridded Faraday cup. The output of the detector was monitored on an electrometer. The

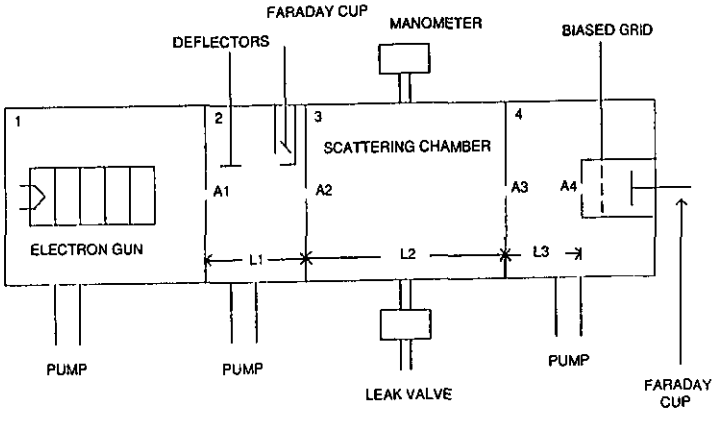

Figure 1. A schematic representation of the attenuation apparatus for the present measurements.

electrons inelastically scattered in the forward direction can give rise to serious experimental errors in the attenuation measurements. A grid has been used in the present measurements in order to avoid this effect. Total scattering cross sections were deduced by using the following expression:

$$I_d(n) = I_d(0) \exp(-nL\sigma_m) \tag{1}$$

where $I_d(n)$ is the detected current at the Faraday cup with gas inside the scattering chamber, $I_d(0)$ is the detected current at the Faraday cup without gas inside the scattering chamber, n is the gas density inside the scattering chamber, L is the scattering length and σ_m is the *measured* total cross section. The *measured* cross section σ_m differs from the *true* cross section σ and the fractional deviation between σ_m and σ is given by:

$$\frac{\sigma - \sigma_m}{\sigma} = \frac{2\pi}{\sigma} \int_0^{\theta_{max}} \frac{d\sigma}{d\Omega} \sin\theta \, d\theta \simeq \frac{1}{\sigma} \overline{|d\sigma/d\Omega|} \langle \Delta\Omega \rangle \tag{2}$$

where $\overline{|d\sigma/d\Omega|}_{\theta=0}$ is the average differential elastic scattering cross section in the forward direction, $\langle \Delta\Omega \rangle$ is the solid angle subtended by the detector averaged over the length of the scattering chamber and θ_{max} is the maximum scattering angle which can contribute to the transmitted signal. The detected current I_d was measured as a function of pressure in the scattering cell for a selected electron impact energy (E_0). The gas density in the cell was determined by using the ideal gas law $P = nkT$, where k is the Boltzman constant and T is the temperature of the scattering cell. A plot of the pressure against the logarithm of detected current yielded a straight line with a negative slope whose magnitude was equal to $\sigma_m L$. A least-squares fitting routine was employed in order to obtain the best fit to the data. The pressure range was chosen so that multiple scattering effects could be ignored. Any drift in the current during a run was monitored by checking the current after the pressure was returned to zero. Typically, the drifts, if any, were a few per cent and were corrected for. Since the temperature of the scattering cell was typically 29–32°C and the MKS sensor head was maintained at 45 °C, the pressure in the scattering chamber is expected to be slightly lower than the pressure indicated by the MKS capacitance manometer due to thermal transpiration effects. The present data indicate that the thermal transpiration effect is not important in our measurements for the gases of interest. This fact was determined by comparing the cross sections obtained with the MKS unit in thermal equilibrium with the scattering cell and with those obtained by using the thermostated MKS. In the present work, electron impact energies below 20 eV have been calibrated by using the well known helium resonance at 19.37 eV energy. As a final note on the experimental procedure, all the measurements reported in this article were made in a range where the incident electron current was typically on the order of 10^{-11} A and all gases used were Matheson research grade. The purity was 99.997% for O_2, 99.99% for CO and 99.995% for Kr as stated by Matheson.

2.2. Error estimation

The errors in these measurements fall into two categories, statistical and systematic.

2.2.1. Statistical. The cross sections reported here are an average of at least three independent experimental runs and each run contains several measurements for the

same energy. The statistical error associated with the cross sections is given by:

$$\% \text{ error} = \frac{100}{\langle\sigma\rangle}\left(\sum_{i=1}^{N}\frac{(\sigma_i - \langle\sigma\rangle)^2}{N-1}\right)^{1/2}$$

where $\langle\sigma\rangle$ is the average cross section, σ_i is the ith measured cross section and N is the number of measurements.

2.2.2 Systematic. There are several sources of systematic errors.

A systematic error of 1% resulting from pressure measurements is assumed since the MKS manometer is specified by the manufacturer with an accuracy better than 1%. Scattering in the forward direction may be another cause of systematic errors. As was mentioned earlier, the measured cross section and the true cross section may not have the same value due to the contribution to the transmitted current in the forward direction. In the present apparatus, $\theta_{max} = 0.89°$ and $\langle\Delta\Omega\rangle = 2.2 \times 10^{-4}$ sr. Under these circumstances, the error due to the forward scattering is negligible compared to the other sources of errors according to calculations using very small angle differential cross sections.

Another type of systematic error is due to the uncertainty of the physical length of the scattering cell L_2 (14.43 cm). Since the electron beam passes through differential pumping chambers of L_1 (7.0 cm) and L_3 (7.1 cm), presence of any gas in these chambers will make the effective attenuation length differ from L_2 and higher values of cross sections will be obtained. For our case, we assign 1% error to this effect according to the formula:

$$\frac{\sigma_m - \sigma}{\sigma} = \frac{\alpha(L_1 + L_3)}{L_2} \simeq \alpha$$

where α is the ratio of the density in the differential pumping chambers to the density in the scattering chamber.

Thermal transpiration effects can be another source of systematic error. The present data indicate that the thermal transpiration effect is not important in our measurements and an error associated with it is negligible compared to the other errors.

As a result, the combined systematic error in the present data is of the order of 2%.

3. Results and discussion

In this part of the work, the results of the measurements of total electron scattering cross sections together with the statistical errors are reported. The measurements have been made in the electron impact energy range of 5–300 eV for Kr, O_2 and CO and the results are summarized in table 1. Each entry given in table 1 is the average of at least three (usually more) independent experimental runs taken over a period of several months.

Figure 2 compares the present data for Kr with those of Wagenaar and de Heer (1980) and Dababneh *et al* (1982) in the energy range 20–300 eV, Dababneh *et al* (1980) in the energy range 4.7–99.4 eV, Jost *et al* (1983) in the energy range 7.5–6.0 eV and the remeasured data of Wagenaar and de Heer (1985) in the energy range 20–300 eV. The present measurements are found to be in good agreement with other experimental data. Discrepancies between the present data set and those of other workers are found to be within 5% (ususally much less) at all energies of overlap.

Table 1. Total electron scattering cross sections (Å^2). The numbers in parentheses refer to statistical errors (%).

Impact energy (eV)	Kr	O_2	CO
5	16.73 (2.2)	7.40 (3.0)	14.73 (0.9)
6	20.22 (2.5)	7.96 (0.6)	13.63 (0.3)
7	—	—	13.61 (0.7)
8	25.98 (1.3)	8.70 (2.1)	13.88 (0.3)
9	—	—	13.62 (0.5)
10	28.16 (1.1)	10.14 (1.4)	13.27 (1.0)
11	—	—	13.18 (0.5)
12	28.42 (1.8)	10.62 (0.1)	13.34 (0.1)
14	27.09 (0.8)	10.76 (0.7)	13.75 (0.2)
16	25.54 (1.0)	10.74 (0.5)	14.07 (0.3)
18	24.24 (0.8)	10.75 (1.7)	14.26 (0.2)
20	23.32 (1.5)	10.79 (0.3)	14.46 (0.5)
25	21.04 (1.3)	11.10 (0.9)	14.06 (0.5)
30	19.05 (1.0)	11.12 (0.5)	13.54 (0.5)
40	16.53 (1.1)	10.83 (0.4)	12.67 (0.3)
50	14.91 (0.1)	10.36 (0.9)	11.90 (0.1)
60	13.87 (1.1)	9.77 (0.9)	11.19 (0.6)
70	13.00 (1.0)	9.41 (0.8)	10.62 (0.6)
80	12.09 (0.9)	9.07 (0.4)	10.11 (0.2)
90	11.32 (0.9)	8.76 (0.7)	9.69 (0.3)
100	10.59 (0.6)	8.26 (0.4)	9.29 (0.5)
125	9.69 (0.3)	7.42 (1.2)	8.41 (0.7)
150	8.73 (0.6)	6.97 (0.7)	7.65 (0.2)
200	7.44 (1.2)	5.97 (0.6)	6.60 (0.7)
250	6.82 (0.8)	5.21 (0.8)	5.79 (0.1)
300	6.00 (1.0)	4.88 (0.2)	5.23 (0.2)

The present measurement of $e^- + O_2$ total scattering cross sections is shown in figure 3, together with other measurements. Our results are about 5% lower than those of Dalba *et al* (1980) above 100 eV. The present measurements agree fairly well and are lower by about 5% below 12 eV and higher by about 2% (which is in the experimental error limits) above 14 eV than the results of Zecca *et al* (1986), except at 100 eV where the disagreement is 10%. The results of Griffith *et al* (1982) are lower than ours by about 6% in the full 5–50 eV energy range. This discrepancy may be due to an ineffective discrimination against electrons inelastically scattered in the forward direction in their experimental arrangement. In the peak region, the results of Dababneh *et al* (1988) are appreciably higher than our measurements and those of other workers. It should be pointed out that the same type of discrepancy exists between their data and those of Zecca *et al* (1991) and Kanik *et al* (1992) for CH_4, again in the same region where the cross sections peak. The reason for this systematic discrepancy is not clear. Below 20 eV and above 100 eV, the agreement between our measurements and those of Dababneh *et al* is fair and our results are, in general, 5% lower. Since the filament emission current is usually affected by oxygen, the electron current was monitored carefully after each set of runs to make sure that no significant changes in the emission took place. For the present measurements, no filament emission current changes have been noticed. This may be due to the differential pumping system in the gun area as well as the insensitivity to oxygen of the particular filament used.

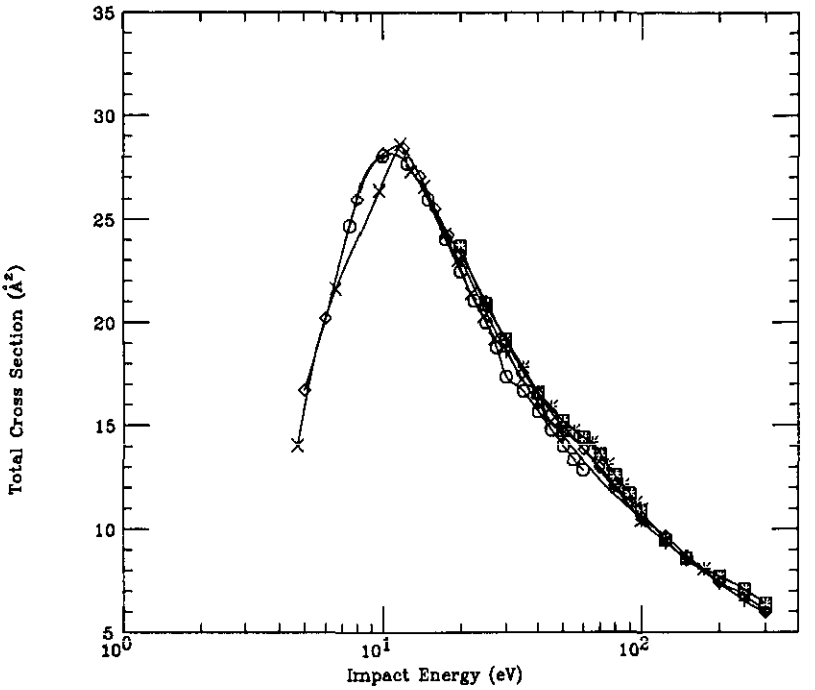

Figure 2. Total electron cross section results for Kr. ◇, present data; ×, Dababneh *et al* (1980); □, Wagenaar and de Heer (1980); +, Dababneh *et al* (1982); ○, Jost *et al* (1983); *, Wagenaar and de Heer (1985).

Figure 4 shows the present results for the total cross sections of CO compared with those of Kwan *et al* (1983). The present measurements agree remarkably well with those of Kwan *et al* (1983). The discrepancy in these measurements is typically less than 2% over the entire energy range. It is interesting to note that around 20 eV both data sets exhibit a maximum. This may be associated with the resonance observed in the vibrational excitation channel by Chutjian *et al* (1972). They observed that the differential cross sections show large enhancements near 20 eV impact energy. Their calculations indicated that this enhancement cannot be accounted for by purely potential (non-resonant) scattering processes. The results of Sueoka and Mori (1984) are estimated to be about 10–15% lower than ours. Agreement gets better in the higher impact energy region. We were unable to make a direct comparison between their and our data sets since their results were not tabulated.

4. Conclusion

We have presented the total electron scattering cross sections for Kr, O_2 and CO in the electron impact energy range of 5–300 eV. Good to excellent agreement has been found with the results of other groups except in the case of oxygen. For this particular gas, a comparison shows that the disagreement between the present measurements and those of other groups is large compared to experimental error limits between 20–100 eV except those of Zecca *et al* (1986). In the energy range above 100 eV, the agreement

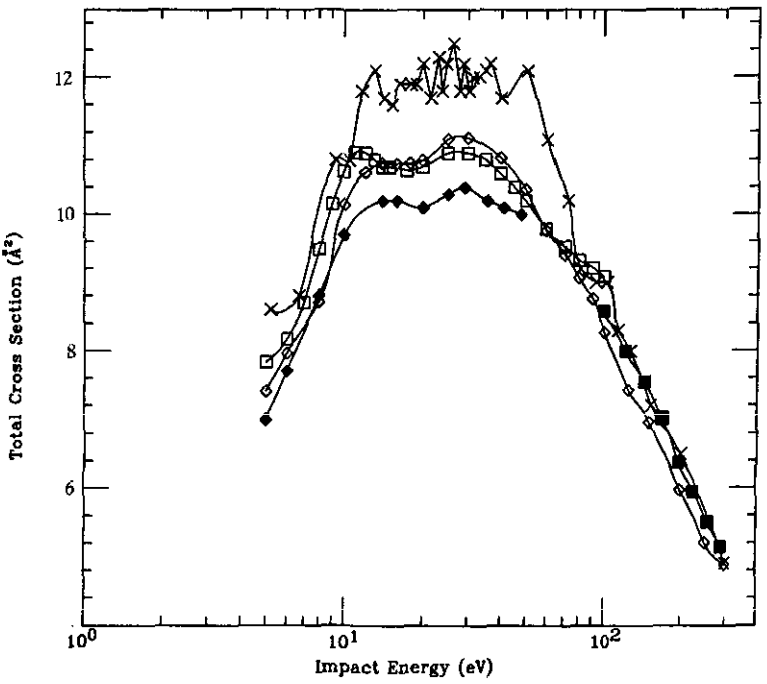

Figure 3. Total electron cross section results for O_2. ◇, present data; ■, Dalba *et al* (1980); ◆, Griffith *et al* (1982); □, Zecca *et al* (1986); ×, Dababneh *et al* (1988).

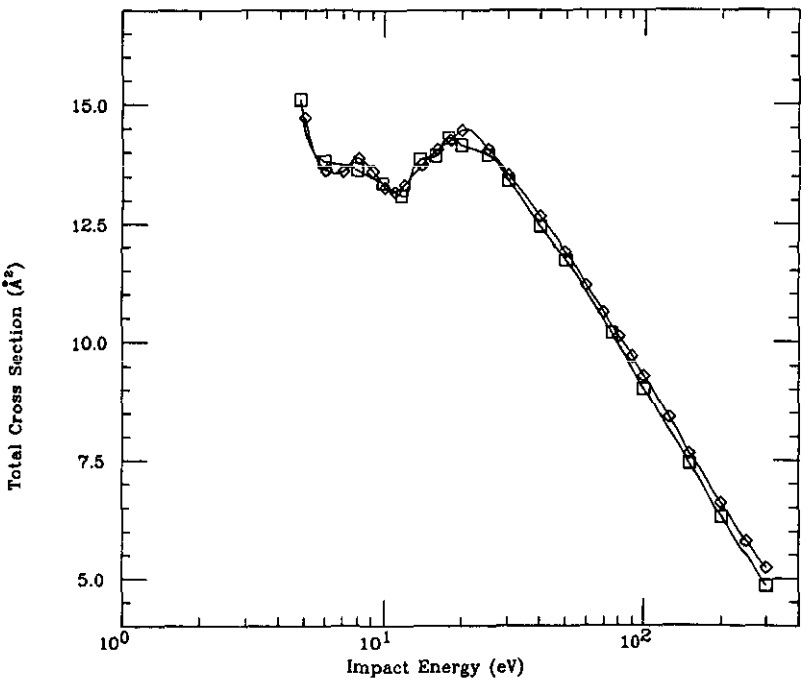

Figure 4. Total electron cross section results for CO. ◇, present data; □, Kwan *et al* (1983).

gets better (ususally less than 5%). The CO total cross section curve exhibits a broad peak near 20 eV which may indicate a resonant excitation process.

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