PRAMANA
—journal of
physics

Vol. 50, No. 5,
May 1998
pp. 447–457

Total electron scattering cross sections for carbon dioxide at low electron energies

P RAWAT, K P SUBRAMANIAN and VIJAY KUMAR
Physical Research Laboratory, Navrangpura, Ahmedabad 380 009, India
E-mail: vkumar@prl.ernet.in

MS received 9 January 1998

Abstract. Absolute total electron scattering cross sections for carbon dioxide have been measured at low electron energies using a photoelectron source. The measurements have been carried out at 27 electron energies varying from 0.91–9.14 eV with an accuracy of ±3%. The cross sections obtained in the present experiment have been compared with other measurements and theoretical computations.

Keywords. Electron scattering; total cross sections; carbon dioxide.

PACS No. 34.80

1. Introduction

In recent years, there has been considerable interest in the measurement of total electron scattering cross sections of carbon dioxide, especially at low electron energies. Also, a lot of activity in the theoretical study of e-CO_2 collisions has started in the recent past. One of the reasons for such an interest lies in the fact that CO_2 plays an important role in the study of planetary atmospheres, laser fusion plasma and gas lasers. Also, this is one polyatomic molecule for which accurate low energy electron scattering cross section calculations are available.

The electron scattering cross section measurements for carbon dioxide have been carried out using various techniques. This includes the work reported by Brüche [1], Ramsauer and Kollath [2], Szmytkowski and Zubek [3], Ferch *et al* [4], Hoffman *et al* [5], Sueoka and Mori [6], Szmytkowski *et al* [7] and Buckman *et al* [8]. These measurements show an increase in cross section with decreasing electron energy below 1.8 eV and at around 70 meV, the cross sections have been found to exceed the value at the maximum of the $^2\Pi_u$ resonance at around 3.8 eV by a large factor [4]. The cross sections have also been theoretically computed by Morrison *et al* [9] using coupled channels procedure together with the adiabatic nuclei approximation. Comparison of the measured and the theoretically computed cross section values shows a general agreement in the shape of the cross section curve in the electron energy range from 0–10 eV but quantitatively, the cross section values at the peak of the resonance and at electron energies ranging between 5 to 10 eV show a large discrepancy. In view of this, more measurements are needed in this direction, possibly at higher electron energy resolution.

This paper is a part of the ongoing research work which aims to measure total electron scattering cross sections for atoms and molecules at low electron energies using a photoelectron source. Previously, cross section measurements have been carried out for helium, neon [10], argon, krypton, xenon [11], molecular hydrogen [12] and molecular oxygen [13] at electron energies from 0–10 eV. In this paper, we present the cross sections for carbon dioxide in the electron energy range between 0.91 and 9.14 eV at an electron energy resolution of 45 meV.

2. Experimental set up

The experimental set up used for the study, the method for analysis of the data and error analysis have been described in detail previously by Kumar *et al* [10] and Subramanian and Kumar [11]. In brief, the experiment consists of measuring the intensities of the peaks in the photoelectron spectra of the source gas such as argon, krypton, xenon or carbon dioxide itself. The photoelectrons thus produced by the source gas are scattered by the target gas, the cross section of which is to be determined. Each peak in the photoelectron spectrum of the source gas provides one point in the electron energy scale.

Electrons are produced by photoionization of the source gas in a small ionization region located close to the electron energy analyser. Vacuum ultraviolet photons from strong atomic emission lines are allowed to impinge on the source gas which is photoionized and electrons of different energies corresponding to the states of the ions are produced. With different combination of photons of three different wavelengths (He I 58.4, Ne I 73.6 and 74.4 nm) and argon, krypton, xenon and carbon dioxide as source gases, a large number of electron energies are accessible from 0.91 to 9.14 eV. The resonant emission lines He I (58.4 nm) and Ne I (73.6 and 74.4 nm) are produced by microwave discharge of helium and neon respectively. The intensity of the photon beam is monitored using a beam splitter which consists of a high transparency wire mesh mounted at an angle of 45° to the beam axis. More than 90% of the light is transmitted and the rest is reflected towards a light detector which includes a perspex light pipe coated at the front end with a scintillator, *p*-terphenyl, and an EMI 6199 photomultiplier. Any change in the light intensity could thus be monitored using the beam splitter, and the change in intensity, if any, during the experiment could be incorporated in the results.

The transmitted photon beam was allowed to pass through a large number of circular baffles before emerging into a small region where photoionization of the source gas takes place. The pressure of the source gas was kept low to avoid any electron scattering by the source-gas atoms/molecules. The photoelectrons thus produced were energy analysed using a cylindrical mirror analyser (CMA) and were detected by a channeltron (4029, Galileo Electro-Optics Corp., USA) operated in the counting mode. After proper amplification, the signals were stored in a microprocessor-controlled multichannel analyser operated in the multiscaling mode.

The CMA has a slit-to-slit focusing geometry and the diameter of the inner and outer cylinders were 10.2 and 25.4 cm respectively. The photoelectrons produced in the ionization region were allowed to enter the first slit of the analyser at an angle of $54°44' \pm 3°$. The distance between the two slits was kept at 15.9 cm, in accordance with the best focusing conditions around 55°. A slit width of 2 mm was used for both the slits. The

photoelectrons, thus, produced were allowed to be scattered by the target gas and the scattering path length, limited between the centre of the ionization region and the first slit used to define the 55° angle over the 2π geometry, was 2.37 cm. Without any target gas, the amplitudes of the photoelectron peaks produced by the source gas were monitored at a fixed but low source gas pressure in the ionization region. The target gas was then introduced and if the source gas and target gas were not the same, the amplitudes of the photoelectron peaks would decrease with increasing target gas pressure. This decrease was attributed to electron scattering by target gas species whose number density increases with increasing pressure. When the source and target gas were the same (e.g. in case of carbon dioxide), the amplitudes of the photoelectron peaks would first increase with increase of source/target gas pressure and after a certain gas pressure was attained, the amplitudes would start decreasing with subsequent increase in gas pressure. To begin with, the increase in peak amplitudes would be due to the increase in photoelectron production rate followed by small electron scattering, but the subsequent decrease in amplitudes was because of scattering alone. The absolute gas pressure in the ionization and scattering regions was measured using an MKS capacitance manometer (head 310 MH-1). The details about pressures in different regions of the instrument have been given in a previous publication [10].

3. Method and error analysis

Using the technique described above, electron scattering cross sections for carbon dioxide have been measured at 27 energies. When source and target species are different, the electron scattering cross section σ can be evaluated by using the following equation:

$$\ln\left(\frac{I_{e2}}{I_{e1}}\frac{I_{\lambda 01}}{I_{\lambda 02}}\right) = \frac{P_1 - P_2}{760}[n_0\sigma x + k(al_1 + l_2)]. \tag{1}$$

Here I_{e1} and I_{e2} are the amplitudes of the photoelectron peak at two different target gas pressures P_1 and P_2, $I_{\lambda 01}$ and $I_{\lambda 02}$ are the incident photon intensities monitored by the beam monitor during the experiment at two pressures, l_1 is the distance from the centre of the beam splitter to the circular aperture covering the ionization region, l_2 is the distance from the same aperture to the actual ionization region defined geometrically by different slits in the accelerator region and cylindrical mirror analyser, x is the scattering path length, a is the ratio of the pressures of the target gas outside and inside the ionization region and k is the photoabsorption coefficient of the target gas at a particular photon wavelength (figure 1). The total photoabsorption coefficients for carbon dioxide at the three incident photon wavelengths have been taken from Samson and Yin [14]. The ratios of $I_{\lambda 01}$ and $I_{\lambda 02}$ were determined from the beam splitter as described previously [10].

When source and target gas species are the same, the electron scattering cross sections could be evaluated by the equation given below:

$$\ln\left(\frac{I_{e2}}{I_{e1}}\frac{I_{\lambda 01}}{I_{\lambda 02}}\frac{P_1}{P_2}\right) = \frac{P_1 - P_2}{760}[n_0\sigma x + k(al_1 + l_2)]. \tag{2}$$

Error analysis in the measurement of electron scattering cross sections has been discussed in detail previously [10]. Based on those discussions, the probable error in the

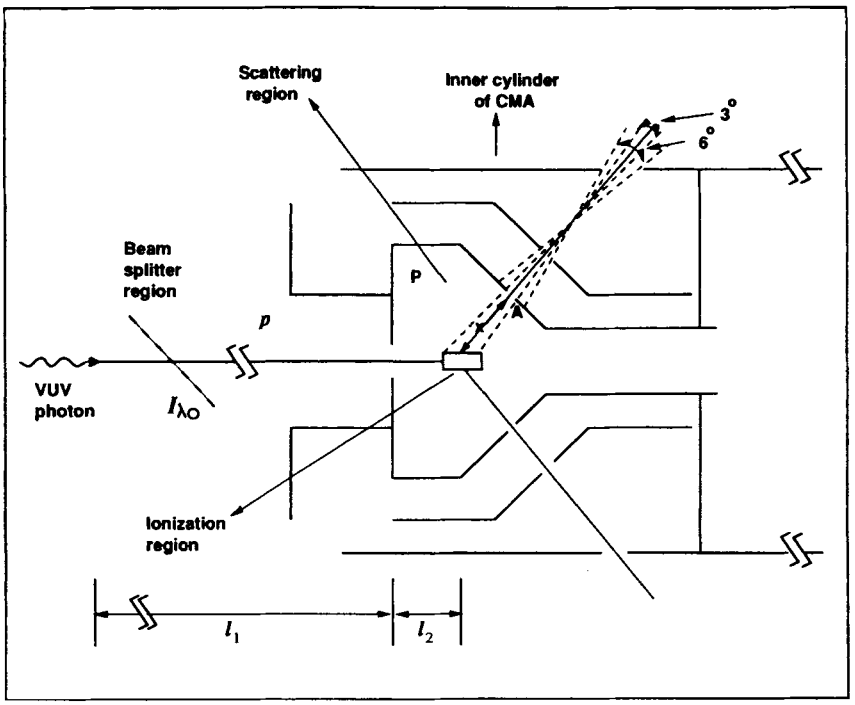

Figure 1. Schematic diagram showing ionization as well as the electron scattering region in the cylindrical mirror analyser of the photoelectron spectrometer.

present experiment was estimated to be $\pm 3\%$. The electron scattering cross sections for carbon dioxide were measured using equations (1) and (2) respectively in the two cases described above. In both these equations, all parameters $I_{e1}, I_{e2}, I_{\lambda 01}, I_{\lambda 02}, P_1$ and P_2 could be determined experimentally and cross sections could be calculated.

The problem of inadequate discrimination against forward scattered electrons is a difficult one. Such an inadequacy is due to the inability of the experimental system to discriminate low angle scattered electrons which, in general, have large amplitudes. Attempts to estimate the magnitude of this effect on the measured cross sections in a certain experimental set up becomes much more difficult as almost no experimental values of elastic and inelastic differential scattering cross sections at very low angles are available. An attempt, however, has been made in this direction for our experimental set up using a numerical simulation method.

In the present experimental set up, the geometry of the apparatus allows a full cone angle of 3° beam of electrons into the analysing region (figure 1). Taking into account the forward scattering of the electrons near the exit slit of the scattering region, it would be safe to assume that the overall angle of emergence is increased by a factor of two, giving the full cone angle of 6° around the nominal angle of projection of 54°44′.

In order to study the problem of inadequate discrimination against forward scattered electrons, a Monte Carlo method was developed. The electron trajectories originating from the ionization region and terminating at the detector were numerically studied using

five random generators. These random generators appropriately took care of the spread in parameters related to (i) the finite length of the ionization region where photoelectrons are produced, (ii) random angle of projection within the allowed cone of ejection determined by the geometry, (iii) spread in energy of the photoelectron determined by the thermal broadening, (iv) place nearby the first slit A (figure 1) where a chosen fraction of the emitted photoelectrons are undergoing forward scattering and (v) deflection in angle within a specified cone due to the forward scattering. Assuming cylindrical symmetry of the spectrometer, the analysis was carried out in the in-plane geometry. In the absence of values of differential cross section available at small angles, the forward scattering cross section at the exit slit was arbitrarily chosen as $100\,\text{Å}^2$ per steradian, which is about 6 times larger than the peak value of the measured total cross section in the present work.

The discrimination due to geometry was computed using normal trigonometrical relations. The discrimination due to the range differences are computed with the standard equation for range of electron trajectory in the analysing field of a slit-to-slit focussing type CMA given by

$$L = r_1 \times \sqrt{4\pi k}\cos\theta \exp(-k\sin^2\theta)\text{erf}\,(\sqrt{k}\sin\theta). \tag{3}$$

Equation (3) has been derived by Karras *et al* [15]. The error function $\text{erf}(\sqrt{k}\sin\theta)$ is defined as

$$\text{erf}(x) = \frac{2}{\sqrt{\pi}}\int_0^x e^{-t^2}\mathrm{d}t,$$

where $x = \sqrt{k}\sin\theta$. The analyser constant, $k = E/eV\ln(r_2/r_1)$, E is the energy of the electron in eV, e is the electronic charge, V is bias potential applied to the analysing field electrode, θ is the angle of projection and r_1 and r_2 are the radii of the inner and outer cylinders of CMA.

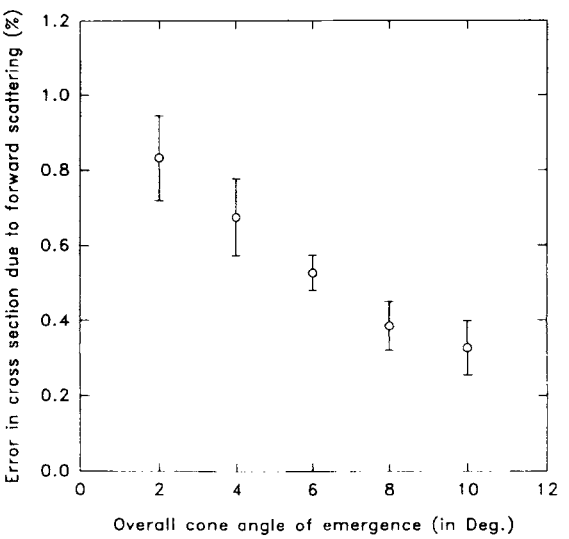

Figure 2. Result of Monte Carlo calculations showing angular discrimination of the forward scattered electrons in the apparatus used in the present experiment.

In the present study, 250,000 trajectories were analysed for different values of $\Delta\epsilon/E$, where E is the energy of the photoelectron and $\Delta\epsilon$ is the spread in energy due to thermal broadening. For each value of $\Delta\epsilon/E$, five sets of data were generated for deriving standard deviation values. Finally, similar data were generated for different angles of emergence for forward scattering giving the full cone angles of 2, 4, 6, 8 and 10°.

The result shows that the average value of error in cross section due to lack of discrimination is more or less independent of $\Delta\epsilon/E$ in the chosen range of 0.2 to 0.6%. However, it is very much dependent on the overall cone angle of emergence. The results of the present study are shown in figure 2, where the error in cross section value is plotted against the overall cone angle of emergence.

For our experimental system where the overall cone angle of emergence has been estimated to be 6°, the maximum error due to inadequate discrimination against forward scattering has been found to be about 0.5%.

4. Results and discussion

The total electron scattering cross sections for carbon dioxide as measured in the present experiment are shown in figure 3 for electron energies ranging from 0.91 to 9.14 eV along with error bars at four energies only. Also shown in the figure are the measured cross sections reported by Ferch *et al* [4], Hoffman *et al* [5], Buckman *et al* [8], and Szmytkowski *et al* [7] and theoretically computed cross sections by Morrison *et al* [9]. Transmission measurements made with an electron time-of-flight spectrometer were reported by Ferch *et al* [4] in the low electron energy region (0.07 to 4.62 eV) with an energy resolution of 10 meV at 0.07 eV and 250 meV at 3.8 eV respectively. The measurements of Hoffman *et al* [5] were carried out using a beam transmission technique at electron energies from 2–50 eV at an energy resolution of 140 meV. The retarding potential time-of-flight technique was used by Sueoka and Mori [6] and a time-of-flight technique was also used by Buckman *et al* [8] to measure cross sections at electron energies from 5 to 403 eV and 0.10–5.0 eV with an energy resolution of 300 and 250 meV respectively. A linear transmission method was employed by Szmytkowski *et al* [7] for electron energies varying from 0.5 to 80 eV at the energy resolution of 50 meV. The cross sections were also measured using the Ramsauer technique by Brüche [1] and Ramsauer and Kollath [2] and the normalized values of cross section were reported by Szmytkowski and Zubek [3] using a linear transmission method in the electron energy 1–49 eV, 0.2–2 eV and 2–8 eV respectively. The theoretically computed cross sections were reported by Morrison *et al* [9], Morrison and Lane [16], Collins and Morrison [17], and Lynch *et al* [18]. A theoretical coupled channels investigation was reported by Morrison *et al* [9] for incident electron energies from 0.07 to 10.0 eV. The fixed nuclei approximation was made with the molecule in the ground state and the nuclei frozen at their equilibrium positions. The static-model exchange-polarization interaction potential was used to calculate total integrated cross sections. The improvement in the method was carried out by Collins and Morrison [17] at electron energies ranging from 0.1 to 2 eV by using orthogonalized model potential. Lynch *et al* [18] calculated the integrated elastic electron scattering cross sections from 0–100 eV using the continuum multiple scattering model with the Hara exchange approximation. For the sake of convenience and for reasons of clarity, the cross

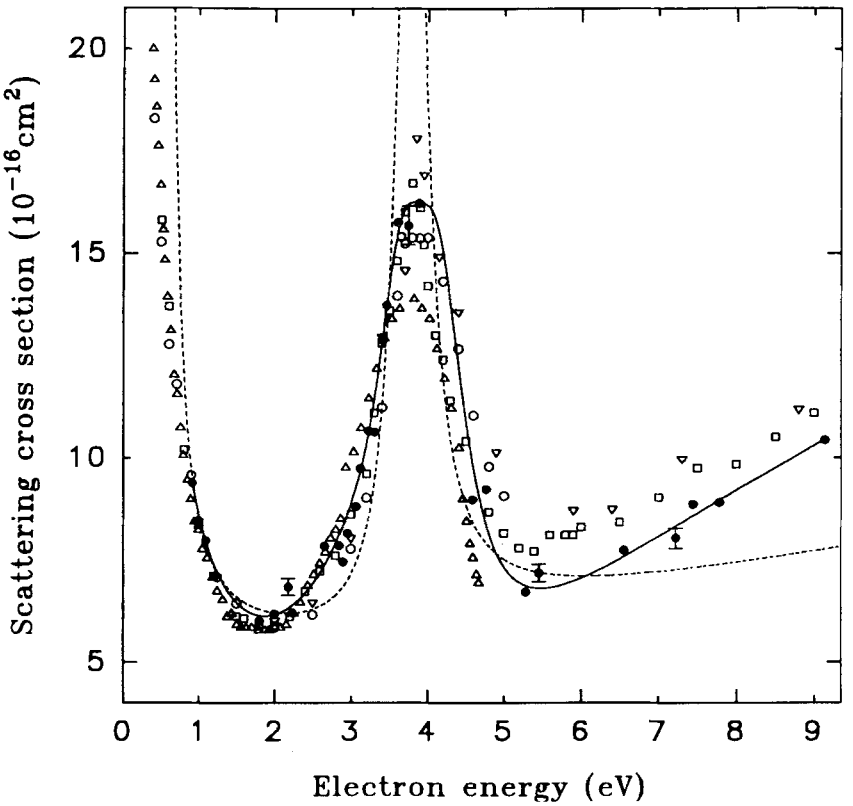

Figure 3. Total electron scattering cross sections for carbon dioxide as a function of incident energy from 0.91 to 9.14 eV obtained by various researchers. The symbols denote: ○, Buckman *et al* [8]; ▽, Hoffman *et al* [5], ..., Morrison *et al* [9]; □, Szmytkowski *et al* [7]; △, Ferch *et al* [4]; •, present work; ————, cross section curve after proper curve fitting (present work).

section values reported by Brüche [1], Ramsauer and Kollath [2], Szmytkowski and Zubek [3], Morrison and Lane [16], Collins and Morrison [17] and Lynch *et al* [18] have not been included in figure 3.

For the sake of discussion, the cross section curve (figure 3) in the total electron energy range from 0–9 eV has been divided into three regions. These include energy regions below 2 eV, between 2 to 5 eV and between 5 to 9 eV. In the first energy region, the cross section has been found to decrease rapidly with increasing energy followed by a sharp increase at higher energies. This rapid decrease is mainly due to s-wave scattering and thus can be explained by a nearly bound $l = 0$ state in the e-CO_2 potential [9, 19]. The existence of such a virtual state has been verified both experimentally by Kochem *et al* [20] as well as theoretically by Estrada and Domcke [21]. At energies below 1.1 eV, there is an excellent agreement in cross section values reported by Buckman *et al* [8], Szmytkowski *et al* [7], Ferch *et al* [4], Morrison *et al* [9] and those obtained in the present experiment. But the agreement worsens at increasing energies. There is a large discrepancy between the results shown in figure 3 compared to values reported by Lynch

et al [18] at all energies below 2 eV. Also, both the cross section values as well as the electron energies at the minimum have been reported to be different by different researchers. The cross section and the energy minima have been reported in the present work and by Szmytkowski *et al* [7] to be 6.13 and 5.84 $Å^2$ at 1.88 and 1.90 eV respectively whereas Ferch *et al* [4], Hoffman *et al* [5], Buckman *et al* [8] and Morrison *et al* [9] have reported the cross section values of 5.85, 6.02, 5.84 and 6.21 $Å^2$ at the minima of around 1.8, 2.0, 2.0 and 2.0 eV respectively. It may be pointed out here that the minima stated above are not those directly measured by the respective groups, but rather are the results obtained by fitting curves to the values measured by them. Also, it may not be possible to have an exact energy minima in case of Buckman *et al* [8] and Hoffman *et al* [5]. In the first case [8], the energy steps used are large (0.5 eV) and therefore, elude finding the exact minimum; in the second case [5], there is no data available below 2.0 eV. A comparison of all these values shows that the largest disagreement in cross sections at the minimum is about 6.3%.

The results obtained in the present experiment in the energy region 2–5 eV (figure 3) shows a sharp increase in cross section up to the well known maximum centered around 3.8 eV followed by a sharp decrease up to 5 eV energy. The peak around 3.8 eV was attributed to the formation of a shape resonance [22]. The temporary state involved was the $^2\Pi_u$ of the CO_2^- ion having a short lifetime. In general, the shape of the resonance peak has been faithfully reproduced by all the work shown in figure 3 but the cross section values at the maximum of the resonance peak and also at the wings around the peak show some discrepancies. To have a clear comparison, the cross section curves reported by Ferch *et al* [4], Buckman *et al* [8], Hoffman *et al* [5], Szmytkowski *et al* [7], and Morrison *et al* [9] along with the curve obtained in the present experiment have been made to undergo proper curve fitting procedure. The cross section curve after proper curve fitting to the results obtained in the present experiment has also been shown in figure 3. This has been carried out using an appropriate mathematical function in the library of large number of such functions available in the Tablecurve-2D (Jandel Scientific) software. After proper fitting, the values of electron energy and cross section at the peak of the shape resonance, width of the peak at 75% of the maximum value and the slopes of the peak at 75% value on both wings of the peak have been obtained and these are given in table 1. The values of 75% was chosen as in most of the curves, it was difficult to get full width at half maximum. Also given in the table are the values of energy resolution used by researchers in their respective experiments. From the table, it is clear that there is a good agreement in the energy values obtained at the peak of the resonance but the cross section values show a large discrepancy between the present results and other investigations. There is large overestimation of cross section of 30.88 $Å^2$ by Morrison *et al* [9] and this is most likely due to the neglect of nuclear motion in the calculation [8]. The cross section values given by Ferch *et al* [4] and Buckman *et al* [8] are 14.2 and 5% lower as compared to the cross section reported in the present work whereas the cross section value (not given in table 1) reported by Sueoka and Mori [6] is almost 30% smaller. There is a fairly good agreement in the cross section value reported by Szmytkowski *et al* [7] and Hoffman *et al* [5] as compared to that given in the present experiment. It is expected that higher the energy resolution used in the experiment, higher is the value of the peak of the shape resonance. But this is not the case as is clear from table 1. The results of all experimental groups at their respective peaks agree with each

Table 1. Some characteristic parameters of the shape resonance as obtained after proper curve fitting to the results reported by different experimental groups. Also given in table is the energy resolution used in different experiments.

CO_2	Energy resolution in meV	Peak value: Electron energy (eV)	Peak value: Cross section (Å^2)	ΔE at 75% of peak value (eV)	|Slope| in Å^2/eV at 75%: Rising	|Slope| in Å^2/eV at 75%: Falling
Frerch *et al* [4]	~250	3.8	13.9	1.3	6.4	9.7
Buckman *et al* [8]	~250	3.9	15.4	1.1	13.4	8.7
Hoffman *et al* [5]	~140	3.9	16.9	1.0	12.1	9.8
Szmytkowski *et al* [7]	~50	3.8	16.7	0.8	13.1	12.4
Morrison *et al* [9]	–	3.8	30.9	0.3	77.6	77.6
Present work	~45	3.8	16.2	0.9	13.9	14.7

other within the experimental uncertainties except possibly those of Ferch *et al* [4]. It appears that such a behaviour cannot be explained by the above argument alone but it is felt that the above behaviour could be explained by the combined effect of narrower electron energy width and better discrimination against small angle scattering in different experiments. In the present experiment, it has been shown that error in cross section values due to lack of discrimination against low angle scattering is about 0.5%. Hoffman *et al* [5] have pointed out that their measurements may be 1% too low at 4 eV and less than 1% too low at 10 eV because of inadequate discrimination against forward scattered electrons. In a subsequent paper, Buckman and Lohmann [23] have discussed about the problem of low angle scattering in their experimental system and estimated this error to be less than 0.1% at about 2 eV electron energy. The small angle contribution was estimated to be below 0.5% at all electron energies of interest in the experimental system reported by Szmytkowski *et al* [7] where as no such estimate was reported by Ferch *et al* [4].

Also given in table 1 are the ΔE values at 75% of the peak value of the shape resonance and modulus of the slopes at the two sides of the peak at 75% peak value. The values of the modulus of the slopes on the rising and falling sides of the peak as given by different experimental groups show that the resonance peak is more or less symmetrical around the maximum in the present work as well as in the experiment reported by Szmytkowski *et al* [7] whereas the experiments by Ferch *et al* [4], Buckman *et al* [8] and Hoffman *et al* [5] show that the resonance peak is asymmetrical in nature. This may be attributed to the energy resolution used in the experiment. It has been found (table 1) that higher the energy resolution, more symmetrical is the resonance peak around the maximum.

In the energy region from 5–9 eV, cross section values reported by the three experimental groups only ([5, 7] and present work) have been shown in figure 3 along with the theoretically computed values of Morrison *et al* [9]. Unfortunately, Ferch *et al* [4] and Buckman *et al* [8] have not carried out these measurements beyond 4.62 and 5.0 eV respectively. The general trend in this energy region as suggested by different research groups is that the cross section curve passes through a minimum on the decreasing wing of the main shape resonance peak followed by an increase in cross sections at higher energies. The minimum as reported in the present experiment as well as Szmytkowski

Table 2. Total electron scattering cross sections for carbon dioxide at various electron energies. Also given are the photon wavelength, the source gas and the photoion state for the corresponding electron energy.

Wavelength λ (Å^2)	Source gas	Photo-ion state	Electron energy (eV)	Cross section (Å^2)
744	Ar	$^2P_{3/2}$	0.91	9.38
736	Ar	$^2P_{3/2}$	1.09	7.96
584	CO_2	$\tilde{C}^2\Sigma_g^+$	1.80	6.01
744	Kr	$^2P_{1/2}$	2.00	6.19
736	Kr	$^2P_{1/2}$	2.18	6.84
744	Kr	$^2P_{3/2}$	2.66	7.83
736	Kr	$^2P_{3/2}$	2.85	7.84
744	CO_2	$\tilde{X}^2\Pi_g$	2.90	7.44
584	CO_2	$\tilde{B}^2\Sigma_u^+(\nu=1)$	2.96	8.15
736	CO_2	$\tilde{X}^2\Pi_g$	3.07	8.80
584	CO_2	$\tilde{B}^2\Sigma_u^+(\nu=0)$	3.12	9.74
744	Xe	$^2P_{1/2}$	3.23	10.65
584	CO_2	$\tilde{A}^2\Pi_u(\nu=4)$	3.31	10.62
736	Xe	$^2P_{1/2}$	3.41	12.89
584	CO_2	$\tilde{A}^2\Pi_u(\nu=3)$	3.46	13.74
584	CO_2	$\tilde{A}^2\Pi_u(\nu=2)$	3.61	15.75
584	CO_2	$\tilde{A}^2\Pi_u(\nu=1)$	3.75	15.68
584	CO_2	$\tilde{A}^2\Pi_u(\nu=0)$	3.89	16.22
744	Xe	$^2P_{3/2}$	4.59	8.95
736	Xe	$^2P_{3/2}$	4.77	9.21
584	Ar	$^2P_{1/2}$	5.28	6.71
584	Ar	$^2P_{3/2}$	5.46	7.18
584	Kr	$^2P_{1/2}$	6.55	7.73
584	Kr	$^2P_{3/2}$	7.22	8.02
584	CO_2	$\tilde{X}^2\Pi_g$	7.44	8.85
584	Xe	$^2P_{1/2}$	7.78	8.88
584	Xe	$^2P_{3/2}$	9.14	10.43

et al [7] and Hoffman *et al* [5] occurs almost at the same energy of about 5.4 eV with different cross section values of 6.9, 7.9 and 8.5 Å^2 respectively. Morrison *et al* [9] reported a minimum value of 7.1 Å^2 at the electron energy of 6.0 eV but the increase in cross section values was rather slow at higher electron energies. At electron energies between 5.5 and 9 eV, rate of change of cross section per unit electron energy has been found to be almost similar in the three cases, but absolute values of cross sections are quite different. At the two typical energies 7.5 and 9.0 eV, the cross section values reported in the present work are lower by 10% and 7% as compared to those given by Szmytkowski *et al* [7] and by 15 and 9% with respect to cross sections obtained by Hoffman *et al* [5].

Electron scattering cross sections

The values of cross sections for carbon dioxide as measured in the present experiment are given in table 2 along with the photon wave length, source gas and photoion state for the corresponding electron energy.

References

[1] E Brüche, *Ann. Phys. Lpz.* **83**, 1 (1927)
[2] C Ramsauer and R Kollath, *Ann. Phys. Lpz.* **4**, 91 (1930)
[3] C Szmytkowski and M Zubek, *Chem. Phys. Lett.* **57**, 105 (1978)
[4] J Ferch, C Masche and W Raith, *J. Phys. At. Mol. Phys.* **14**, L97 (1981)
[5] K R Hoffman, M S Dababneh, Y-F Hsiech, W E Kauppila, V Pol, J H Smart and T S Stein, *Phys. Rev.* **A25**, 1393 (1982)
[6] O Sueoka and S Mori, *J. Phys. Soc. Jpn.* **53**, 2491 (1984)
[7] C Szmytkowski, A Zecca, G Karwasz, S Oss, K Maciag, B Marinkovic, R S Brusa and R Grisenti, *J. Phys.* **B20**, 5817 (1987)
[8] S J Buckman, M T Elford and D S Newman, *J. Phys.* **B20**, 5175 (1987)
[9] M A Morrison, N F Lane and L A Collins, *Phys. Rev.* **A15**, 2186 (1977)
[10] V Kumar, E Krishnakumar and K P Subramanian, *J. Phys.* **B20**, 2899 (1987)
[11] K P Subramanian and V Kumar, *J. Phys.* **B20**, 5505 (1987)
[12] K P Subramanian and V Kumar, *J. Phys.* **B22**, 2387 (1989)
[13] K P Subramanian and V Kumar, *J. Phys.* **B23**, 745 (1990)
[14] J A R Samson and L Yin, *J. Opt. Soc. Am.* **B6**, 2326 (1989)
[15] M Karras, M Pessa and S Aksela, *Ann. Acad. Sci. Finnicae* **AVI**, 289 (1968)
[16] M A Morrison and N F Lane, *Phys. Rev.* **A16**, 975 (1979)
[17] L A Collins and M A Morrison, *Phys. Rev.* **A25**, 1764 (1982)
[18] M G Lynch, D Dill, J Siegel and J L Dehmer, *J. Chem. Phys.* **71**, 4249 (1979)
[19] M A Morrison, *Phys. Rev.* **A25**, 1445 (1982)
[20] K H Kochem, W Sohn, N Hebel, K Jung and H Ehrhardt, *J. Phys.* **B18**, 4455 (1985)
[21] H Estrada and W Domcke, *J. Phys.* **B18**, 4469 (1985)
[22] C R Claydon, G A Segal and H S Taylor, *J. Chem. Phys.* **52**, 3387 (1970)
[23] S J Buckman and B Lohmann, *Phys. Rev.* **A34**, 1561 (1986)