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# Ionization and dissociative ionization of $\text{CO}^+$ by electron impact

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**Abstract.** Absolute cross sections for  $\text{CO}^{2+}$ ,  $\text{C}^{2+}$  and  $\text{O}^{2+}$  formation from  $\text{CO}^+$  by electron impact have been measured in the energy range from below the respective ionization or dissociative ionization thresholds to approximately 2500 eV. The animated crossed-beams method has been employed. The cross sections at the maximum are found to be  $1.45 \times 10^{-17}$ ,  $3.4 \times 10^{-19}$  and  $1.3 \times 10^{-19}$  cm<sup>2</sup>, for these reactions respectively and the corresponding threshold energies are determined to be  $27.0 \pm 0.5$ ,  $42.3 \pm 1$  and  $48.1 \pm 1$  eV. From an energy analysis of the collected dissociation products ( $\text{C}^{2+}$  and  $\text{O}^{2+}$ ) the maximum centre-of-mass energy available is found to be  $12.1 \pm 1$  and  $7.2 \pm 1$  eV and the width of the Franck–Condon transition band available is found to be  $2.5 \pm 1$  and  $5 \pm 1$  eV, respectively.

## 1. Introduction

Molecular ions are currently of great interest to plasma modellers because of their presence observed at the edge of fusion plasma devices. They are also observed in the interstellar medium and are important constituents of the Earth's ionosphere. The paucity of relevant data concerning these species, in particular for electron impact ionization, is related to their complex nature. They constitute difficult systems for both experimentalists and theoreticians. The theory is complicated by the structure and number of particles involved in collisions, especially when dissociation channels are to be considered. We are aware of no theoretical attempt to calculate electron-impact ionization cross sections of molecular ions.

Only a limited number of measurements has been carried out, concerning single ionization of small, singly charged molecular ions by electron impact. Difficulties are associated first with the production of a beam of molecular ions with a low internal energy, i.e. in their ground electronic and vibrational levels. The threshold for dissociation extends to relatively low energies and dissociation products are distributed over wide angular and energy ranges. Furthermore, in order to be detected, product molecular ions need to be stable against dissociation, with lifetimes longer than the timescale of the actual experiment. A review of molecular monocation dissociation and dissociative ionization by electron impact has been given by Janev (1995).

The first observation of the carbon monoxide dication was performed by Vaughan (1931) and Friedlander *et al* (1932), though until recently the experimental data available consisted

only of low accuracy values for the appearance potential and some molecular properties. In the last decade,  $\text{CO}^{2+}$  has been the subject of several experiments: electron capture, Auger electron spectroscopy, ion translational energy spectroscopy, photoionization and more recently ion storage-ring experiments (Andersen *et al* 1993). The formation of  $\text{CO}^{2+}$  by electron impact from CO has also been reported (Hille and Märk 1978). Many theoretical calculations are available, in particular dealing with the shape of potential curves and the corresponding ion lifetimes. Details can be found in review articles by Mathur (1991, 1993) or Eland (1991) for instance. Despite such activity, until recently there persisted considerable uncertainty concerning the  $\text{CO}^{2+}$  appearance potential, the order of the dication states and their corresponding lifetimes.

The ground state of  $\text{CO}^+$  is  $X^2\Sigma^+$  with a  $1\sigma^2 2\sigma^2 3\sigma^2 4\sigma^2 1\pi^4 5\sigma$  electronic configuration. Its potential energy well is 8.33 eV deep. There is disagreement between the calculations performed by different groups regarding the order of the  $\text{CO}^{2+}$  states ( $X^3\Pi$ ,  $^1\Sigma^+$ ,  $^1\Pi$ ,  $^3\Sigma^+$ ,  $2^1\Sigma^+$ , ...). The lowest state is generally agreed to be a  $^3\Pi$ , as was first suggested by Hurley (1976). Above this state, the order is predicted by some authors (e.g. Wetmore *et al* 1984) to be  $^1\Pi$  followed by  $^1\Sigma^+$ . This order is reversed by others (e.g. Andersen *et al* 1993). The theories do agree however that both of these states are bound. Two further bound states are predicted by Larsson *et al* (1989) to be  $^3\Sigma^+$  and  $2^1\Sigma^+$ . This order is finally assigned through the comparison of calculated molecular constants using recent TPEsCO data (Dawber *et al* 1994), theory of Larsson *et al* (1989) and recent storage-ring data interpretation (Andersen *et al* 1993).

One electron ejection from  $\text{CO}^+$  ions via Franck–Condon transitions leads to purely dissociative states or to doubly charged  $\text{CO}^{2+}$  ions which are metastable against dissociation. The different dissociative channels to be considered are: (i) the formation of a pair of singly charged ions (symmetrical dissociation) and (ii) the formation of doubly charged atomic ions produced together with a neutral (C or O) atom (asymmetrical dissociation):



Other dissociative ionization channels are not considered in this experiment.

In this paper, we present absolute cross section measurement results for electron impact ionization, reaction (1) ( $\sigma_1$ ) and for the asymmetrical dissociative ionization channels, reaction (3) ( $\sigma_3$ ) and reaction (4) ( $\sigma_4$ ) from below their respective thresholds to approximately 2500 eV. The maximum kinetic energy available in the centre of mass (CM) is determined from an energy analysis of the collected dissociation products ( $\text{C}^{2+}$  and  $\text{O}^{2+}$ ). We are aware of no other attempt to measure or calculate cross sections for these processes.

## 2. Experimental method and apparatus

In this experiment, the animated crossed-beams method has been employed (Defrance *et al* 1981). The apparatus has been described elsewhere (Zambra *et al* 1994) and only a brief outline is given here.

$\text{CO}^+$  ions are extracted from a Penning ion source and accelerated to 4 keV. The ion beam is selected by means of a  $30^\circ$  magnetic analyser and focused into the collision region. The ribbon-shaped electron beam is produced by a Pierce-type cathode–anode configuration.

It is focused into the collision region where it crosses the ion beam at right angles. A pair of parallel plates acts simultaneously as a lens and beam deflector, needed for the application of the animated-beam method. During the measurements the electron beam is swept across the ion beam in a linear see-saw motion, at a constant velocity. This velocity is measured by means of two thin wires located on both sides of the ion beam symmetrically, perpendicular to the electron-beam trajectory.

Product ions are selected by means of a  $90^\circ$  magnetic analyser. They are additionally deflected by a spherical  $90^\circ$  electrostatic deflector and directed onto a channel plate detector. This apparatus does not allow the study of reaction (2) because in this case a second detector must be installed in order to detect both ions ( $\text{C}^+$  and  $\text{O}^+$ ) in coincidence. The signal delivered by the detector is stored in a multichannel analyser which is synchronized with the electron beam sweeping voltage. At a given electron energy, the recorded spectrum exhibits two peaks corresponding to upward and downward beam crossings, which enable the determination of the net signal. The primary ion beam is collected in a wide Faraday cup located inside the magnetic field. From the measured quantities the ionization cross section is determined by the following expression:

$$\sigma = \frac{v_e v_i u K}{(v_e^2 + v_i^2)^{1/2} (I_e/e)(I_i/qe)} \quad (5)$$

where  $u$  is the electron beam scanning velocity,  $K$  is the total number of events produced during one passage of electrons across the ion beam,  $v_e$  and  $v_i$ ,  $I_e$  and  $I_i$ ,  $e$  and  $qe$  are the velocities, currents and charges of electrons and ions, respectively.

Typical working conditions in this experiment are:  $I_e = 1\text{--}3$  mA,  $I_i = 100$  nA,  $u = 3.75$  m s $^{-1}$  and  $K = 2$ . All slits and apertures between the collision region and the ion detector are dimensioned to provide total ion transmission in the ionization experiments (Zambra *et al* 1994). In cases where dissociation takes place, the products exhibit wider angular and energy distributions so that the transmission is not total. The angular divergence is controlled by means of an appropriate lens, but the restricted energy acceptance of the magnetic analyser prevents total ion transmission being achieved. In order to estimate this transmission, the apparent cross section is measured as a function of the magnetic field ( $B$ ) and the transmission can be estimated from the observed profile. The values deduced from this procedure are 50 and 46.6% for the  $\text{C}^{2+}$  and  $\text{O}^{2+}$  transmissions, respectively. In addition, the field limits of the recorded profile ( $B_m$  and  $B_M$ ) correspond to the transmission of products with minimum and maximum energy available in the laboratory, that is, to ions emitted with the maximum velocity in the backward and in the forward directions, respectively. Simple kinematic calculations allow the determination of this velocity from the experimental conditions and subsequently, the maximum energy given to the dissociation products in the CM. The ion time of flight from the collision region to the detector is about 9  $\mu\text{s}$ .

The total absolute uncertainty of the cross section is obtained as the quadrature sum of counting statistics and systematic uncertainties of all measured quantities. Systematic errors are estimated as follows: sweeping velocity  $\pm 2\%$ , electron current  $\pm 1\%$ , ion current  $\pm 1\%$ , beam velocities  $\pm 0.5\%$  and detection efficiency  $\pm 1.7\%$ . The statistical error of the counting statistics is typically less than  $\pm 1\%$ ,  $\pm 4\%$  and  $\pm 6\%$ , and the total absolute uncertainty is found to be less than  $\pm 5\%$ ,  $\pm 6\%$  and  $\pm 8\%$  at the cross section maximum for processes 1, 3 and 4, respectively. The electron energy is corrected for contact potentials and for the ion velocity. The error on the true collision energy ( $E$ ) is about  $\pm 0.5$  eV.

For reaction (1) the cross section below the predicted ionization threshold is found to be greater than zero from 17 to 27 eV but of the order  $1.8 \times 10^{-19}$  cm $^2$ , i.e. only about 1.3% of

the cross section value at its maximum. This weak contribution is slowly decreasing with increasing energy. This effect may be explained in three different ways. First, it may be due to ions formed in long-lived excited state ions in the ion source. These ions have a very low ionization threshold. Second, it could be due to the (non-Franck–Condon) autoionization of Rydberg states of singly charged molecular ions, excited by electron impact, which lie in the double ionization continuum close to but slightly below the apparent threshold (Price and Eland 1991). And third, it may be induced by the background modulation signal resulting from the space charge interaction of two charged particle beams at low relative velocities (Harrison 1966).

No significant effect on the cross section below or above threshold was found by varying the ion source parameters, discharge voltage for instance and the dissociative ionization data do not show any evidence of long-lived excited state ions in the primary beam. For the second explanation, there exists no experimental evidence of autoionization and its role seems to be negligible because of the structureless form of the cross section below the ionization threshold. The spurious signal produced by the background modulation can be significant particularly for low collision energies and it decreases as  $v_e^{-1}$  (Harrison 1966). Since the apparent ionization cross section behaves with this shape below the threshold in this experiment, the following correction procedure to the data is applied. Cross section data below the threshold are fitted by the function  $AE^{-1/2}$ .  $A$  is found to be equal to  $7.8 \times 10^{-19} \text{ cm}^2 \text{ eV}^{1/2}$ . The ionization cross sections have been corrected according to this value. The correction terms for higher energies are fairly small, far below the respective absolute error bars.

### 3. Results and discussion

Results are listed in table 1 for process (1), and in table 2 for processes (3) and (4), together with the corresponding electron energies and associated statistical errors which represent one standard deviation of the counting statistics, only. The data have been corrected according to the above-mentioned procedures, in order to take into account the weak background modulation for ionization and the nontotal dissociation product ion transmission. Results are also shown in figure 1 for ionization and in figure 3 for dissociative ionization. In figure 1, the error bars represent the total absolute uncertainty and in figure 3, they represent the statistical error of the counting statistics only. To our knowledge, there are no other measurements or sophisticated theoretical predictions to be compared with these data.

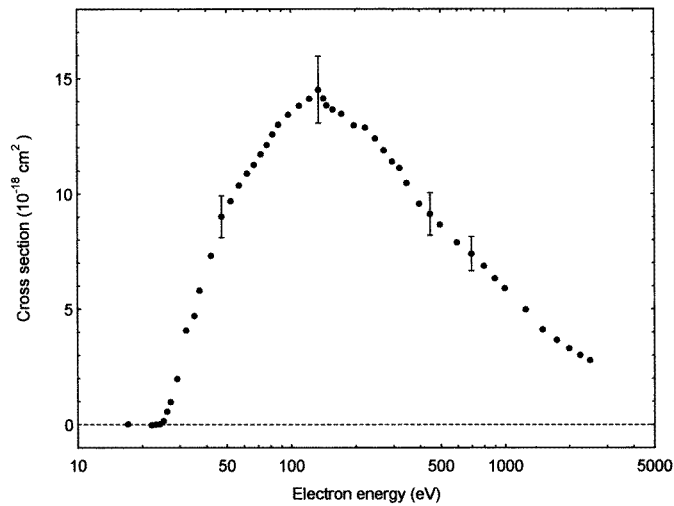
#### 3.1. Ionization

The ionization cross section at the maximum is found to be  $(1.45 \pm 0.14) \times 10^{-17} \text{ cm}^2$  at an electron energy of 134 eV. This value represents only a fraction of the net ionization signal because  $\text{CO}^{2+}$  ions are metastable against symmetrical dissociation (reaction 2) whose products are not collected in this experiment. The branching ratio for symmetrical dissociation and the subsequent ionization signal reduction could be evaluated knowing the time of flight of the ions (9  $\mu\text{s}$ ) from the collision region to the detector and the state lifetimes and corresponding populations.

There is again disagreement between the various attempts to estimate the lifetimes of the lowest  $\text{CO}^{2+}$  dication states. The lifetime of the  $^3\Pi$  state was first predicted by Hurley (1976) to be of the order of a few tens of microseconds. Newton and Sciamanna (1970) measured the mean lifetime for all states to be in the range 15–30  $\mu\text{s}$ , Hirsch *et al* (1975) have estimated a value of 16  $\mu\text{s}$ , Curtis and Boyd (1984) 9  $\mu\text{s}$ , Wetmore (1984) predicted several lower bound states with lifetimes ranging from  $10^{-8}$  to  $10^{-4}$  s. The most recent

**Table 1.** Absolute cross sections for ionization of  $\text{CO}^+$  by electron impact.

$Ee$ (eV)	$\sigma_1$ ( $10^{-18} \text{ cm}^2$ )	$\Delta\sigma$ ( $10^{-18} \text{ cm}^2$ )	$Ee$ (eV)	$\sigma_1$ ( $10^{-18} \text{ cm}^2$ )	$\Delta\sigma$ ( $10^{-18} \text{ cm}^2$ )
17.2	0.01	0.06	142.2	14.12	0.08
22.2	-0.03	0.06	147.2	13.82	0.05
23.2	0	0.09	157.2	13.63	0.04
24.2	0.02	0.09	172.2	13.46	0.04
25.2	0.15	0.08	197.2	12.96	0.04
26.2	0.56	0.08	222.2	12.86	0.04
27.2	0.98	0.07	247.2	12.38	0.04
29.2	1.98	0.08	272.2	11.87	0.05
32.2	4.07	0.1	297.2	11.39	0.04
35.2	4.7	0.1	322.2	11.11	0.04
37.2	5.8	0.07	347.2	10.45	0.04
42.2	7.31	0.08	397.2	9.56	0.04
47.2	9.01	0.1	447.2	9.12	0.04
52.2	9.67	0.09	497.2	8.66	0.04
57.2	10.35	0.09	597.2	7.88	0.04
62.2	10.87	0.11	697.2	7.4	0.03
67.2	11.25	0.1	797.2	6.87	0.03
72.2	11.7	0.08	897.2	6.33	0.03
77.2	12.11	0.08	997.2	5.89	0.03
82.2	12.56	0.07	1247.2	4.97	0.03
87.2	12.98	0.1	1497.2	4.12	0.03
97.2	13.41	0.08	1747.2	3.66	0.02
109.2	13.8	0.09	1997.2	3.3	0.02
122.2	14.11	0.07	2247.2	3	0.02
134.2	14.5	0.09	2497.2	2.78	0.02

**Figure 1.** Absolute cross sections versus energy for electron impact ionization of  $\text{CO}^+$ . Representative error bars are total absolute uncertainties.

estimation based on a storage-ring experiment by Andersen *et al* (1993) ranges from 20 ms up to more than 3.8 s for the lowest  $^3\Pi$  ( $v = 0$ ) state. Mathur *et al* (1995) concluded that

**Table 2.** Absolute cross sections for asymmetrical dissociative ionization of  $\text{CO}^+$  by electron impact:  $\sigma_3$ ,  $\text{C}^{2+}$  formation and  $\sigma_4$ ,  $\text{O}^{2+}$  formation.

$Ee$ (eV)	$\sigma_3$ ( $10^{-19} \text{ cm}^2$ )	$\Delta\sigma$ ( $10^{-19} \text{ cm}^2$ )	$\sigma_4$ ( $10^{-19} \text{ cm}^2$ )	$\Delta\sigma$ ( $10^{-19} \text{ cm}^2$ )
31.2	-0.04	0.06		
36.2	-0.01	0.10	-0.05	0.13
41.2	-0.03	0.18	0.05	0.11
44.2	0.07	0.18	0.04	0.11
46.2	0.40	0.18		
51.2	0.79	0.17	0.07	0.13
56.2	1.11	0.22	0.30	0.15
61.2	1.54	0.10		
66.2	1.86	0.16	0.56	0.13
76.2	2.34	0.14	0.71	0.13
86.2	2.78	0.20	0.88	0.13
96.2	3.14	0.15	1.03	0.11
106.2	3.26	0.20	1.08	0.11
121.2	3.44	0.15	1.22	0.11
131.2	3.44	0.14		
146.2	3.42	0.12	1.29	0.09
171.2	3.32	0.08	1.20	0.06
196.2	3.10	0.10	1.07	0.06
221.2	2.98	0.09		
246.2	2.73	0.07	0.97	0.05
296.2	2.42	0.07	0.82	0.06
346.2	2.22	0.07		
396.2	2.10	0.07	0.67	0.06
496.2	1.83	0.08	0.52	0.05
596.2	1.58	0.08		
696.2			0.39	0.06
796.2	1.26	0.04		
996.2	1.04	0.08	0.30	0.06
1246.2	0.93	0.08		
1496.2	0.78	0.07	0.21	0.06
1996.2	0.62	0.04	0.13	0.06

$\text{CO}^{2+}$  exhibits many more lifetime components in the millisecond range than for instance the isoelectronic  $\text{N}_2^{2+}$  ion and some of them extend over a few seconds. In this experiment product  $\text{CO}^{2+}$  dications need about  $9 \mu\text{s}$  to reach the detector. Therefore, only the dications with a lifetime larger than this value are detected. Unfortunately, in this experiment it is not possible to vary significantly the ion kinetic energy in order to check for the cross section dependence upon the time of flight. The populations and lifetimes of states formed in the collision not being known, no estimation of the branching ratio can be given, but it is clear that a substantial fraction of dications dissociates before reaching the detector.

By extrapolation of the cross section the threshold energy is determined to be  $(27.0 \pm 0.5) \text{ eV}$ . In the TPEsCO experiment (Dawber *et al* 1994) the  $\text{CO}^{2+}$  appearance potential (in the  $^3\Pi$ ,  $v = 0$  state), relative to the  $v = 0$  of the ground  $X^1\Sigma$  state of neutral CO is determined to be  $(41.294 \pm 0.010) \text{ eV}$ . The difference between this value and the CO single ionization threshold (13.99 eV, Krisnamurthi *et al* 1991) gives a value of 27.3 eV for the  $\text{CO}^+$  ionization threshold. This figure is in very good agreement with ours and this fact could indicate that very few  $\text{CO}^+$  ions are formed in the ion source in long-lived metastable vibrational states.

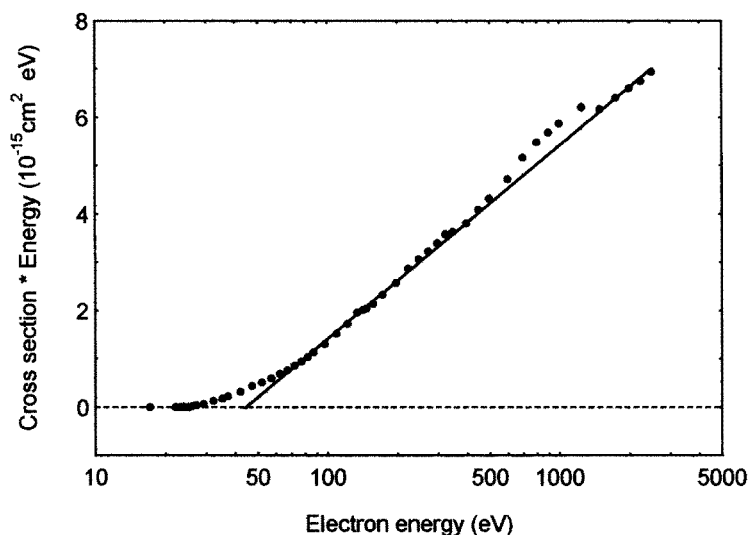
The weak structures observed at the lower energy side may be due to the opening of new ionization channels corresponding to the formation of highly excited  $\text{CO}^{2+}$  states. The cross section exhibits irregularities around and above 250 eV. This is probably associated with excitation of a quasi-atomic carbon K-electron followed by autoionization. Similar effects have been observed in Auger spectra of neutral CO molecules ionized by electron impact (Moddeman *et al* 1971). A very intense spectral line is observed at 250 eV electron energy. In this case one carbon K-shell electron is excited to one unoccupied molecular orbital and this is followed by autoionization. For  $\text{CO}^+$  production, one outer-shell electron is ejected from CO and the binding energy of inner-shell electrons is not significantly affected by this reaction. For this reason, a similar Auger ionization process could occur in this case at roughly the same energy. This process coincides with the observed structure between 200 and 250 eV. Another similar contribution from oxygen K–L Auger ionization should be expected around 500 eV incident electron energy. However, this contribution is not seen from our results. This higher energy process also has significantly lower yield in the Auger spectra of Moddeman *et al* (1971).

The Bethe plot of cross sections usually shows the high-energy dependence of data which is of the following form for electron impact ionization of atoms or ions:

$$\sigma = \frac{a}{EI} \left( \ln \left( \frac{E}{I} \right) + b \right). \quad (6)$$

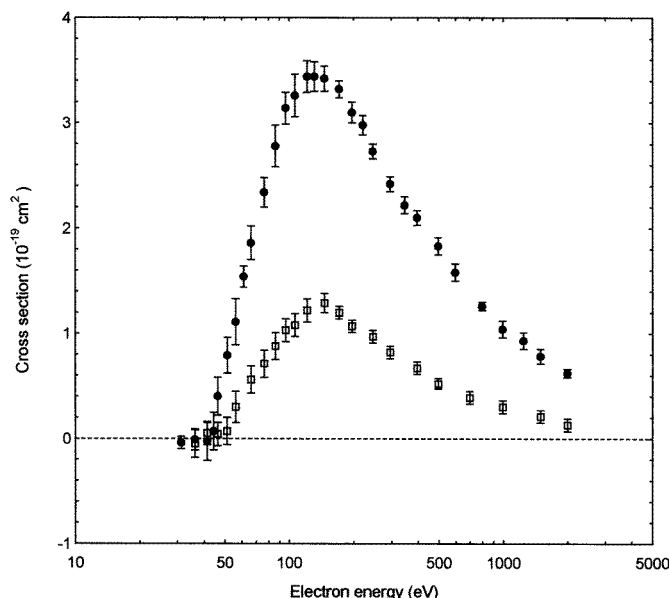
The Bethe plot of our data is shown in figure 2. The straight line is a least-square fit of the high-energy cross sections according to formula (6):  $a$  and  $b$  are determined to be  $4.72 \times 10^{-14} \text{ cm}^2 \text{ eV}$  and  $-0.556$ , respectively. As can be seen from the figure, this dependence extends down to relatively low energies, below 100 eV. The difference between data points and fitted values exhibit peaks which correspond to the inner shell ionization processes, discussed above.

The semiempirical Lotz formula (Lotz 1968) was developed for atom and ion ionization cross section prediction and corresponds to formula (6) with  $a = 4.5 \times 10^{-14} \text{ cm}^2 \text{ eV}$  and



**Figure 2.** Bethe plot of absolute cross sections for  $\text{CO}^+$  ionization by electron impact. The full line is the least-square fit using equation (6).





**Figure 3.** Absolute cross sections versus energy for asymmetrical dissociative ionization of  $\text{CO}^+$  by electron impact: ( $\bullet$ ),  $\text{C}^{2+}$  formation and ( $\square$ ),  $\text{O}^{2+}$  formation. The error bars are one standard deviation statistical uncertainty.

$b = 0$ . In the present  $\text{CO}^+$  molecular ion case, only the outermost  $5\sigma$  electron is assumed to play a role, with a binding energy of 27.3 eV. The result ( $1.9 \times 10^{-17} \text{ cm}^2$ ) is some 30% higher than the measured one and the cross section maximum is located around 95 eV. A similar agreement is also obtained for electron impact ionization of other molecular ions, but it would be hazardous to make any further conclusion from this comparison: the Lotz formula is only able to predict the order of magnitude of cross sections but not the details of physical processes.

### 3.2. Dissociative ionization

Results for reactions (3) and (4) are shown in figure 3. These processes are very weak: the cross sections lie in the  $10^{-19} \text{ cm}^2$  range, that is, a factor of 20 smaller than the ionization one. The reason for this situation cannot be explained by the classical scaling law for ionization: the ionization thresholds are not very different (of the order 50% only, so that the application of the classical scaling law does not explain the large difference. The explanation of this situation will probably be found in the symmetry of the  $\text{CO}^{2+}$  dissociative states.

From extrapolating the results, the respective thresholds are determined to be  $42.3 \pm 1$  and  $48.1 \pm 1$  eV, that is,  $56.3 \pm 1$  and  $62.1 \pm 1$  eV above the  $\text{CO}$  ground state. For  $\text{C}^{2+}$  production, the value is in good agreement with the result obtained by photoionization ( $56.4 \pm 1.0$  eV, Masuoka and Nakamura 1993) and not with the electron impact result ( $54.2 \pm 0.20$  eV, Hierl and Franklin 1967). For  $\text{O}^{2+}$  production, the situation is reversed, the present result is in poor agreement with the photoionization result ( $70.00 \pm 1.0$  eV, Masuoka and Nakamura 1993), but in good agreement with the electron impact one ( $61.3 \pm 0.3$  eV Hierl and Franklin 1967). Our experimentally determined threshold values are above the lowest dissociation

limits corresponding to these reactions (46.74 and 59.87 eV). The difference (9.6 eV for  $\text{C}^{2+}$  and 2.2 eV for  $\text{O}^{2+}$ ), corresponds to the minimum kinetic energy distributed between the dissociation products.

Additional information can be deduced from the analysis of the product energy spectra in the laboratory frame: these spectra can be deconvoluted in order to obtain the corresponding energy spectra in the CM frame. This experiment does not allow the determination of this kind of detailed information, but the maximum kinetic energy transferred to dissociation products is obtained from a magnetic field scan of apparent cross sections used to determine the ion transmission. According to this procedure (see section 2), these energies are determined to be  $12.1 \pm 0.5$  and  $7.2 \pm 0.5$  eV for  $\text{C}^{2+}$  and  $\text{O}^{2+}$  respectively. The energy range available in Franck–Condon transitions is then  $2.5 \pm 1$  eV for  $\text{C}^{2+}$  and  $5 \pm 1$  eV for  $\text{O}^{2+}$ .

The potential energy curves leading to asymmetrical dissociation are located well above those leading to symmetrical dissociation and to our knowledge, they have not been extensively studied so that no information can be given on the states responsible for the asymmetrical dissociative ionization processes. Nevertheless, the width and position of the Franck–Condon transition bands may give indications on these states.

In the case of  $\text{C}^{2+}$  production, this width is narrow (2.5 eV) and located well above (9.6 eV) the dissociation limit, probably indicating that a few states only are responsible for reaction (3) and that these states are purely dissociative ones. In the case of  $\text{O}^{2+}$  production, the Franck–Condon region is wider (5 eV) and located close (2.2 eV) above the corresponding dissociation limit. This could indicate that many states contribute to this reaction and that some of them could be metastable against dissociation. Detailed calculations should enlighten this situation and eventually confirm these conclusions by providing us with the required potential energy curves allowing the dissociative and metastable states to be determined.

#### 4. Summary

Absolute cross sections for electron impact ionization and asymmetrical dissociative ionization of the  $\text{CO}^+$  molecular ion are reported. The cross section values at the maximum are found to be  $1.45 \times 10^{-17}$ ,  $3.4 \times 10^{-19}$  and  $1.3 \times 10^{-19}$   $\text{cm}^2$ , for the  $\text{CO}^{2+}$ ,  $\text{C}^{2+}$  and  $\text{O}^{2+}$  formation, respectively. The ionization and dissociative ionization thresholds are found to be in good agreement with results deduced from electron or photon impact on CO molecules. In addition, the maximum kinetic energy transferred to dissociation products has been determined, so that the Franck–Condon transition energy range has been delimited.

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