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Absolute partial and total ionization cross sections of carbon monoxide with electron collision from 350 eV to 8000 eV

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The absolute partial and total cross sections for electron impact ionization of carbon monoxide are reported for electron energies from 350 eV to 8000 eV. The product ions (CO^+, C^+, O^+, CO^{2+}, C^{2+}, and O^{2+}) are measured by employing an ion imaging mass spectrometer and two ion-pair dissociation channels ($C^+ + O^+$ and $C^{2+} + O^+$) are identified. The absolute cross sections for producing individual ions and their total, as well as for the ion-pair dissociation channels are obtained by normalizing the data of CO^+ to that of Ar^+ from CO–Ar mixture target with a fixed 1:1 ratio. The overall errors are evaluated by considering various kinds of uncertainties. A comprehensive comparison is made with the available data, which shows a good agreement with each other over the energy ranges that are overlapped. This work presents new cross-section data with electron energies above 1000 eV.

Keywords: electron impact, ionization cross sections, carbon monoxide, ion imaging mass spectrometer

PACS: 34.50.Gb, 34.80.Gs, 34.80.Ht **DOI:** 10.1088/1674-1056/ad20dd

1. Introduction

Electron impact ionization of atoms and molecules is one of the most fundamental processes in gas discharges, plasmas, and planetary atmospheres, etc.[1–20] The corresponding ionization cross sections can play an important role in modelling the momentous physical and chemical processes occurred in these objectives. Carbon monoxide (CO) is one of significant molecules in the atmospheres of Earth, Mars, Venus, Comet, and in the interstellar space.[1,2] For example, on the Mars, CO has a considerable influence on the Martian temperature and weather patterns. It contributes to the movement of water vapor from the polar regions to the equator[6–8] and participates in the chemical reactions that lead to the production of larger and more complex organic molecules,[9] making it an important component of the chemistry of the Martian atmosphere. In these subjects, electron impact ionization and dissociation of CO are of importance. The absolute accurate cross-section data over a wide energy range are required as the fundamental input parameters in the models developed for planetary atmospheres[10–14] and various plasmas.[15–20]

In the past decades, great efforts have been made to measure and compute the absolute values of total ionization cross section (TICS) and partial ionization cross section (PICS) of CO with a series of electron impact energies.[21–38] In 1932, Tate and Smith[21] performed the first measurement of the TICS of CO in the electron energy range from 14 eV to 750 eV. After that, several groups[22–24] measured the TICS with electron energies below 100 eV. Rapp and Englander-Golden[25] measured the TICS from threshold up to 1000 eV, whose data were widely accepted as the standard for quite some time. The PICS for the product of parent ion CO^+ were measured by Hille and Mark[26] and Freund *et al.*[27] with the electron energies below 200 eV. Adamczyk *et al.*[28] measured the PICSs of CO^+, C^+, O^+, and CO^{2+} in the electron energies from 20 eV to l000 eV. Tian and Vidal[29,30] reported the PICSs for singly and doubly charged fragments and dissociation channels from 15 eV to 600 eV and Gavin *et al.*[31] measured the PICSs for CO^+ and CO^{2+} below 600 eV. Both the PICSs and the TICS for direct ionization and dissociative ionization of CO have been measured in different electron energy ranges by Orient and Srivastava[32] (15 eV–510 eV), Tian and Vidal[29] (17.5 eV–600 eV), Mangan *et al.*[33] (15 eV–1000 eV) and Chung[34] (100 eV–1000 eV), respectively. Theoretical calculations for the TICS of CO were performed by Jain and Khare[35] using a semi-empirical approach, by Hwang *et al.*[36] using the Binary–Encounter–Bethe (BEB) model, and by Zhong *et al.*[37] using the BEB model, the Deutsch–Mark (DM) model and their combination. Itikawa[38] collected and reviewed the PICS and TICS data of CO with electron impact. He recommended the PICS values of CO^+, C^+, and O^+, together with the TICS data from 25 eV to 1000 eV obtained by Mangan *et al.*[33] and those below 25 eV from Rapp and Englander-Golden.[25] While for the PICS values of CO^{2+}, C^{2+}, and O^{2+}, he adopted the data of Tian and Vidal.[29]

As reviewed above, one can see that the existing absolute TICS and PICS data are restricted to electron energies below 1000 eV. The data for electron energies as high as several keV are completely unexplored. Due to a vast energy range of solar wind electrons, to model the electron impact ionization

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process of planetary atmospheres, the cross-section data over a considerably wide energy range up to 10 keV are urgently required.[10–14] The present work is devoted to the measurement on the absolute electron-impact PICSs and TICSs of CO in a high energy range up to 8000 eV. In the experiments, using a relative gas flow technique, CO–Ar mixture target with a fixed ratio (1:1) is ionized by electron impact with a series of energies from 350 eV to 8000 eV. The product ions of CO^+, C^+, O^+, CO^{2+}, C^{2+}, and O^{2+} are measured by employing an ion imaging mass spectrometer[39] and two ion-pair dissociation channels of $C^+ + O^+$ and $C^{2+} + O^+$ are identified by a time-of-flight (TOF) correlation of ion pairs detected in coincidence. The relative cross sections for each ion, as well as the dissociation channels are derived from the measured time of flight mass spectra. They are then put on an absolute scale with the well-established data of Ar^+.[40–42] The TICSs are simply obtained via the sum of the PICSs for all observed ionic fragments.

2. Experimental apparatus and method

The experimental apparatus used in the present study mainly consists of a pulsed electron gun, a faraday cup, a Wiley–McLaren-type TOF mass spectrometer[43] along with a position-sensitive detector (PSD). Details of this apparatus have been described in the previous paper.[39] In the experiments, an energy-variable pulsed electron beam with 100-ns width and 20-kHz repetition rate is introduced into the center between a pair of parallel electrodes with high transmittance molybdenum wire meshes (namely push and pull electrodes) and collides with the targets that are the mixed gases of CO and Ar with a fixed 1:1 ratio controlled by a pair of high precise flowmeters. The working pressure is around 1.7×10^{-5} Pa, while the background pressure is better than 3×10^{-6} Pa. Following closely the collision, to extract the ionized molecules and their dissociation fragments in 4π solid angle, a synchronously pulsed uniform electric field (133 V/cm) is applied in a direction perpendicular to both the electron beam and the molecular beam. The extracted ions are accelerated by a uniform electric field of 133.3 V/cm and then pass through the field-free region until they hit the PSD composed of a pair of microchannel plates (MCP) and a delay line anode (DLA). Signals from the MCP and DLA are amplified and discriminated, and finally recorded by multichannel timetodigital converters (TDCs). The digitized data from the TDCs are stored event by event on a computer disk for off-line data analysis. The mass spectrum of the produced ions can be deduced by using their TOF.

The relative ionization cross sections for the ions produced from the target are directly corresponding to their relative intensity (i.e., counts) that can be deduced from the measured TOF mass spectra. As a CO–Ar mixture target used here, the ion counts for both gases were recorded at the same time and the same experimental conditions. The influences from the fluctuation of electron current, gas pressure, temperature, and the size of reaction region can be neglected. Therefore, absolute ionization cross sections of molecular ions can be obtained by normalizing the data of CO^+ to those of Ar^+ that are well-known accurate cross sections.[40–42]

For a particular ion product X^{q+}, its absolute PICS can be expressed by

$$\sigma(X^{q+}) = \sigma_{\rm ref}(Ar^+)\frac{N(X^{q+})}{N(Ar^+)}C, \tag{1}$$

where $\sigma_{\rm ref}(Ar^+)$ represents the absolute cross sections of Ar^+. C is the number density ratio of the target atoms and molecules in the reaction region, which is kept a constant of 1 in the experiment by a pair of high precise flowmeters. $N(X^{q+})$ and $N(Ar^+)$ are the real count rates for X^{q+} and Ar^+, which can be expressed as

$$N(X^{q+}) = \frac{D(X^{q+})}{\varepsilon(X^{q+})\eta}, \tag{2}$$

$$N(Ar^+) = \frac{D(Ar^+)}{\varepsilon(Ar^+)\eta}, \tag{3}$$

in which D, ε, and η are the detected count rates, the detection efficiency of the MCPs, and the transmission efficiency of the meshes in the TOF system, respectively.

Equation (1) is therefore written further as

$$\sigma(X^{q+}) = \sigma_{\rm ref}(Ar^+)\frac{D(X^{q+})\varepsilon(Ar^+)}{\varepsilon(X^{q+})D(Ar^+)}. \tag{4}$$

Similarly, for a certain ion-pair dissociation channel $X^{q+} + Y^{p+}$, the absolute cross sections can be expressed as

$$\begin{aligned}\sigma(X^{q+}+Y^{p+}) &= \sigma_{\rm ref}(Ar^+)\frac{N(X^{q+}+Y^{p+})}{N(Ar^+)}C \\ &= \sigma_{\rm ref}(Ar^+)\frac{D(X^{q+}+Y^{p+})\varepsilon(Ar^+)}{\varepsilon(X^{q+})\varepsilon(Y^{p+})\eta D(Ar^+)}.\end{aligned} \tag{5}$$

3. Results and discussion

The TOF mass spectra for electron impact ionization and dissociative ionization of CO molecule have been measured in a wide energy range from 350 eV up to 8000 eV. Seventeen TOF mass spectra are obtained at seventeen definite electron impact energies. As a representative, a TOF mass spectrum for the product ions measured at the electron impact energy of 350 eV is presented in Fig. 1(a). One can see that the peaks for the product CO^+, C^+, O^+, CO^{2+}, C^{2+}, and O^{2+}, together with Ar^+, Ar^{2+}, and Ar^{3+} were separated clearly. To assure the formation of ion-pair dissociation channels, the ion–ion TOF correlation map is plotted. As shown in Fig. 1(b), for a certain ion-pair channel, the true events distribute along an island on the map, the slope of which reflects the momentum correlation of the fragments. Therefore, two ion-pair dissociation

channels ($C^+ + O^+$ and $C^{2+} + O^+$) are identified according to the observed islands. The presently observed ions from CO may originate from the following processes, for example,

$$e^- + CO \rightarrow CO^+ + 2e^-, \quad (6)$$

$$e^- + CO \rightarrow CO^{2+} + 3e^-, \quad (7)$$

$$e^- + CO \rightarrow C^+ + O + 2e^-, \quad (8)$$

$$e^- + CO \rightarrow C + O^+ + 2e^-, \quad (9)$$

$$e^- + CO \rightarrow C^{2+} + O + 3e^-, \quad (10)$$

$$e^- + CO \rightarrow C + O^{2+} + 3e^-, \quad (11)$$

$$e^- + CO \rightarrow C^+ + O^+ + 3e^-, \quad (12)$$

$$e^- + CO \rightarrow C^{2+} + O^+ + 4e^-. \quad (13)$$

The channels (6) and (7) come from the direct single and double ionizations, respectively. The channels (8)–(13) correspond to the dissociative ionizations, of which channels (12) and (13) are the ion-pair dissociation due to the Coulomb explosion of doubly or triply charged molecules.

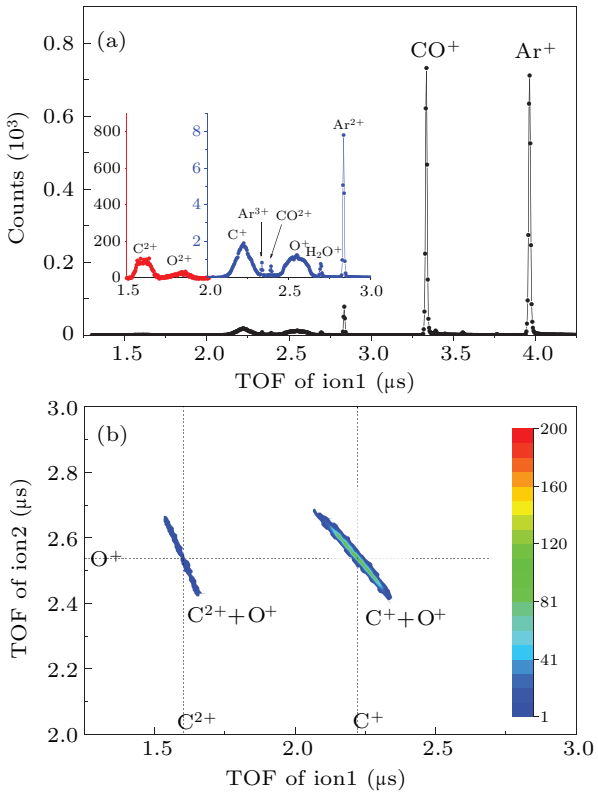


Fig. 1. (a) The TOF mass spectrum of CO molecule measured at 350-eV electron impact energy and the insert graphs for displaying the fragment ions with low intensity clearly. (b) The TOF correlation map for the first ion and the second ion measured in coincidence, in which the background counts from the accidental coincidence are subtracted by considering the conservation of momenta of ion pairs.

Although the experimental technique is generally well developed, the absolute cross sections are not easy to be accurately detected. To obtain the absolute PICSs of CO molecule, according to the above formulas (4) and (5), the absolute PICS $\sigma(Ar^+)$ is referred to the reliable absolute measurements from three groups.[40–42] The detected counts of the desirable ions can be derived from the TOF spectra, corresponding to the peak area, in which a key point is to eliminate the background signals. Besides these, it is also necessary to determine the detection efficiency of the MCPs and the transmission efficiency of the meshes. The total transmission efficiency $\eta = 46.1\%$ is concerned here from the values estimated by Wang *et al.*[44] because four sets of meshes are used in the TOF system in which one set with 90% transition efficiency and the other three with 80% respectively. For different ion species and energies, the MCP detection efficiency becomes different, whose maximum efficiency is close to the MCP open-area ratio (OAR). We have carried out the measurement for some specific ion species with different energies and analyzed their relative detection efficiencies versus the energies divided by the square root of the ion masses ($E/M^{0.5}$) according to the method of Krems *et al.*[45] and Matoba *et al.*[46] A single curve of MCP efficiencies as a function of $E/M^{0.5}$ is obtained, the maximum approach to the MCP's OAR (60% used here), which could represent the absolute detection efficiency of various ions. In the present experiment, the MCP detection efficiencies for the product ions of Ar^+, CO^+, C^+, O^+, CO^{2+}, C^{2+}, and O^{2+} are determined to be 44.4%, 47.3%, 54.7%, 52.2%, 58.3%, 60%, and 59.8%, respectively.

For the error estimation, from the Eqs. (1)–(5), one can see that there are several kinds of error sources including the reference $\sigma(Ar^+)$, the statistical uncertainties and the MCP efficiencies for various types of the desirable ions, the transmission efficiency of the meshes and the CO–Ar mixture gas flow ratio. The reference values of Ar^+ cross sections for all energy points are acquired from three different groups.[40–42] For the energy points at and below 1000 eV, the data of Straub *et al.*[40] with the uncertainty of 3.5% for $\sigma(Ar^+)$ are employed. At 1500-eV energy point, the result of Nagy *et al.*[41] with the total error of 10% for $\sigma(Ar^+)$ is referred. For the rest of the energy points up to 8000 eV, the absolute PICS $\sigma(Ar^+)$ of Schram *et al.*[42] with the total error of about 7% are used as the reference data. In the present experiment, the uncertainty of MCP detection efficiencies is evaluated to be 3% or better. The uncertainty of a high-precision gas flowmeter is less than 1%. The statistical uncertainties for the double charged ions and ion-pair channels are evaluated to be 5% or less, while those for the single charged ions are quite small and can be ignored due to the large number of counts. The total errors for the present absolute cross sections have carefully assessed according to the error sources mentioned above in which the error propagation was also considered.

Table 1 compiles the present data of absolute PICSs for the product ions (CO^+, C^+, O^+, CO^{2+}, C^{2+}, and O^{2+}) and two ion-pair dissociation channels ($C^+ + O^+$ and $C^{2+} + O^+$) measured in a wide electron energy range from 350 eV to 8000 eV, together with the corresponding overall errors listed

in the brackets. It can be seen from Table 1 that the PICS values for the parent ion CO^+ are the largest one with the order of 10^{-16} cm^2. They are about one order of magnitude larger than those of C^+ and O^+, and two orders or more than those of doubly charged ions CO^{2+}, C^{2+}, and O^{2+}. The total ionization cross sections are also tabulated in Table 1, which is simply obtained by the charge-weighted sum of all the PICSs values for the measured product ions, i.e.,

$$\sigma(\text{total}) = \sum q\sigma(X^{q+}) = \sigma(CO^+) + \sigma(C^+) + \sigma(O^+) + 2\sigma(CO^{2+}) + 2\sigma(C^{2+}) + 2\sigma(O^{2+}). \quad (14)$$

As illustrated in Table 1, the TICS values are of dominant contributions from the singly charged ions of CO. Those of multiply charged ions contributed to the TICS are extremely small and can be ignored. As a result, the TICS are usually obtained by adding the PICS data of the singly charged ions from molecules in the literatures.

Figures 2–5 depict an intuitive comparison between the present results and the existing available data over the energy range that is overlapped. These cross sections are generally in accordance with each other when taking the errors into account. For the singly charged ionic fragments CO^+, C^+, and O^+, their PICSs are presented in Fig. 2. Orient and Srivastava[32] used a quadruple mass spectrometer (QMS) and an absolute normalization of the relative flow technique to determine the PICSs in electron impact energies ranging from 10 eV to 510 eV with the uncertainty of 15%. Tian and Vidal[29] used a focusing TOF spectrometer and a normalization of argon data to obtain the PICSs from threshold to 600 eV with the uncertainty of 10%. Mangan *et al.*[33] used a short TOF mass spectrometer to derive the PICSs of CO^+, C^+, and O^+ from threshold to 1000 eV with the uncertainty of 5%, 6%, and 6%, respectively. Chung[34] also measured the absolute PICSs with the uncertainty of 7.7% using a long TOF mass spectrometer at electron energies from 100 eV to 1000 eV. As shown in Fig. 2(a), the PICS data of CO^+ presented by Orient and Srivastava[32] and Chung[34] display slightly higher values, while the data of Tian and Vidal[29] are a bit low. The present data with the uncertainty of 5.1% are in good agreement with those of Mangan *et al.*[33] whose data were recommended by Itikawa[38] in the overlap energy region. For the PICSs of C^+ ion, as plotted in Fig. 2(b), the data from Orient and Srivastava[32] are obviously lower than others. While for the PICSs of O^+ ion in Fig. 2(c), the data from Orient and Srivastava[32] are severely smaller than others. The present data for both C^+ and O^+ ions are in accordance with those from Tian and Vidal,[29] Mangan *et al.*,[33] and Chung[34] in the overlap energy region.

Table 1. Experimental absolute PICS and TICS for electron impact ionization and dissociation of CO molecule. The uncertainties are presented in the brackets.

Energy (eV)	$\sigma(CO^+)$ (10^{-16} cm^2)	$\sigma(C^+)$ (10^{-16} cm^2)	$\sigma(O^+)$ (10^{-16} cm^2)	$\sigma(CO^{2+})$ (10^{-18} cm^2)	$\sigma(C^{2+})$ (10^{-18} cm^2)	$\sigma(O^{2+})$ (10^{-18} cm^2)	$\sigma(C^+ + O^+)$ (10^{-18} cm^2)	$\sigma(C^{2+} + O^+)$ (10^{-18} cm^2)	σ(total) (10^{-16} cm^2)
350	1.339 (5.1%)	0.237 (5.6%)	0.213 (5.8%)	0.783 (9.6%)	1.100 (5.8%)	0.285 (11.3%)	8.132 (6.6%)	0.400 (9.4%)	1.843 (3.9%)
400	1.172 (5.1%)	0.182 (5.6%)	0.168 (5.8%)	0.656 (9.5%)	0.912 (5.5%)	0.269 (8.8%)	6.009 (6.6%)	0.260 (9.8%)	1.565 (3.9%)
500	1.023 (5.1%)	0.141 (5.5%)	0.131 (5.5%)	0.508 (10.8%)	0.676 (7.7%)	0.224 (16.5%)	4.691 (7.2%)	0.264 (14.7%)	1.328 (4.0%)
600	0.897 (5.1%)	0.123 (5.5%)	0.111 (5.6%)	0.392 (11.4%)	0.637 (8.1%)	0.192 (20.3%)	4.165 (7.3%)	0.212 (15.7%)	1.160 (4.0%)
700	0.806 (5.1%)	0.105 (5.5%)	0.096 (5.6%)	0.374 (11.0%)	0.522 (7.3%)	0.187 (15.2%)	3.400 (7.1%)	0.194 (13.4%)	1.032 (4.1%)
800	0.735 (5.1%)	0.094 (5.7%)	0.087 (6.0%)	0.304 (11.7%)	0.469 (6.7%)	0.169 (13.4%)	2.959 (6.9%)	0.182 (11.2%)	0.938 (4.1%)
900	0.698 (5.1%)	0.087 (5.8%)	0.081 (6.1%)	0.308 (11.7%)	0.469 (7.1%)	0.147 (14.7%)	2.723 (7.0%)	0.146 (13.2%)	0.887 (4.1%)
1000	0.640 (5.1%)	0.083 (5.7%)	0.076 (6.0%)	0.271 (12.0%)	0.415 (6.2%)	0.134 (11.6%)	2.595 (6.8%)	0.148 (10.9%)	0.817 (4.1%)
1500	0.464 (10.7%)	0.058 (11.1%)	0.054 (11.3%)	0.183 (17.3%)	0.299 (11.6%)	0.099 (16.1%)	1.851 (11.7%)	0.130 (15.4%)	0.589 (8.5%)
2000	0.384 (7.9%)	0.047 (8.4%)	0.043 (8.7%)	0.138 (16.3%)	0.232 (9.0%)	0.073 (13.6%)	1.4443 (9.3%)	0.089 (14.4%)	0.484 (6.4%)
2500	0.304 (7.9%)	0.033 (8.4%)	0.031 (8.7%)	0.100 (15.5%)	0.184 (8.5%)	0.063 (10.3%)	1.048 (9.0%)	0.059 (11.6%)	0.376 (6.5%)
3000	0.264 (7.9%)	0.030 (8.4%)	0.027 (8.6%)	0.087 (14.9%)	0.155 (8.4%)	0.050 (11.2%)	0.899 (9.0%)	0.060 (10.6%)	0.328 (6.5%)
4000	0.214 (7.9%)	0.024 (8.4%)	0.022 (8.7%)	0.077 (14.9%)	0.127 (8.4%)	0.038 (10.3%)	0.722 (9.0%)	0.048 (11.0%)	0.265 (6.5%)
5000	0.186 (7.9%)	0.021 (8.4%)	0.019 (8.7%)	0.069 (15.7%)	0.113 (8.6%)	0.031 (10.2%)	0.620 (9.1%)	0.043 (11.6%)	0.231 (6.5%)
6000	0.166 (8.0%)	0.020 (8.4%)	0.019 (8.6%)	0.060 (16.7%)	0.094 (8.4%)	0.025 (10.3%)	0.581 (9.0%)	0.042 (10.6%)	0.207 (6.5%)
7000	0.134 (8.0%)	0.015 (8.4%)	0.015 (8.7%)	0.055 (15.9%)	0.079 (8.4%)	0.025 (12.0%)	0.409 (9.0%)	0.026 (11.5%)	0.168 (6.5%)
8000	0.129 (7.9%)	0.016 (8.4%)	0.015 (8.7%)	0.059 (15.5%)	0.081 (8.4%)	0.024 (9.3%)	0.520 (8.9%)	0.032 (9.9%)	0.164 (6.3%)

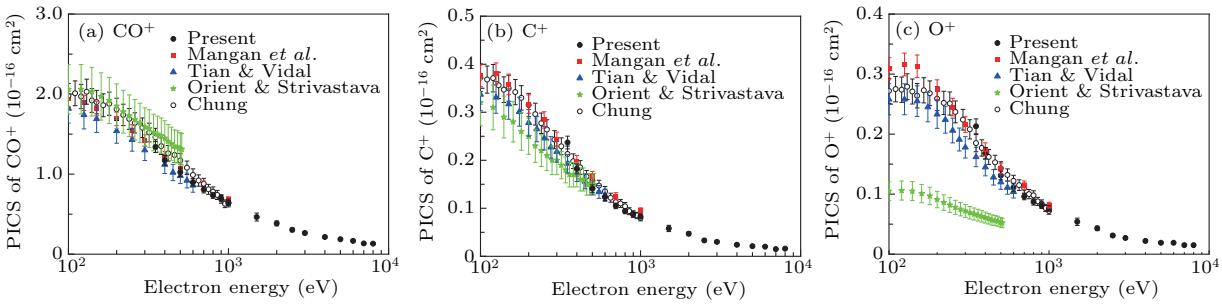


Fig. 2. The PICSs for the singly charged ion products: (a) CO^+, (b) C^+, and (c) O^+. The previous experimental data are from Mangan *et al.*,[33] Tian and Vidal,[29] Orient and Srivastava,[32] and Chung,[34] respectively.

Figure 3 presents the PICSs for the doubly charged CO^{2+}, C^{2+}, and O^{2+} ions. Only two groups reported the relevant data in the energy range overlapped with ours. Tian and Vidal[29] and Mangan *et al.*[33] obtained the PICSs of CO^{2+} with the uncertainties of 15% and 30%, respectively. One can see from Fig. 3(a) that the data of Tian and Vidal[29] are slightly low and the present data well agree with those of Mangan *et al.*[33] As for the C^{2+} and O^{2+} ions, the PICSs values for these ions are very scarce as only one group of Tian and Vidal[29] reported their measurements in a low energy range below 600 eV, which are also included in Figs. 3(b) and 3(c) for comparisons. In the overlap energy range our measurements for both ions are in good agreement with those of Tian and Vidal[29] within the error bars.

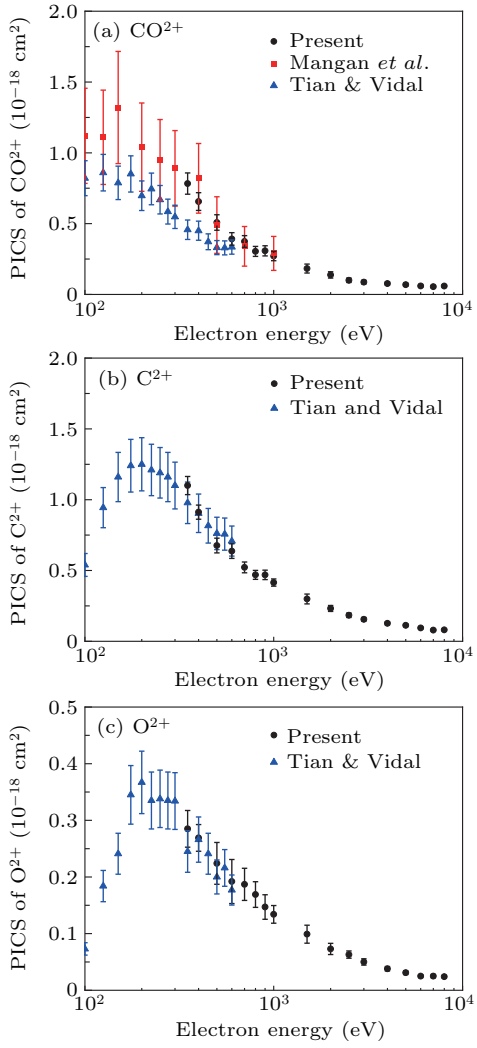


Fig. 3. The PICSs for the doubly charged ion products: (a) CO^{2+}, (b) C^{2+}, and (c) O^{2+}. The previous data are from Mangan *et al.*[33] and Tian and Vidal.[29]

According to Eq. (14), the absolute TICS can be obtained and presented in Fig. 4, along with the previous experimental and theoretical data[25,29,31,32,34,36] for comparisons. Rapp and Englander-Golden[25] measured the TICS from threshold up to 1000 eV in a total ionization tube with 7% errors. Orient and Srivastava[32] obtained the TICS data using QMS from 15 eV to 510 eV with 15% errors. Another three groups also presented the TICSs using TOF spectrometers, i.e., the data of Tian and Vidal[29] from 17.5 eV to 600 eV with 10%–15% errors, Mangan *et al.*[33] from 15 eV to 1000 eV with 5% errors and Chung[34] from 100 eV to 1000 eV with 7.7% errors, respectively. On the theoretical side, Hwang *et al.*[36] calculated the TICS of CO using the BEB model with an average accuracy of 15%. Itikawa[38] collected and reviewed the absolute cross sections of CO with electron impact. He recommended the TICS data from 25 eV to 1000 eV obtained by Mangan *et al.*[33] As shown in Fig. 4, our data of TICSs for the CO molecule are in good agreement with the measured result of Mangan *et al.*[33] and the BEB calculations of Hwang *et al.*[36]

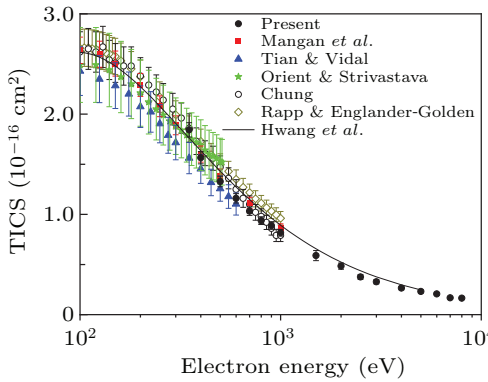


Fig. 4. The TICSs for the electron impact ionizaiton of CO molecule. The previous experimental data are from Mangan *et al.*,[33] Tian and Vidal,[29] Orient and Srivastava,[32] Rapp and Englander-Golden[25] and Chung,[34] respectively. The theoretical result is from the BEB calculations of Hwang *et al.*[36]

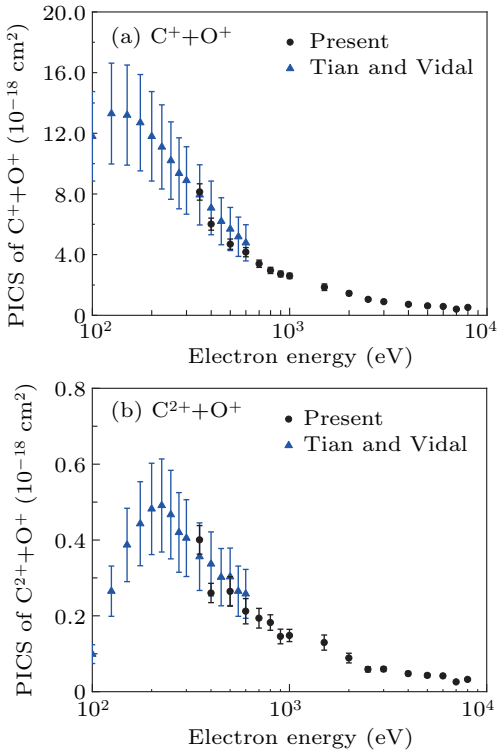


Fig. 5. The PICSs for the ion-pair dissociation channels: (a) $C^+ + O^+$ and (b) $C^{2+} + O^+$. The previous data are from Tian and Vidal.[30]

By detecting ion pairs in coincidence, the complete Coulomb explosion channels (12) and (13) have been identified. The corresponding absolute PICSs for these two channels can be determined according to Eq. (5). Figure 5 represents the present absolute PICSs for two ion-pair dissociation channels ($C^+ + O^+$ and $C^{2+} + O^+$). Only Tian and Vidal[30] reported the PICSs values for these dissociation channels in the low energy range from threshold to 600 eV with 25% overall errors, whose data are also included in Fig. 5 for comparisons. For both two dissociation channels, the present data are slightly smaller than those of Tian and Vidal,[30] which may be due to the inadequately complete detection of ions. In general, the present results exhibit a commendable agreement with those of Tian and Vidal,[30] falling within the range of uncertainties.

4. Conclusion

The absolute partial ionization cross sections for the ionic fragments (CO^+, C^+, O^+, CO^{2+}, C^{2+}, and O^{2+}) and two ion-pair dissociation channels ($C^+ + O^+$ and $C^{2+} + O^+$), as well as the absolute total ionization cross sections are measured in a wide electron impact energies from 350 eV to 8000 eV. The previously available cross-section data have been reviewed and included in figures for comparisons with the present data. Generally, in the overlap energy range, the present PICSs and TICS data are in good agreement with the data of Mangan *et al.*[33] which were recommended by Itikawa[38] as the most reliable values. For the two ion-pair channels, the present PICSs are also in accordance with the data of Tian and Vidal.[30] This study marks the first exploration of absolute partial ionization cross sections for the CO molecule, expanding the energy range to encompass higher values up to 8000 eV. The presently supplemented data will play an important role in the models for exploring the planetary environment like Mars or others.

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References

[1] Campbell L and Brunger M J 2009 *Geophys. Res. Lett.* **36** L03101
[2] Campbell L, Allan M and Brunger M J 2011 *J. Geophys. Res.* **116** A09321
[3] Artamonov A, Mironova I, Kovaltsov G, Mishev A, Plotnikov E and Konstantinova N 2017 *Adv. Space Res.* **59** 2295
[4] Shull J M and Van Steenberg M 1982 *Astrophys. J. Suppl. Ser.* **48** 95
[5] Shen Z J, Wang E L, Gong M M, Shan X and Chen X J 2018 *J. Electron Spectrosc. Relat. Phenom.* **225** 42
[6] Krasnopolsky V A 2015 *Icarus.* **253** 149
[7] Olsen K S, Lefèvre F, Montmessin F, Fedorova A A, Trokhimovskiy A, Baggio L, Korablev O, Alday J, Wilson C F, Forget F, Belyaev D A, Patrakeev A, Grigoriev A V and shakun A 2021 *Nat. Geosci.* **14** 67
[8] Smith M D, Daerden F, Neary L and Khayat A 2018 *Icarus.* **301** 117
[9] Ehrenfreund P and Charnley S B 2000 *Annu. Rev. Astron. Astrophys.* **38** 427
[10] Lillis R J and Fang X 2015 *J. Geophys. Res: Planets.* **120** 1332
[11] Bougher S W, Belly P L, Combi M, Fox J L, Mueller-Wodarg I, Ridley A and Roble R G 2008 *Space Sci. Rev.* **139** 107
[12] Fang X, Randall C E, Lummerzheim D, Wang W, Lu G, Solomon S C and Frahm R A 2010 *Geophys. Res. Lett.* **37** L22106
[13] Lillis R J, Fillingim M O, Peticolas L M, Brain D A, Lin R P and Bougher S W 2009 *J. Geophys. Res. Planets*. **114** E11009
[14] Lillis R J, Mitchell D L, Steckiewicz M, Brain D, Xu S, Weber T, Halekas J, Connerney J, Espley J, Benna M, Elrod M, Thiemann E and Eparvier F 2018 *J. Geophys. Res. Space Phys.* **123** 4349
[15] Hagelaar G J M and Pitchford L C 2005 *Plasma Sources Sci. Technol.* **14** 722
[16] Mirić J, Bošnjaković D, Simonović I, Petrović Z Lj and Dujko S 2016 *Plasma Sources Sci. Technol.* **25** 065010
[17] Rabie M and Franck C M 2016 *Comput. Phys. Commun.* **203** 268
[18] Capitelli M, Colonna G, Ammando G D and Pietanza L D 2017 *Plasma Sources Sci. Technol.* **26** 055009
[19] Hösl A, Pachin J, Egüz E, Chachereau A and Franck C M 2020 *J. Phys. D: Appl. Phys.* **53** 135202
[20] Pietanza L D, Colonna G and Capitelli M 2017 *Plasma Sources Sci. Technol.* **26** 125007
[21] Tate J T and Smith P T 1932 *Phys. Rev.* **39** 270
[22] Schulz G J 1962 *Phys. Rev.* **128** 178
[23] Asundi R K, Craggs J D and Kurepa M V 1963 *Proc. Phys. Soc.* **82** 967
[24] Srinivasan V and Rees J A 1967 *Brit. J. Appl. Phys.* **18** 59
[25] Rapp D and Englander-Golden P 1965 *J. Chem. Phys.* **43** 1464
[26] Hille E and Mark T D 1978 *J. Chem. Phys.* **69** 4600
[27] Freund R S, Wetzel R C and Schul R J 1990 *Phys. Rev. A* **41** 5861
[28] Adamczyk B, Bederski K and Wojcik L 1988 *Biomed. Environ. Mass Spectrom.* **16** 41
[29] Tian C and Vidal C R 1998 *J. Phys. B: At. Mol. Opt. Phys.* **31** 895
[30] Tian C and Vidal C R 1999 *Phys. Rev. A* **59** 1955
[31] Gavin J, Ortiz M and Campos J 2002 *Int. J. Mass Spectrom.* **219** 351
[32] Orient O J and Srivastava S K 1987 *J. Phys. B: At. Mol. Phys.* **20** 3923
[33] Mangan M A, Lindsay B G and Stebbings R F 2000 *J. Phys. B: At., Mol. Opt. Phys.* **33** 3225
[34] Chung Y S 2002 *J. Korean Phys. Soc.* **41** 682
[35] Jain D K and Khare S P 1976 *J. Phys. B: At. Mol. Phys.* **9** 1429
[36] Hwang W, Kim Y K and Rudd M E 1996 *J. Chem. Phys.* **104** 2956
[37] Zhong L, Wu B, Zheng S and Gu Q 2021 *Phys. Plasmas* **28** 083505
[38] Itikawa Y 2015 *J. Phys. Chem. Ref. Data* **44** 013105
[39] Wang E L, Tang Y G, Shen Z J, Gong M M, Shan X and Chen X J 2013 *Rev. Sci. Instrum.* **84** 123110
[40] Straub H, Renault P, Lindsay B, Smith K and Stebbings R 1995 *Phys. Rev. A* **52** 1115
[41] Nagy P, Skutlartz A and Schmidt V 1980 *J. Phys. B: At. Mol. Phys.* **13** 1249
[42] Schram B, De Heer F, Van der Wiel M and Kistemaker J 1965 *Physica* **31** 94
[43] Wiley W and McLaren I H 1955 *Rev. Sci. Instrum.* **26** 1150
[44] Wang E L, Shen Z J, Yang H J, Tang Y G, Shan X and Chen X J 2014 *Chin. Phys. B* **23** 113404
[45] Krems M, Zirbel J, Thomason M and DuBois R D 2005 *Rev. Sci. Instrum.* **76** 093305
[46] Matoba S, Ishikawa G, Moriya S, Takahashi K, Koizumi T and Shiromaru H 2014 *Rev. Sci. Instrum.* **85** 086105