DISSOCIATION OF CARBON DIOXIDE
IN AN AL/AL₂O₃ MICROCHANNEL PLASMA REACTOR
AT ATMOSPHERIC PRESSURE

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THESIS
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ABSTRACT

The dissociation of CO$_2$, using a microcavity plasma in an Al/Al$_2$O$_3$ reactor flowing pure CO$_2$ is achieved with a maximum energy efficiency of 12.4%. This figure corresponds to a maximum dissociation rate of ~70 g/kWh. Additionally, optical emission spectra in UV and visible regions show the evidence of CO$_2$ dissociation. This thesis compares favorably to other methods, even those operating at sub-atmospheric pressures, and is achieved here at atmospheric and even super-atmospheric pressures. This is important because not only is CO$_2$ problematic in terms of its environmental impact, but the primary product of dissociation, CO, is used as a reducer gas in the production of industrially valuable chemicals such as methanol and formic acid.
To my family
ACKNOWLEDGMENTS

I am extremely thankful for my adviser, Professor J. Gary Eden, for his consistent support and guidance. I would also like to express my gratitude towards Professor Sung-Jin Park, who shared his insightful thoughts and guided my academic pathways. I would especially like to thank both of them for the support and advice whenever I am having personal struggle throughout my academic and research life. Many thanks to all members, including former members, of the Laboratory for Optical Physics and Engineering for their help to achieve this thesis. Last but not least, I would like to give my biggest thanks to my family, especially my parents, for their consistent support. I would not have been able to achieve this without their love and support. I sincerely appreciate their love and considerate advice.
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CHAPTER 1

INTRODUCTION

Global concern over carbon dioxide (CO$_2$) emission has been increasing over the past several decades. CO$_2$ is primarily produced by burning complex hydrocarbons for electric power generation and transportation. Table 1.1 [1-3] shows the CO$_2$ emission rates for various fuels and electrical power generators. A global report in 2010 [4] showed that ~ 5.4 billion metric tons of CO$_2$ were emitted only in the United States alone, and ~ 32 billion metric tons of CO$_2$ were reported to have been emitted worldwide.

Table 1.1 Measured CO$_2$ emission rates [1-3].

<table>
<thead>
<tr>
<th>CO$_2$ Emission</th>
<th>Steam Generator</th>
<th>Gas Turbine</th>
<th>Internal Combustion</th>
<th>Combined Cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural Gas</td>
<td>545 g/kWh</td>
<td>600 g/kWh</td>
<td>530 g/kWh</td>
<td>400 g/kWh</td>
</tr>
<tr>
<td>Petroleum</td>
<td>790 g/kWh</td>
<td>1040 g/kWh</td>
<td>790 g/kWh</td>
<td>550 g/kWh</td>
</tr>
<tr>
<td>Coal</td>
<td>970 g/kWh</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In this thesis, microcavity plasmas are used to decompose CO$_2$, according to an overall reaction given by

\[
\text{CO}_2 \rightarrow \text{CO} + \frac{1}{2}\text{O}_2 \quad \Delta H = 2.9 \text{ eV} \tag{1.1}
\]

Not only is CO$_2$ problematic in terms of its environmental impact, but CO has significantly more industrial value than CO$_2$, as it is used as a reducer gas in the production of industrially valuable chemicals such as methanol and formic acid [5]. CO is also used in various industrial applications such as laser, medicine [6] or bulk chemical processing [7]. The characteristic properties of
microcavity plasmas \( (n_e \sim 10^{10} - 10^{16} \text{ cm}^{-3}, T_e \sim 1-5 \text{ eV}) \) [8, 9] suggest that they can be used to efficiently decompose CO\(_2\) by direct electron impact dissociation.
CHAPTER 2
THEORETICAL BACKGROUND

2.1 DC Discharge

The term plasma refers to an ionized gas consisting of positive ions and free electrons in approximately equal proportions, such that overall charge neutrality is maintained. In order to understand the characteristics of microplasmas, a DC glow discharge is first considered as a simple model for a low temperature, non-equilibrium plasma, as its characteristics can be applied to microcavity plasmas to gain insight to their properties. The electron density is one of the most significant properties of a plasma. The electron density of a plasma is the number of free electrons per unit volume. Typical glow discharges exhibit electron densities ranging from $10^{10} - 10^{16} \text{ cm}^{-3}$ [9]. In most gas discharges, the electron density is related to the electric current through the medium. Along with the electron density, the electron temperature is another significant characteristic value of plasmas. The electron temperature is directly related to the electron velocity and is typically defined through a classical Maxwell-Boltzmann distribution, which is given by

$$f(E) = 2 \left( \frac{E}{\pi kT_e} \right)^{3/2} \exp \left( -\frac{E}{kT_e} \right)$$

(2.1)

where $T_e$ is the electron temperature (eV), $E$ is the energy (eV) and $k$ is the Boltzmann constant. For such a distribution the electron temperature, $T_e$, is then related to $<v^2>$ by [10]

$$\frac{m<v^2>}{2} = \frac{3kT_e}{2}$$

(2.2)

where $<v^2>$ is the mean square of the electron velocity (m$^2$/s$^2$), $m$ is the mass (kg), $k$ is the Boltzmann constant (J/K) and $T_e$ is the electron temperature (K). Typical electron temperatures vary from $10 - 10^5$ K for a typical glow discharge.
The Debye length is a characteristic length over which mobile charge carriers screen out electric fields in a plasma. This phenomenon is also called Debye shielding and is given by

$$\lambda_{\text{De}} = \left( \frac{\varepsilon T_e}{e n_e} \right)^{\frac{1}{2}}$$

(2.3)

where $\varepsilon_0$ is the permittivity of free space (F/m), $T_e$ is the average electron temperature (eV), $e$ is the elementary charge (C) and $n_e$ is the electron density (cm$^{-3}$). Depending on the electron temperature and density, the Debye length can range from nanometers to 10s of micrometers. Furthermore, the electron plasma frequency is an important characteristic value for plasmas. Because of Debye shielding effect, it is known that charged particles, electrons and ions, will adjust their positions to nullify the charge perturbation. Electron plasma frequency corresponds to the typical electrostatic oscillation in response to a charge separation. It is given by

$$\omega_{\text{pe}} = \left( \frac{e^2 n_e}{\varepsilon_0 m_e} \right)^{\frac{1}{2}}$$

(2.4)

where $e$ is the elementary charge (C), $\varepsilon_0$ is the vacuum permittivity (F/m) and $m_e$ is the mass of electron. The electron Debye length and the electron plasma frequency are related to the thermal velocity of electrons, and the relationship is given by,

$$V_{\text{thermal}} = \lambda_{\text{De}} \cdot \omega_{\text{pe}}$$

(2.5)

The sheath region is another important characteristic of a plasma that describes the positively charged layer that forms near a surface. It is due to the fact that the electron temperature is usually two orders of magnitude higher than the ion temperature, and the mass of an electron is three orders of magnitude lighter than the mass of ions. Typical sheath thicknesses are on the order of a few $\lambda_{\text{De}}$. 


Along with the sheath region, the presheath region is important because its potential drop in front of the sheath enables the ions to accelerate so that the charge neutrality of the plasma can be sustained. The presheath thickness is on the order of 10’s of Debye lengths. Figure 2.1 [11] shows the qualitative behavior of the sheath and the presheath.

The above parameters and characteristics pertain to a discharge at (quasi) steady state, but they say nothing about what is required to initiate that discharge. Paschen’s law describes the relationship between the breakdown voltage (the voltage required to initiate a plasma), the gas pressure and the gap between the two plane electrodes. Paschen’s law is given by [12],
\[ V = \frac{B(pd)}{\ln(\ln(1 + \gamma))} \]

\[ = \frac{B(pd)}{C + \ln(pd)} \]

where \( A \) and \( B \) are species dependent numerical parameters, \( p \) is the pressure, \( d \) is the plane gap and \( \gamma \) is the secondary electron emission coefficient [12].

**Figure 2.2.** Paschen’s curve for various molecular gases [12].

Figure 2.2 [12] shows Paschen’s curve for various molecular gases. As \( p \cdot d \) goes to either zero or infinity, the breakdown voltage of any gas becomes infinite. As the pressure increases, more collisions occur (due to a reduced mean free path) and lead to a higher electric field requirement. When the pressure is too low, there are not enough ionizing collisions occurring as the charged particle progresses from one electrode to the other. This results in a higher electric field being required, as the mobility of ionization per collision must increase to make up for this.
2.2 Microplasma

Microcavity plasmas are defined as low-temperature, non-equilibrium plasmas that have a characteristic length ranging from 1 µm to 1 mm. Over this range of characteristic lengths, the breakdown voltage can be as low as 1 kV$_{\text{rms}}$ for near atmospheric pressures. A calculation using Equation 2.6 shows that a plane gap of 300 µm at atmospheric pressure (760 Torr) of pure CO$_2$ requires a breakdown voltage of 1.7 kV.

Microcavity plasmas are reported to have electron densities of up to ~5×10$^{16}$ cm$^{-3}$ [11] and average electron temperatures ranging from 0.6 – 5 eV [13]. Since most of the dissociation of CO$_2$ is expected to be due to electron impact dissociation, a high electron density and electron temperature are expected to help the dissociation process of CO$_2$.

Another advantage of having such a small size is a high surface area-to-volume ratio. Typical dielectric barrier discharge devices with a size of 10 cm × 10 cm × 5 mm have surface-area-to-volume ratios of about 4.4 cm$^{-1}$, whereas the microcavity plasma devices used in this work have a ratio of ~215 cm$^{-1}$. With microcavity plasma devices, plasma-surface interactions become significant, and alumina (the dielectric used in this work) has been shown to catalyze various chemical reactions. Furthermore, for the dissociation of CO$_2$, the ceramic surface of Al$_2$O$_3$ is expected to help the stabilization of oxygen atoms detached from CO$_2$ [14].
CHAPTER 3

EXPERIMENT

3.1 Device Fabrication

The devices used in this thesis consist of multiple layers of aluminum, each of which has been electrochemically anodized such that it is coated in nanoporous alumina (Al₂O₃). Nanoporous alumina is known for its stability and robustness, and has been used extensively in atmospheric-pressure microcavity plasma devices [15, 16]. These devices were fabricated by bonding two strips of anodized aluminum. One strip is etched with the microchannel reactor design, and the second strip serves as a cover. Two glass tubes are then attached to the device and serve as an inlet and an outlet for flowing CO₂. The dielectric layer (alumina) is prepared by electrochemical anodization, growing nanoporous aluminum oxide on top of aluminum sheets (99.999 % Al). The aluminum strips have an initial thickness of 1.25 mm, a length of 3 cm, and a height of 10 cm aluminum strips are used. Before electrochemical anodization, the strips are flattened by heating them inside a furnace at 500 °C under compression for approximately 1 hour. The strips are then anodized in 0.3 M sulfuric acid at 30 VDC for 12 hours. This process results in an aluminum electrode embedded inside a dielectric alumina layer. Typical Al₂O₃ thickness grown by this process is about 100 µm. Afterward, channels are etched into the alumina via a process known as micropowder ablation.

A typical device has an Al₂O₃ thickness of ~ 100 µm, with embedded channels having a thickness of ~50 µm. Between the two strips of Al/Al₂O₃, a mica spacer having a thickness of 100 – 150 µm is placed. If the device is intended for optical spectroscopy, a window is bonded onto the side of the device. A schematic of the prototypical device is shown in Figure 3.1.
3.2 Experimental Arrangement

Figure 3.1. Device dimension and operation schematic.

Figure 3.2. Schematic description of gas input and vacuum chamber.
Figure 3.2 is a schematic of the experimental arrangement. The input gas (99.999 % CO₂) is controlled by a mass flow controller (MFC from Aalborg). Flow rates ranging from 40-100 sccm were used. The gas leaving the device is sampled by a leak valve and subsequently analyzed by a residual gas analyzer (a quadrapole mass spectrometer). The remaining (unsampled) gas is vented out to an exhaust line after passing through a check valve. A 20 kHz driving waveform is applied between the top and bottom electrodes of the microplasma device, as is shown in Figure 3.1, and the current and voltage are measured with a 1 GHz oscilloscope (from Agilent Technologies). The partial pressure of CO₂, CO and O₂ are monitored using residual gas analyzer (RGA). The RGA is maintained at a pressure of ~10⁻⁹ Torr. An ICCD camera and monochromator (from Princeton Instruments) are used to record ultraviolet and visible emission spectra.
CHAPTER 4
RESULTS AND DISCUSSION

4.1 Dissociation Rate and Energy Efficiency

The energy efficiency of CO$_2$ dissociation was studied here not only to assess the efficacy of this technology, but also to permit a comparison between the performance of microcavity plasmas and other techniques. The energy efficiency is defined as the total energy expended divided by the theoretical minimum amount of energy required, which is 2.9 eV.

The relative intensity of the mass spectrometer signal was used to calculate the relative decrease in the CO$_2$ concentration according to

\[
A(\%) = \left( \frac{[CO_2]_{initial} - [CO_2]_{product}}{[CO_2]_{initial}} \right) \times 100
\]

where A describes the dissociation rate. The efficiency, \( \eta \), of this process is then given by

\[
\eta(\%) = A \cdot \left( \frac{\dot{m}}{\mu} \right) \cdot \left( \frac{2.9 \text{ eV}}{P} \right)
\]

where A is the dissociation rate calculated above, \( \dot{m} \) is the flow rate CO$_2$ into the device, \( \mu \) is the reduced mass of CO$_2$ and P is the discharge power of the device.

Typical breakdown voltages for the devices used in this work ranged from 0.9 kV$_{rms}$ - 1.5 kV$_{rms}$, and the device discharge power was computed from the measured by current and voltage waveforms. Flow rates of 40-100 sccm were used, and the internal device pressure varied from ~740 Torr to ~800 Torr. Calculation shows that the residence time of the gas inside the discharge zone was 219 ms at 60 sccm, whereas a flow rate of 100 sccm had a 131 ms residence time.

Figure 4.1 shows the dissociation rate and energy efficiency as a function of discharge power driven by 20 kHz sinusoidal waveform. Flow rates of 40, 70 and 100 sccm were tested. A flow of
40 sccm resulted in the highest dissociation rate. The energy efficiency ranged from 8-11% with only a weak dependence on flow rate and power. Although the dissociation rate was higher at higher discharge powers, the maximum energy efficiency was observed at lower discharge powers. The maximum dissociation rate was recorded at the lowest flow rate with the highest power tested. A dissociation rate of 7.7% was recorded at 40 sccm of flow rate with the power of 7 W. At the maximum recorded energy efficiency of 11.1% (40 sccm, 4.1 W), a dissociation rate of 62.9 g/kWh was recorded. The device temperature was measured to be ~100 °C regardless of the flow rate, and the Al/Al₂O₃ structure is robust enough to withstand the temperature increase.

Figure 4.1 shows a typical waveform supplied by the pulse generator. The rise time of the pulse generator was ~200 ns with a pulse width of ~2-2.5 µs. Figure 4.3 shows the dissociation rate and energy efficiency as functions of discharge power when driven by ~20 kHz pulsed waveform. Similar to sinusoidal driving, the highest dissociation rate was recorded at the lowest flow rate with the highest power applied. A maximum dissociation rate of 9.3% was recorded.
with a flow rate of 40 sccm and a power of 8 W. A maximum energy efficiency of 12.4% (70 sccm, 5 W) was recorded, as was a maximum dissociation rate of 70.1 g/kWh. The overall energy efficiency was fairly constant ranging from 9-12.5%. The device temperature was measured to be ~40 °C regardless of the flow rate, which was about 60 °C lower than when the device was driven with a sinusoidal waveform.

Figure 4.2. A typical one cycle of a pulse generator waveform when device power was ~4 W.

Figure 4.3. Dissociation rate and energy efficiency, respectively. Pulse waveform driven.
When a thinner Al electrode strip (~100-500 µm) was used, a flow rate of 100 sccm resulted in an escalated internal pressure (as high as 1.1 atm), which caused a gap to form between the electrodes, and the pressure increased to 1.5 atm. This gap resulted in not only a higher breakdown voltage, but it also shortened the lifetime of devices. Furthermore, an irregular gap between the electrodes caused a non-uniform plasma, which resulted in lower dissociation rate and energy efficiency.

Table 4.1 Reported highest energy efficiency for various type of discharges.

<table>
<thead>
<tr>
<th>Discharge Type</th>
<th>Energy Efficiency (%)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theoretical maximum of thermal plasma</td>
<td>48</td>
<td>[17]</td>
</tr>
<tr>
<td>Arc discharge</td>
<td>15</td>
<td>[18]</td>
</tr>
<tr>
<td>Low pressure glow discharge</td>
<td>8</td>
<td>[19]</td>
</tr>
<tr>
<td>Pulsed microwave discharge</td>
<td>90</td>
<td>[20]</td>
</tr>
<tr>
<td>Dielectric barrier discharge</td>
<td>&lt;10</td>
<td>[21-23]</td>
</tr>
<tr>
<td>Microcavity plasma</td>
<td>12.4</td>
<td>This work</td>
</tr>
</tbody>
</table>

The theoretical maximum efficiency of a thermal plasma was reported to be 48% [17], while CO₂ decomposition using an arc discharge was ~15% [18]. In the case of low pressure reactors, the highest energy efficiency was reported to be 8% [19] for a glow discharge. Although the pulsed microwave discharge had the highest energy efficiency, which was reported to be 90% [20], the pressure it was operated at was less than 200 Torr. Also, the flow was controlled to be supersonic. Using the dielectric barrier discharge was reported to have less than 10% [21-23]. In this study, it is reported that the highest energy efficiency of microcavity plasma dielectric barrier discharge is 12.4%. Unlike other techniques, this study shows that the energy efficiency of
microcavity plasmas is higher than most other techniques, even though the pressure was at atmospheric or even super-atmospheric (~1.5 atm). Table 4.1 shows the summarized chart of highest energy efficiency reported by each technique.

4.2 Optical Emission Spectroscopy

![Optical Emission Spectrum](image)

Figure 4.4. Optical emission spectrum of pure (99.999%) CO$_2$ dissociation under atmospheric pressure. The device power was ~ 4 W and the flow rate was 40 sccm.
Optical emission spectroscopy also shows the evidence of CO\textsubscript{2} dissociation as well as reactive intermediates. Figure 4.4 shows the optical emission spectrum ranging from the UV (~320 nm) to the visible region (~700 nm).

Table 4.2. Assigned peaks for CO\textsubscript{2} microplasma discharge at atmospheric pressure [24-26]; peaks are shown in Figure 4.4.

<table>
<thead>
<tr>
<th>Species</th>
<th>Peak Positions [nm]</th>
<th>Transition</th>
</tr>
</thead>
<tbody>
<tr>
<td>C\textsubscript{2}</td>
<td>473.7</td>
<td>Swan System, (d^3\pi_g \rightarrow a^3\pi_u), (\Delta\nu = 1)</td>
</tr>
<tr>
<td></td>
<td>516.5</td>
<td>Swan System, (d^3\pi_g \rightarrow a^3\pi_u), (\Delta\nu = 0)</td>
</tr>
<tr>
<td></td>
<td>563.6</td>
<td>Swan System, (d^3\pi_g \rightarrow a^3\pi_u), (\Delta\nu = -1)</td>
</tr>
<tr>
<td>CO</td>
<td>451.1</td>
<td>Angstrom System, (B'\Sigma \rightarrow A^1\Pi), ((0\rightarrow v'\nu)), (\Delta\nu = 0)</td>
</tr>
<tr>
<td></td>
<td>483.5</td>
<td>Angstrom System, (B'\Sigma \rightarrow A^1\Pi), ((0\rightarrow v'\nu)), (\Delta\nu = -1)</td>
</tr>
<tr>
<td></td>
<td>519.8</td>
<td>Angstrom System, (B'\Sigma \rightarrow A^1\Pi), ((0\rightarrow v'\nu)), (\Delta\nu = -2)</td>
</tr>
<tr>
<td></td>
<td>561.0</td>
<td>Angstrom System, (B'\Sigma \rightarrow A^1\Pi), ((0\rightarrow v'\nu)), (\Delta\nu = -3)</td>
</tr>
<tr>
<td></td>
<td>608.0</td>
<td>Angstrom System, (B'\Sigma \rightarrow A^1\Pi), ((0\rightarrow v'\nu)), (\Delta\nu = -4)</td>
</tr>
<tr>
<td>CO\textsubscript{2}\textsuperscript{+}</td>
<td>325.4</td>
<td>Fox, Duffendack and Barker (FDB), (A^2\Pi \rightarrow X^2\Pi), (((v',0,0)\rightarrow(v'',0,0)), (\Delta\nu = 2)</td>
</tr>
<tr>
<td></td>
<td>337.8</td>
<td>FDB, (A^2\Pi \rightarrow X^2\Pi), (((v',0,0)\rightarrow(v'',0,0)), (\Delta\nu = 1)</td>
</tr>
<tr>
<td></td>
<td>351.1</td>
<td>FDB, (A^2\Pi \rightarrow X^2\Pi), (((v',0,0)\rightarrow(v'',0,0)), (\Delta\nu = 0)</td>
</tr>
<tr>
<td></td>
<td>367.4</td>
<td>FDB, (A^2\Pi \rightarrow X^2\Pi), (((v',0,0)\rightarrow(v'',0,0)), (\Delta\nu = -1)</td>
</tr>
<tr>
<td></td>
<td>385.2</td>
<td>FDB, (A^2\Pi \rightarrow X^2\Pi), (((v',0,0)\rightarrow(v'',0,0)), (\Delta\nu = -2)</td>
</tr>
<tr>
<td></td>
<td>404.7</td>
<td>FDB, (A^2\Pi \rightarrow X^2\Pi), (((v',0,0)\rightarrow(v'',0,0)), (\Delta\nu = -3)</td>
</tr>
<tr>
<td></td>
<td>424.0</td>
<td>FDB, (A^2\Pi \rightarrow X^2\Pi), (((v',0,0)\rightarrow(v'',0,0)), (\Delta\nu = -4)</td>
</tr>
<tr>
<td>CO\textsubscript{2}\textsuperscript{+}</td>
<td>363.8</td>
<td>FDB, (A^2\Pi \rightarrow X^2\Pi), (((v',0,0)\rightarrow(v'',0,2)), (\Delta\nu = 2)</td>
</tr>
<tr>
<td></td>
<td>377.4</td>
<td>FDB, (A^2\Pi \rightarrow X^2\Pi), (((v',0,0)\rightarrow(v'',0,2)), (\Delta\nu = 1)</td>
</tr>
<tr>
<td></td>
<td>396.2</td>
<td>FDB, (A^2\Pi \rightarrow X^2\Pi), (((v',0,0)\rightarrow(v'',0,2)), (\Delta\nu = 0)</td>
</tr>
<tr>
<td></td>
<td>410.9</td>
<td>FDB, (A^2\Pi \rightarrow X^2\Pi), (((v',0,0)\rightarrow(v'',0,2)), (\Delta\nu = -1)</td>
</tr>
<tr>
<td></td>
<td>434.2</td>
<td>FDB, (A^2\Pi \rightarrow X^2\Pi), (((v',0,0)\rightarrow(v'',0,2)), (\Delta\nu = -2)</td>
</tr>
</tbody>
</table>

Table 4.2 [24-26] lists the peak intensities assigned in Figure 4.4. This optical emission spectrum is evidence that a microcavity discharge is beneficial not only for dissociating CO\textsubscript{2} into CO, but also for making a radical species such as CO\textsubscript{2}\textsuperscript{+}. 
CHAPTER 5

CONCLUSION

Thus far, the maximum recorded energy efficiency of microcavity plasma devices is 12.4%, which corresponds to 70.1 g/kWh with the pulse generator operation. This result is very promising in terms of reaching the break-even point of 400 g/kWh (for a combined-cycle natural-gas generator) because, with almost no optimization, this result is already nearly at the half of the heat capacity of natural gas (180 g/kWh). Future work will involve manipulating the device design and geometry, the gas residence time in the discharge zone, the device temperature and the applied power waveform, to achieve greater efficiencies and surpass the breakeven point. Also, optical emission spectrum provides the evidence that microcavity plasma can be useful not only for reaching the break-even point, but also for synthesizing complex hydrocarbon species that can be used as a recyclable fuel source.
REFERENCES


[25] J. C. McCallum and R. W. Nicholls. "Relative intensity measurements on the Fox-Duffendack-Barker (A^2Π u – X^2Π_g) and the ultraviolet doublet (B^2Σ_u^+ – X^2Π_g) band systems"

[26] L. Curtis, B. Engman and P. Erman, "High resolution lifetime studies of the d$^3\Pi_g$, C$^1\Pi_g$ and D$^1\Sigma_u^+$ states in C$_2$ with applications to estimates of the solar carbon abundance," *Physica Scripta*, vol. 13, no. 5, pp. 270-274, 1976.