Key Parameters Controlling the Photodesorption Yield in Interstellar CO Ice Analogs: The Influence of Ice Deposition Temperature and Thickness

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Abstract

The overabundance of gas molecules in the coldest regions of space points to a nonthermal desorption process. Laboratory simulations show the efficient desorption of CO ice that is exposed to ultraviolet radiation, known as photodesorption, which decreases with increasing ice deposition temperature. However, our understanding of this abnormal phenomenon still remains elusive. In this work, we show that the same phenomenon—and, in particular, a dramatic drop in the photodesorption yield—is observed when the deposition temperature is 19 K and higher. Also, the minimum ice thickness that accounts for a constant photodesorption yield of CO ice is dependent on the deposition temperature, an observation that is reported here for the first time. We propose that the key parameters dominating the absorbed photon energy transfer in CO ice, and contributing to the measured photodesorption yields, are the energy transfer length, the desorption yield contributed by a single ice layer, and the relative effective surface area. These parameters should be incorporated into astrophysical models that simulate the photodesorption of the top CO-rich ice layer in icy dust populations, with a size distribution that is related to the ice thickness.

Unified Astronomy Thesaurus concepts: Molecular spectroscopy (2095); Laboratory astrophysics (2004); Interstellar medium (847)

1. Introduction

The thermal desorption of molecules depleted from ice-covered dust grains is efficient in hot cores, but the low temperatures that reign in dark cloud interiors and radiation-protected circumstellar regions invoke a different desorption mechanism, to account for the observed molecular abundances in the gas phase. Along with other processes, such as cosmic-ray bombardment and chemical desorption (Minissale et al. 2016; Dartois et al. 2018), photon-induced desorption or photodesorption is expected to contribute to the ejection of molecules from ice in cold regions of space. Although external UV photons do not permeate these environments, allowing dust temperatures to drop near to 10 K, and ice mantle accretion onto dust, the secondary UV photons produced by cosmic-ray-driven hydrogen excitation can still impinge onto dust grains and drive photochemistry and photodesorption (Cecchi-Pestelini & Aiello 1992; Shen et al. 2004). In particular, carbon monoxide (CO) is one of the dominant gaseous species in the coldest regions, and it is also the dominant component of the top ice layer, with the second ice layer at the bottom being dominated by water and other species (Pontoppidan et al. 2003, 2004; Boogert et al. 2015; Penteado et al. 2015). According to laboratory simulations, the photodesorption of CO ice is efficient, and it could significantly contribute to the CO gas abundances observed toward dense clouds (Muñoz Caro et al. 2010). The CO ice deposition temperature and deposition angle change the ice morphology and have an impact on the photodesorption yield (Öberg et al. 2009; Muñoz Caro et al. 2016; González Díaz et al. 2019).

Nevertheless, the photodesorption yield of CO ice as a function of deposition temperature has not been sufficiently investigated. In Öberg et al. (2009), the CO ice samples were deposited between 15 and 27 K, and UV irradiated at the temperature of deposition. The photodesorption yield of CO seems to decrease linearly with increasing deposition temperature, but the contribution of thermal desorption might lead to an overestimated photodesorption yield when irradiation proceeds at temperatures above 20 K. Muñoz Caro et al. (2016) have shown that the photodesorption yield also decreases linearly when the deposition temperature is increased from 7 to 20 K (all irradiated at 7 K). We have tried to use structure (which is related to deposition temperature) to explain this phenomenon. We have observed the IR absorption band of shifting CO ice that is relative to the ice deposition temperature, and succeeded in explaining that this shifting is due to the spontelectric field ($E_s$) of CO ice—and, furthermore, that the shifting of vacuum UV (VUV) CO ice absorption bands is caused by Wannier–Mott excitation formation (Chen et al. 2017). However, we cannot explain the linear decrease in photodesorption yield with deposition temperature by means of ice structures or $E_s$ variations (VUV absorption band shifting), since these two phenomena occur above 20 K. In the present work, the effect of the deposition temperature of CO ice on photodesorption is explored from 12.5 to 25 K, in steps of 2 K, to investigate this intriguing phenomenon in more detail. Furthermore, Chen et al. (2014) have reported that the different microwave-discharge hydrogen-flow lamp (MDHL) operation configurations, which produce different photon energy distributions, can cause the photodesorption yields of CO ice to range from $(6.4 \pm 0.2) \times 10^{-2}$ to $(2.1 \pm 0.3) \times 10^{-1}$ molecules

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The incident photon densities of different MDHL configurations are taken into account to calculate the wavelength-weighted absorption intensities, and the discrepancies in the photodesorption yields of CO, CO₂, and O₂ between Sie et al. (2019) and Martin-Doménech et al. (2015) can be explained by considering the absorption cross section and the MDHL spectra of different configurations, which provide a linear relation between the photodesorption yield and the integrated absorption intensity. Muñoz Caro et al. (2016) mention that the CO photodesorption rate values that were reported by Muñoz Caro et al. (2010) and Chen et al. (2014), at deposition temperatures of 15 K and 14 K, using an F-type microwave-discharged hydrogen UV lamp with comparable spectral emission, were 3.5 × 10⁻² and 8.9 × 10⁻² molecules per incident photon, respectively. If the factor of 2.55 difference in their estimations of the total UV flux at the sample positions—2.5 × 10¹⁴ photons cm⁻² s⁻¹, measured using actinometry, and 9.8 × 10¹⁵ photons cm⁻² s⁻¹, measured with a calibrated Ni mesh, respectively—are taken into account, both works converge to a photodesorption rate of exactly the same value.

The charge or energy transfer has previously been studied in the literature, and desorption induced by electronic transition (DIET) has been proposed as dominating the photodesorption of CO ice, which is the process by which a molecule in the ice is photoexcited, so that the molecules near the surface can photodesorb (Reimann et al. 1988; Avouris & Walkup 1989; Madey 1994; Bonn et al. 1999; Funk et al. 2000; Schwoerer & Wolf 2007; Fayolle et al. 2011; Bertin et al. 2012). So far, we only know that the energy absorbed by the molecules inside the ice can be transferred to the top few monolayers, enabling photodesorption; the parameters influencing the photodesorption yield, however, have not yet been sufficiently investigated.

In this work, we propose that three parameters are involved in the photon energy transfer process in CO ice, namely, the energy transfer length (L(T)), the desorption yield contributed by a single ice layer (Y(T)), and the relative effective surface area (R_e(T)). The instantaneous photodesorption yields (Y_ipd) are calculated as a function of the remaining CO ice column density (N_e(CO)), to figure out the contributions of these parameters—which are dependent on deposition temperature—to photodesorption.

2. Experiment Setup and Procedures

The experiments were conducted in the Interstellar Photo-process System (IPS), which has been described in detail in Chen et al. (2014). In brief, IPS is an ultrahigh vacuum (UHV) chamber, with a base pressure of ≈3 × 10⁻¹⁰ torr, which, in this work, uses a closed-cycle helium cryostat to cool down the CaF₂ substrate for ice deposition at 12.5–25 K. The CO gas (purity 99.9999%) is prepared in a premixing system, and flows into the UHV chamber through a leak valve with pressure 4 × 10⁻⁸ torr during deposition. The column density of the CO ice is monitored in situ by a transmission Fourier transform IR spectrometer, which is calculated by N = ∫_band f(ν) dν, where N is the column density in molecules cm⁻², ν is the optical depth of the band, f(ν) is the vibrational density of the band, and A is the band strength, 1.1 × 10⁻¹⁷ cm molecule⁻¹, adopted from Jiang et al. (1975). Each IR spectrum is taken every 3 minutes with a resolution of 2 cm⁻¹. A quadrupole mass spectrometer (QMS) is used to measure the desorbing molecules in the gas phase during irradiation. The band strength of the CO ice deposited up to 25 K is constant; this was confirmed by another experiment, where the CO ice was deposited at 12.5 K and annealed to 25 K. In this experiment, the integrated absorbance did not change, and the lack of the m/z = 28 signal in the QMS indicates that desorption did not occur during annealing. The energetic UV light source is generated by an MDHL, equipped with an MgF₂ window for an emission spectrum from 114 to 170 nm, and the photon flux is about 4.8 × 10¹³ photons cm⁻² s⁻¹, measured in situ by a calibrated Ni mesh during irradiation periods. The UV emission spectrum generated by the MDHL has great similarity with the secondary UV spectrum in the interiors of dense molecular clouds, as calculated by Gredel et al. (1989), providing a method of mimicking the light source that is responsible for ice mantles (Chen et al. 2014; Cruz-Diaz et al. 2014). The VUV irradiation processes are all performed at 12.5 K for each deposition temperature configuration, to avoid the thermal desorption of CO ice, and the interval between each cycle is controlled so that it is 3 minutes.

3. Results and Discussion

Since the dissociation energy of CO is 11.09 eV (Stamatovic & Schulz 1970), which is higher than the maximum photon energy of 10.88 eV, as provided by the MDHL, in these experiments the triple bond of the CO molecule is only dissociated via the reaction

\[ \text{CO} + \text{CO}^* \rightarrow \text{CO}_2 + \text{C}, \]  

where CO* refers to a photoexcited molecule (Okabe et al. 1978; Gerakines et al. 1996; Loeffer et al. 2005). In our experiments, this process has low efficiency, and the column density of CO₂ is always less than 5% of the initial CO ice column density value, in agreement with previous works (Muñoz Caro et al. 2010; Chen et al. 2014). The integrated ion currents of the desorbed CO molecules detected in the gas phase (m/z = 28) during each CO ice irradiation cycle as a function of fluence show the evolution of the photodesorption, which is consistent with the decrease in the CO ice IR band.

3.1. Thickness Effect

The photodesorption yield of 21 ML thick (1 ML = 10¹⁵ molecules cm⁻²) CO ice is calculated with the carbon balance method, |ΔCO₂ᵢ| = 2ΔCO₂ᵢ, since two CO molecules are needed to form a CO₂ molecule in the solid phase, with the remaining fraction corresponding to the CO molecules photodesorbing from CO ice in the gas phase. At a deposition temperature of 12.5 K, the photodesorption decreases linearly as a function of fluence during VUV irradiation, until the CO thickness is less than 5 ML, as shown in Figure 1(a). The turning point at 5 ML is consistent with Muñoz Caro et al. (2010) and Chen et al. (2014), with the initial ice thickness being less than 21 ML, indicating that the photodesorption process is no longer efficient, since the thickness is not enough. We find an interesting result showing that the photo depletion of CO ice has already started to decrease at larger CO thicknesses in the 25 K experiment, since the linear drop fails when N_e(CO) is ~12 ML. This effect of the deposition temperature on the value of the ice thickness, which corresponds to the turning point from a constant to a decreasing CO depletion rate, has not been reported before. The general fitting method for deriving the photodesorption yield will eliminate the variation.
of the photodesorption in each irradiation period. A novel approach for exploring the behavior of photodesorption is proposed, called the “instantaneous photodesorption yield” ($Y_{ipd}$), which is derived from the decrease in the CO ice column density divided by the fluence in each single irradiation period, to reveal the variations between each cycle. $Y_{ipd}$ is represented as a function of $N_{re}(CO)$ in the 12.5 and 25 K experiments for each irradiation cycle, as in Figures 1(b) and (c). $Y_{ipd}$ for the 12.5 K deposition is constant; it falls within 0.24–0.28 molecules photon$^{-1}$ in the region that coincides with the linear fit in Figure 1(a) for CO ice column density above 5 ML (the vertical line in Figure 1(b)). But only a gradually decreasing $Y_{ipd}$ is observed in the 25 K experiment. The initial CO ice thickness of 21 ML is therefore not sufficient to reach a constant photodesorption yield when CO is deposited at 25 K. Therefore, we experimented with four different thicknesses of CO ice: 21, 45, 63, and 89 ML, deposited at 25 K, to reveal the thickness dependence on the photodesorption yield.

From 21 to 89 ML, $Y_{ipd}$ as a function of $N_{re}(CO)$ follows an identical trend. Constant values within 0.11–0.13 molecules photon$^{-1}$ were measured when $N_{re}(CO)$ was larger than 60 ML (Figure 1(d)). We therefore selected an ice thickness of 89 ML to continue our study of the temperature dependence on the photodesorption of CO ice.

### 3.2. Temperature Effect

CO ice samples of 89 ML were deposited within a temperature range from 12.5 to 25 K, to study the temperature effect on photodesorption yield. $Y_{ipd}$ as a function of $N_{re}(CO)$ is represented in Figure 2(a). At the beginning of VUV irradiation, $Y_{ipd}$ is constant in each configuration. $Y_{ipd}$ drops dramatically at a certain $N_{re}(CO)$, which is dependent on the deposition temperature. The average instantaneous photodesorption yield ($Y_{ipdave}$) in the constant region ($N_{re}(CO)$ >60 ML) represents the photodesorption yields in Figure 2(b), which show two different linear relations as a function of deposition temperature, with the turning point at 19 K. Above this temperature, $Y_{ipdave}$ decreases faster.

### 3.3. Photodesorption Estimation

The first step in the photodesorption process is the photon absorption in the CO ice, which is related to the photon energy distribution of the MDHL emission and its $\sigma(\lambda)$ at this range, as depicted in Figure 2(c). The photodesorption yield is proportional to the summation of the absorbed photons in each single $dn'$ layer, which can be calculated by the following equations. According to the Beer–Lambert law, the transmitted intensity can be presented as

$$I_N(\lambda, N') = W(\lambda) e^{-\sigma(\lambda)N'},$$

where $W(\lambda) = \frac{I_0(\lambda)}{\int_0^\infty I_0(\lambda)d\lambda}$, the normalized incident photon intensity of the MDHL, which means that the integral over the wavelength is normalized to unity. This allows us to know the ratio for each wavelength contributing to the photon intensity spectrum. $I_0(\lambda)$ is the incident photon intensity, $\sigma(\lambda)$ is the VUV absorption cross section of CO ice as a function of wavelength $\lambda$ in cm$^2$, and $N'$ is the column density of the $N'$ th layer in ML. $I_N(\lambda, N')$ is the normalized transmission intensity when the photons go through the $N'$ th layer as a function of wavelength, which can also be seen as the new incident intensity for the next $N' + dn'$ layer in Figure 3. Since this photon intensity is dependent on the layer $N'$, the
derivative with respect to the $N'$ th layer represents the wavelength-weighted absorption ratio of the $N'$ th layer ($I_{\text{abs}}(\lambda, N')$), which is still a function of wavelength. Subsequently, the absorption ratio of the $N'$ th layer is integrated over wavelength, which is the same as the MDHL spectrum, to remove the relation with wavelength:

$$I_{\text{abs}}(N') = \int W(\lambda)\sigma(\lambda)e^{-\sigma(\lambda)N'}d\lambda.$$ (3)

After the absorption of the photon energy in the ice, molecules can desorb into the gas phase following two types of photodesorption: (1) photochemidesorption; and (2) DIET (e.g., Martin-Domenech et al. 2015). The former could lead to the desorption of the CO$_2$ molecules formed on the ice surface by the reaction in Equation (1), but the desorption of the CO$_2$ molecules was not observed in our experiments, probably due to the low abundances, which were lower than the detection limit for the QMS used in these experiments. The direct dissociation of CO on the surface could lead to the desorption of C and O atoms, but as we have already mentioned, this process requires a photon energy higher than the MgF$_2$ window cutoff frequency (Stamatovic & Schulz 1970). However, the C and O can be produced via Equation (1), with the dissociation of the produced CO$_2$ in VUV-irradiated CO ice (Chen et al. 2014).

The method that is responsible for this energy transfer between neighboring CO molecules is not well understood, however. A theoretical study dedicated to CO photodesorption proposed various pathways, but only considered the energy transfer between two close neighbors (van Hemert et al. 2015). In experiments, we have shown that for CO ice deposited near 12.5 K, the turning point from a constant to a decreasing $Y_{\text{ipd}}$ occurs at 5 ML ice column density, or about 12 ML in CO ice deposited at 25 K, suggesting that this is the average transmission distance (see Figure 1(a)). Therefore, we now know that such a model must account for the photon energy transfer between several molecules, before the energy is fully dissipated, as this is expected for exciton propagation in the ice (Chen et al. 2017).

We here propose a method for describing the photo- desorption of CO ice, using three parameters: $Y(T)$, $R_a(T)$, and $L(T)$. $Y_{\text{ipd}}$ can be seen as the accumulated $Y(T)$ from each single layer, by considering the wavelength-weighted absorption ratio as a function of the $N'$ th layer ($I_{\text{abs}}(N')$), while the energy transfer is assumed to have an exponential decay-like behavior, written as $e^{-\eta\tau}$. Moreover, $Y_{\text{ipd}}$ is also related to the flatness, and here we use the relative effective surface area ($R_a(T)$) as an analogy, where “relative” represents the concept of a ratio, since the effective surface area contains a unit, but the real value of this area is not available. $R_a(T)$ is therefore on behalf of the surface flatness; when the surface is rugged, this value is larger, to support more molecules desorbing out. $Y_{\text{ipd}}$ as a function of $N_{\text{rel}}(\text{CO})$, shown in Figure 2(a), can be fitted with the equation including parameters adopted above:

$$Y_{\text{ipd}}(N, T) = \int_0^N I_{\text{abs}}(N') \times e^{-\eta\tau} \times Y(T) \times R_a(T) \, dN', \quad (4)$$

where the first term is the wavelength-weighted absorption ratio of the $N'$ th layer in ML$^{-1}$, as introduced before, and $L(T)$ is the energy transfer length in ML, $N$ is the column density of CO ice in ML, and $Y(T)$ is the desorption yield contributed by a single ice layer in molecules photon$^{-1}$, which means the photodesorption yield contributed by a single layer after absorbing photons. $Y(T)$, $L(T)$, and $R_a(T)$ are parameters that are dependent on the deposition temperature. Excluding $I_{\text{abs}}(N')$, which can be calculated from Equations (2) to (3), the other three parameters should be fitted, to obtain the values shown in Figure 4.

### 3.4. Dominating Parameters for Photodesorption

$L(T)$ represents the energy absorbed along the distance $L$; only 37% ($e^{-1}$) of the initial absorbed energy is left, since the energy dissipates exponentially along the penetration, which is related to the structural properties of the CO ice. At a deposition temperature of 12.5 K, CO ice presents an amorphous structure. As the deposition temperature increases, the structure becomes partially crystalline, with a phase transition at 20 K (Kouchi 1990; Kouchi et al. 2020). Below the phase transition temperature, the structure of the CO ice is the same, leading to a constant $L(T)$. The CO molecules are arranged in a nearly crystalline structure at higher deposition temperatures, i.e., above 20 K, and $L(T)$ is thus larger, as shown in Figure 4(a). In addition, Kouchi et al. (2021) show that the crystalline $\alpha$–CO is formed above 21 K, supported by the transmission electron microscopy (TEM) images and the electron diffraction pattern, while the structure of the CO ice
does not only depend on the temperature, because the substrate used for the CO ice deposition also plays a role: the size of the three-dimensional CO island can reach \( \approx 200 \text{ nm} \) when deposited on amorphous \( \text{H}_2\text{O} \) ice, while it is only \( \approx 50 \text{ nm} \) on \( \text{CO}_2 \) ice. The substrate is \( \text{CaF}_2 \) for all of the deposition temperature configurations in this study. The substrate effect on the crystallization of the CO ice is beyond the scope of this paper. The lower energy transfer length below 20K is related to the nonalignment of the molecular dipole, hindering resonant transfer mechanisms based on dipole–dipole interactions. In addition, this parameter determines the photodesorption trend as a function of \( \text{N}_{\text{pd}}(\text{CO}) \), which means that the photodesorption yield drops either dramatically or gradually at low and high deposition temperatures, respectively.

Due to mathematical limitations, the parameters \( Y(T) \) and \( R_A(T) \) cannot be estimated separately, but the product \( Y(T) \times R_A(T) \) can be obtained. Both \( Y(T) \) and \( R_A(T) \) are related to the CO ice growth temperature. Therefore, the formation temperature of CO ice dominates \( Y(T) \times R_A(T) \). This product of \( Y(T) \) and \( R_A(T) \) remains almost constant below deposition temperatures of 19 K and decreases linearly above 19 K. The declining trend from 19 to 25 K is related to the \( E_\text{fi} \) in the CO ice, which is reported to decrease linearly in this deposition temperature range between 20 and 26 K (Lasne et al. 2015). An observable effect of this \( E_\text{fi} \) is the peak redshift in the VUV absorption spectra of solid CO starting above 20 K (Chen et al. 2017). The orientation and molecular disorder of CO ice deposited at different temperatures are also discussed in Carrascosa et al. (2021). Indeed, the excited states of CO molecules in the ice are shifted to lower levels as a result of the lower \( E_\text{fi} \) at deposition temperatures above 20 K, leading to a decreasing desorption yield contributed by a single ice layer. On the other hand, for nonpolar \( \text{CO}_2 \) ice, the photodesorption yield is independent of the deposition temperature (Sie et al. 2019), and the VUV absorption spectra similarly show no peak shifts, indicating that no spontelectric field is generated in \( \text{CO}_2 \) ice. No peak shifts in the VUV absorption bands were reported for another nonpolar molecule, \( \text{N}_2 \); depositions at 14, 20, and 24 K also show the same results for VUV absorption spectra (Chen et al. 2017). Below 19 K, \( E_\text{fi} \) is constant, therefore \( R_A(T) \) is the primary parameter influencing the photodesorption yield at deposition temperatures ranging from 12.5 to 19 K. When the surface is flat, this value is assumed to be 1, while it becomes larger as the effective surface area becomes larger. When CO ice is deposited at low temperatures, the porosity is larger compared to that at high temperatures, leading to a larger \( R_A(T) \) and causing the higher photodesorption yield value in Figure 2(b). This is supported by Cazaux et al. (2017); the binding energies of the CO ice deposited at 14 K (Figure 14) and 6 K (Figure 15) are calculated by Monte Carlo simulations, and the results show that gas-phase CO molecules can stick where they arrive, without having to rearrange themselves at very low temperatures. This leads to a large binding energy distribution, and many pores can be observed in such ice; when the number of pores is higher, the effective surface area is also thought to be higher.

4. Astrophysical Implications and Conclusions

Substantial literature has been dedicated to exploring the photodesorption of solid CO ice in the laboratory, with yields spanning several scales, from \( 10^{-3} \) to \( 10^{-1} \) molecules photon \(^{-1} \); this includes works by Öberg et al. (2009), Fayolle et al. (2011), Chen et al. (2014), Muñoz Caro et al. (2016), and Paardekooper et al. (2016), using different CO ice thicknesses, deposition temperatures, and irradiation configurations. As in Chen et al. (2014) and Sie et al. (2019), the incident energy distribution of the MDHL plays an important role in the absorption of CO ice, leading to distinct photodesorption behaviors.

In the present paper, we introduce a novel calculation of \( Y_{\text{pd}} \) for the ice thickness and deposition temperature dependence on the photodesorption yield of CO ice, which is discussed in relation to the method of photodesorption at different deposition temperatures, being dominated by three parameters: the energy transfer length, the desorption yield contributed by a single ice layer, and the relative effective surface area. The ice thickness that plays a part in the photodesorption process, supporting a constant photodesorption yield of CO ice, is dependent on the deposition temperature. At higher deposition temperatures, thicker ice is required to reach maximum and constant values of the photodesorption yield. At 25 K, the instantaneous photodesorption yield becomes constant when the thickness of the CO ice is larger than 60 ML. When the ice thickness is less than 30 ML, however, the instantaneous photodesorption yield drops drastically.

In the current model of astrophysical ice mantles covering dust grains, such as those observed toward dense interstellar clouds and cold circumstellar regions, the outer layer comprises the most volatile molecules, with CO being the most abundant species, which likely coexists with \( \text{N}_2 \) and \( \text{H}_2 \), which have very low UV absorption cross sections (Martín-Doménech et al. 2020). CO molecules are also observed in the gas phase of the coldest regions in dense clouds, suggesting that strong accretion is counteracted by nonthermal desorption processes. The reported experimental yields can be applied to the CO photodesorption processes induced by the secondary UV field in the interiors of dense interstellar clouds. While chemical desorption would operate on bare dust grain surfaces (Minissale et al. 2016), the desorption of molecules from ice-covered grains is likely driven by cosmic rays and energetic (UV) photons. We find that the photodesorption yield of CO ice is strongly dependent on temperature and ice thickness. X-rays may dominate the ice processing in young protoplanetary disks (Ciuravella et al. 2020; Jiménez-Escobar et al. 2022); this could restructure the ice mantles and change the \( R_A(T) \) parameter. \( \text{N}(\text{CO}) \), when used as an input for a model of a dense cloud interior, is related to the cloud’s lifetime, but this value reaches a maximum for lifetimes shorter than the total lifetime of the cloud (Muñoz Caro et al. 2010). A typical ice mantle thickness of 10 nm or 30 ML, where only the uppermost layers are composed of CO, will show a reduced photodesorption yield, since we report that maximum photodesorption occurs for ice thicknesses above 60 ML. Such ice thicknesses might be attained in precometary icy grains. On the other hand, the low growth temperature near 10 K for interstellar ice mantles will favor photodesorption, while the temperature gradients in disks will lead to varying photodesorption rates for ice mantles covering a broader range of growth temperatures and ice thickness distributions. Current astrochemical disk models are complex, as they take into account numerous parameters (e.g., Walsh et al. 2010; Woitke et al. 2018). These models can include our experimental findings as inputs, to improve their treatments of CO photodesorption. Woitke et al. (2018) have previously adapted their model in response to our
earlier results, and Cazaux et al. (2017, 2022) used Monte Carlo simulations to interpret our experimental results and extend them to astrophysical scenarios. The extrapolation of our experimental model to an astrophysical model, which simulates a disk environment or a dense interstellar cloud interior, where ice mantles are exposed to UV photons, is beyond the scope of this paper, but may be performed in a future collaboration with modelers.

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