VUV photochemistry of the H$_2$O· · · CO complex in noble-gas matrices: formation of the OH· · · CO complex and the HOCO radical

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Vacuum ultraviolet (VUV, 130–170 nm) photochemistry of the H$_2$O· · · CO complex is studied by matrix-isolation infrared spectroscopy. The H$_2$O· · · CO complexes in Ne, Ar, Kr, and Xe matrices are generated by ultraviolet (UV, 193 and 250 nm) photolysis of formic acid (HCOOH). VUV photolysis of the H$_2$O· · · CO complexes is found to lead to the formation of the OH· · · CO radical–molecule complexes and trans-HOCO radicals. It is shown that the matrix material, local matrix morphology, and possibly the H$_2$O· · · CO complex geometry strongly affect the VUV photolysis pathways. The intrinsic reactivity of the matrix-isolated OH· · · CO complex resulting in the formation of trans-HOCO is directly demonstrated for the first time. This reaction occurs in Ar, Kr, and Xe matrices upon annealing above 25 K and may proceed over the barrier. The case of a Ne matrix is very special because the formation of trans-HOCO from the OH· · · CO complex is observed even at the lowest experimental temperature (4.5 K), which is in sharp contrast to the other matrices. It follows that quantum tunneling is probably involved in this process in the Ne matrix at such a low temperature. Infrared light also promotes this reaction in the Ne matrix at 4.5 K, which is not the case in the other matrices. The last findings show the effect of the environment on the tunneling and infrared-induced rates of this fundamental chemical reaction.

Introduction

Non-covalent interactions play an important role in a great variety of chemical processes. Light-induced chemical transformations in weakly-bound intermolecular complexes represent an intriguing field of supramolecular photochemistry with a remarkable impact on life science, nanotechnology, and chemical synthesis.$^{1,2}$ The matrix-isolation technique has been extensively used for the investigation of non-covalent interactions, particularly, involving radicals and other unstable species.$^{3–13}$ Recent studies have demonstrated an effective approach for the preparation of matrix-isolated complexes in high concentrations using the photolysis of appropriate molecular precursors (see ref. 9 for a review). For example, UV photolysis of formic acid (HCOOH, FA) leads to the formation of the H$_2$O· · · CO complexes.$^{14}$ Furthermore, one can use matrix isolation to investigate the photochemistry (or, in a wider context, radiation-driven chemistry) of intermolecular complexes. The photoinduced transformations of some complexes have been studied previously under matrix-isolation conditions.$^{15–21}$ In general, such reactions can lead to the assembly of new species or “cold synthesis” under the conditions of frozen molecular mobility, which may be particularly significant to model and understand the processes in interstellar and cometary ices.

Water and carbon monoxide are the two most abundant molecules in interstellar ices,$^{22}$ and these species also play an important role in the atmospheric chemistry. The intermolecular complex H$_2$O· · · CO has been studied previously both theoretically and experimentally.$^{14,23–34}$ The reaction of this complex with an H atom produces the radical–molecule complex HCO· · · H$_2$O.$^{35}$ Another related radical–molecule complex, OH· · · CO, is expected to be the key primary product of the photoinduced transformation of H$_2$O· · · CO. The OH· · · CO complex has been extensively examined by ab initio calculations as an intermediate in the OH + CO → CO$_2$ + H reaction, which is significant in combustion and atmospheric processes.$^{36–43}$ Lester et al. reported an experimental detection of the OH· · · CO complex in the gas phase having the OH stretching overtone at 6941.8 cm$^{-1}$ (shifted by -29.6 cm$^{-1}$ with respect to the OH monomer).$^{47}$ The electronic excitation spectrum and the intermolecular vibrational frequencies of this complex have also been characterized experimentally.$^{44}$ Very recently, Brice et al. have reported the OH fundamental frequency of the OH· · · CO complex in He droplets...
at 3551 cm⁻¹ (shifted by −17 cm⁻¹ with respect to the OH monomer). Nevertheless, full experimental characterization of the fundamental IR absorptions of the OH···CO complex is still lacking.1

Another species that is relevant to this system is the carboxyl radical (HOCO) that is separated from the OH···CO complex by a low energy barrier (a few hundred cm⁻¹). This radical has two conformers, the trans form being lower in energy than the cis form by about 500 cm⁻¹. It has been shown that trans-HOCO can be produced in low-temperature matrices upon photolysis or radiolysis of some CO- or CO₂-containing intermolecular complexes.21-23

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The aim of the present work is to study vacuum ultraviolet (VUV) photochemistry of the H₂O···CO complex under matrix-isolation conditions and identify the OH···CO radical–molecule complex. This study is also related to the photochemical preparation of the carboxyl radical HOCO. UV photolysis of matrix-isolated FA is used to produce a sufficient concentration of the H₂O···CO complexes in noble-gas matrices.14

**Experimental details**

The experiments were carried out using FA/Ng mixtures (Ng = Ne, Ar, Kr, and Xe) with typical ratios of 1/1000–1/2000. FA (Merck, >98%) was degassed by several freeze–pump–thaw cycles. Ne (99.999%), Ar (99.999%), Kr (99.999%), and Xe (99.999%) were used as purchased (Linde). The gas FA/Ng mixtures were made in a glass bulb by using standard manometric procedures. Since FA is easily adsorbed on glass surfaces, the bulb was passivated with FA vapors by fill–keep–evacuate cycles prior to the mixture preparation. The FA/Ng matrices were deposited onto a CsI substrate held at 4, 15, 20, and 30 K for Ne, Ar, Kr, and Xe matrices, respectively, in a closed-cycle helium cryostat (RDK-408D2, SHI). The FA/Ng matrices (Ng = Ne, Ar, and Kr) were photolyzed with an excimer laser (MSX-250, MPB) operating at 193 nm (~ 10 mJ cm⁻²) to produce the H₂O···CO complexes. Since 193 nm photons decompose water in a Xe matrix, in this case we used 250 nm radiation (~ 5 mJ cm⁻²) of an optical parametric oscillator (OPO, Sunlite, Continuum). After UV photodecomposition of FA, the matrix was exposed to VUV light (130–170 nm) of a Kr lamp (Opthos). During VUV photolysis, the space between the lamp and the cryostat optical window (MgF₂) was flushed with argon. Reference experiments were also made with FA/Ng matrices initially photolyzed with VUV radiation of a Kr lamp, i.e. without preliminary UV photolysis. Selective excitation in the IR region was performed by narrowband light of an OPO (LaserVision). The IR absorption spectra in the 4000–600 cm⁻¹ range were measured at 4.5 K using an FTIR spectrometer (Vertex 80, Bruker) with 1 cm⁻¹ resolution and 500 scans.

**Results**

In these experiments, the H₂O···CO complex was generated in noble-gas matrices by photodecomposition of FA. The deposited FA/Ng matrices (Ng = Ne, Ar, Kr, and Xe) contained mostly FA monomers (in the more stable trans form)14 with small amounts of FA dimers (tt1 and tt2)55,56 and trans-FA···H₂O complexes.56,57

The obtained spectra of trans-FA are in full agreement with the previous data. UV irradiation of the deposited matrices (~ 5000 pulses at 193 nm for Ng = Ne, Ar, and Kr and ~ 20 000 pulses at 250 nm for Ng = Xe) resulted in efficient decomposition of FA (typically >70%). The difference IR spectra showing the result of UV photolysis in different matrices are presented in Fig. 1. The increase of the absorbance of H₂O···CO bands correlates with the FA photodecomposition. The fundamental frequencies of the H₂O···CO complex isolated in noble gas matrices are given in Table 1. The spectra of the H₂O···CO complex observed in our experiments in Ar, Kr, and Xe matrices are in good agreement with previous works,14,27 however, some additional weak features of the perturbed H₂O fundamentals are also detected. These weaker bands correlate with the other H₂O···CO absorption bands. We suppose that the absence of these features in the earlier work14 may be due to higher temperatures in their experiments (15 K). The IR absorptions of the H₂O···CO complex in the Ne matrix have been previously reported only for ν₁(H₂O) and ν(CO).28 In our work, we also observed the ν₁ and ν₃ bands of water in this complex.

The H₂O···CO complex can have two different structures, HOH···CO and HOH···OC, in which a water hydrogen interacts with different atoms of carbon monoxide (C and O, respectively). These two structures can be distinguished spectroscopically by the CO stretching shift with respect to CO monomer. The computationally more stable HOH···CO complex has a blue shift of this mode, whereas the HOH···OC complex shows a red shift.14,27 In full agreement with the previous results,14 we observed a matrix-specific ratio of these complexes produced by UV photolysis of FA. In fact, only the HOH···CO structure is observed in Ne and Ar matrices; both HOH···CO and HOH···OC structures are found in a Kr matrix, and the HOH···OC form dominates in a Xe matrix. It is worth noting that in Kr and Xe matrices, the bands of water in the H₂O···CO complex are quite structured, which is most probably due to several matrix sites with overlapping absorptions. This fact prevents us from definite assignment of these bands to the two complex structures (HOH···CO and HOH···OC). In addition to the H₂O···CO complex, CO₂ (possibly complexed with H₂) and monomeric CO are also produced by UV photolysis of FA. The relative yield of CO (both complexed and monomeric) with respect to CO₂ decreases with the increase of the matrix dielectric constant, which is discussed elsewhere.14

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1 In ref. 10, the shift of −21.8 cm⁻¹ is mentioned for the OH fundamental mode of the OH···CO complex isolated in an Ar matrix, but no details of the corresponding experimental results are reported.
After the first (UV) photolysis, the matrices contain some remaining amounts of FA. As seen in Fig. 2, FA is partially consumed, and 3699.8 cm$^{-1}$ in Kr; 659.7, 2334.7, 3587.9, and 3691.6 cm$^{-1}$ in Xe).$^{31,36}$ The minor isotopologues of CO$_2$ were also observed ($^{13}$CO$_2$: 2281.8, 2274.2/2277.2 with a shoulder at 2279.3, 2275.1, and 2269.5 cm$^{-1}$ for Ne, Ar, Kr, and Xe respectively; $^{18}$O$^{12}$C$^{18}$O: 2330.5, 2327.7/2325.6 with a shoulder at 2323.0, 2323.3, and 2317.8 cm$^{-1}$ for Ne, Ar, Kr, and Xe respectively; $^{13}$CO$^{12}$O$^{18}$O$^{18}$O$^{18}$O were also detected. In addition, a new absorber with bands at 3546.5 and 2159.8 cm$^{-1}$ in a Ne matrix, at 3526.5 and 2152.5 cm$^{-1}$ in an Ar matrix, and at 3521.9 and 2147.9 cm$^{-1}$ in a Kr matrix was observed. These bands are assigned in this work to the OH···CO complex as discussed below. In this series of experiments, no candidates for the OH···CO absorptions were found after VUV photolysis in the Xe matrix even though the trans-HOCO bands were quite evident. It should be stressed that trans-HOCO and the OH···CO complex were not observed during the initial UV photolysis. It is also worth noting that no evidence for the stabilization of the higher energy cis-HOCO conformer has been found in these studies although it was reported previously in N$_2$ and CO matrices as well as in solid H$_2$O···CO mixtures.$^{19e,52}$ To our knowledge, cis-HOCO has never been observed in noble-gas matrices.

The formation of trans-HOCO and OH···CO tends to saturate for substantial consumption of H$_2$O···CO, whereas the production of CO$_2$ continues. This behavior can be interpreted as an interplay between primary (production of OH···CO and trans-HOCO) and secondary (production of CO$_2$) channels of VUV photolysis of the H$_2$O···CO complex. The direct photoproduction of CO$_2$ from H$_2$O···CO is also possible.

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The effect of Kr-lamp radiation (130–170 nm) on matrices containing the H$_2$O···CO complexes is shown in Fig. 2. This irradiation resulted in gradual bleaching of the H$_2$O···CO bands, an increase of the band of the CO monomer (2149.0, 2138.5, 2135.5 and 2133.0 cm$^{-1}$ in Ne, Ar, Kr, and Xe, respectively)$^{51,56}$ and a noticeable growth of the CO$_2$ bands (668.0, 2347.4, 3611.0, and 3713.2 cm$^{-1}$ in Ne; 662.5, 2344.8/2342.7 with a shoulder at 2339.7, and 3706.6/3703.8 with a shoulder at 3699.8 cm$^{-1}$ in Ar; 660.5, 2340.5 with a shoulder at 2337.2 with a shoulder at 2279.3, 2275.1, and 2269.5 cm$^{-1}$ for Ne, Ar, Kr, and Xe respectively; $^{18}$O$^{12}$C$^{18}$O: 2330.5, 2327.7/2325.6 with a shoulder at 2323.0, 2323.3, and 2317.8 cm$^{-1}$ for Ne, Ar, Kr, and Xe respectively; $^{13}$CO$^{12}$O$^{18}$O$^{18}$O$^{18}$O$^{18}$O were also detected. In addition, a new absorber with bands at 3546.5 and 2159.8 cm$^{-1}$ in a Ne matrix, at 3526.5 and 2152.5 cm$^{-1}$ in an Ar matrix, and at 3521.9 and 2147.9 cm$^{-1}$ in a Kr matrix was observed. These bands are assigned in this work to the OH···CO complex as discussed below. In this series of experiments, no candidates for the OH···CO absorptions were found after VUV photolysis in the Xe matrix even though the trans-HOCO bands were quite evident. It should be stressed that trans-HOCO and the OH···CO complex were not observed during the initial UV photolysis. It is also worth noting that no evidence for the stabilization of the higher energy cis-HOCO conformer has been found in these studies although it was reported previously in N$_2$ and CO matrices as well as in solid H$_2$O···CO mixtures.$^{19e,52}$ To our knowledge, cis-HOCO has never been observed in noble-gas matrices.

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After the first (UV) photolysis, the matrices contain some remaining amounts of FA. As seen in Fig. 2, FA is partially
decomposed by VUV irradiation. In order to estimate the contribution of VUV photolysis of FA to the formation of OH−CO and trans-HOCO, we performed reference experiments with initial VUV photolysis of FA in Ar and Kr matrices. Although both OH−CO and trans-HOCO were also observed in these experiments, their amounts (normalized to the amount of decomposed FA) were markedly lower as compared to the case of VUV photolysis performed after UV photolysis. Moreover, the H₂O−CO complex was also produced upon VUV photolysis of FA, and its photodecomposition evidently occurred. Thus, we conclude that both OH−CO and trans-HOCO are mainly the products of VUV photolysis of the H₂O−CO complex. However, as discussed below, the direct photodissociation channel HCOOH → HOCO + H neither can be excluded.

In a separate series of experiments, we annealed the matrices after UV photolysis (prior to VUV photolysis). The annealing temperatures were 25, 35, and 40 K for Ar, Kr, and Xe matrices respectively. Ne matrices were not treated in this way since they are stable only below 12 K. This annealing led to some changes in the matrix sites of the H₂O−CO complex. An example of the Ar matrix is shown in Fig. 3. Based on the annealing-induced behavior, we distinguish the IR absorptions of the H₂O−CO complex in unrelaxed (decreasing upon annealing) and relaxed (increasing upon annealing) matrix.

Table 2  Experimental vibrational frequencies (in cm⁻¹) of trans-HOCO in noble-gas matrices

| Mode | Ne   | Ar   | Kr   | Xe   |
|------|------|------|------|------|
| v₁   | 3631.3 | 3604.8 | 3581.9 | 3555.5 |
|      | 3627.6 | 3602.6 | 3601 sh | 3548.9 |
| 2v₂  | 2083.9 | 2108.7 | 2112.8 | 2107.6 |
|      | 2081.1 | 2109.2 | 2104.9 |      |
| v₂   | 1847.9 | 1843.5 | 1839.7 | 1834.4 |
|      | 1832.0 | 1839.8 | 1836.8 | 1825.4 |
| v₃   | 1210.5 | 1211.1 | 1210.9 | 1209.9 |
|      | 1208.8 | 1205.9 | 1202.4 |      |
|      | 1205.6 | 1202 sh |      |      |
| v₄   | 1052 sh | 1066 sh | 1066 sh | 1062.9 |
|      | 1050.6 | 1064.5 | 1064.9 |      |

* Our data are in good agreement with the previous studies; 21,51,56,58,61 new assignments are in bold; sh – shoulder.

Fig. 2  VUV photolysis (130–170 nm) of the H₂O−CO complex in different matrices. All traces are difference spectra showing the result of VUV photolysis (for ~ 70 min) of initially UV-photolyzed FA/Ng matrices (Ng = Ne, Ar, Kr, and Xe). The bands marked with diamonds, asterisks, and circles are due to the H₂O−CO complex, CO monomer, and residual FA, respectively. The weak features marked with crosses are the (2ν₂ + ν₁) absorptions of CO₂ (this peak in the Ar matrix is masked by the band of trans-HOCO).

![Fig. 2](image)

![Fig. 3](image)
sites irrespective of the geometry of the complex (see Table 1). The absorptions attributed to the unrelaxed sites are broader and/or more structured compared to the ones of the relaxed sites. It should be noted that the complete conversion to the relaxed matrix site (as in the case of the Ar matrix) was not achieved in the Kr matrix. In the Xe matrix, the weak band at 2141.0 cm\(^{-1}\) slightly increased in intensity, whereas no candidates for the relaxed site were found in the water stretching region. To remind, the yield of the H\(_2\)O\(\cdot\cdot\cdot\)CO complex in the Xe matrix was lower than in the other matrices. The observed effect of annealing on the H\(_2\)O\(\cdot\cdot\cdot\)CO complex in the Xe matrix was in good agreement with the previous observations.\(^{46}\) We have also found that annealing of the UV-irradiated FA/Ng matrices leads to the formation of HCO (Ar: 1863.4 cm\(^{-1}\); Kr: 2467.1 and 1860.3 cm\(^{-1}\); Xe: 2442.4, 1856.6, and 1076.2 cm\(^{-1}\)), HCO\(\cdot\cdot\cdot\)H\(_2\)O (Ar: 1853.8 cm\(^{-1}\); Kr: 2530.5, 1858.8, 1853.3, and 1856.0 cm\(^{-1}\); Xe: 3710.4, 3707.5, 2516.4, 2510.7, 1850.0, 1847.6, 1092.8, and 1090.8 cm\(^{-1}\)).\(^{35,56}\) and trace amounts of trans-H\(_2\)COOH (Ar: 967.3 and 964.9 cm\(^{-1}\); Kr: 964.6 and 962.2 cm\(^{-1}\); Xe: 959.6 and 957.8 cm\(^{-1}\)).\(^{56,62}\) In the Xe matrix, relatively intense bands of HXeH (1166.5 and 1181.4 cm\(^{-1}\))\(^{63}\) are observed after annealing. Since the used annealing temperatures activate the mobility of H atoms,\(^{51,64}\) these results clearly indicate that UV photolysis of FA produces considerable amounts of H atoms.

Annealing of the matrices prior to VUV photolysis significantly affects the branching ratio of the photoproducts. In fact, the ratio of the OH\(\cdot\cdot\cdot\)CO and trans-HOCO amounts markedly increased in the annealed matrices. Fig. 4 illustrates this result for the Ar matrix. A similar trend was observed in the Kr matrix. In the Xe matrix annealed after UV photolysis, VUV photolysis produced a weak band at 2145.0 cm\(^{-1}\), which was attributed to the CO absorption of the OH\(\cdot\cdot\cdot\)CO complex; however, no band of this complex in the OH stretching region was found in this experiment.

Annealing of the matrices after VUV photolysis results in a decay of the OH\(\cdot\cdot\cdot\)CO complex as illustrated for the Ar matrix in Fig. 5a. In Ar and Kr matrices, the OH\(\cdot\cdot\cdot\)CO bands almost disappear after annealing at 30–35 K. Fig. 5b shows the effect of annealing on the OH\(\cdot\cdot\cdot\)CO decay and the formation of trans-HOCO and HCO\(\cdot\cdot\cdot\)H\(_2\)O in the Ar matrix. First, there is no correlation between the formation of HCO\(\cdot\cdot\cdot\)H\(_2\)O, which is due to the H + CO \(\cdot\cdot\cdot\) H\(_2\)O reaction\(^{45}\) and the OH\(\cdot\cdot\cdot\)CO decay. This fact evidences that the main decomposition channel of OH\(\cdot\cdot\cdot\)CO is not connected with mobile H atoms. Second, there is a good overall correlation between the decomposition of OH\(\cdot\cdot\cdot\)CO and the formation of trans-HOCO, particularly above 25 K, which features the OH\(\cdot\cdot\cdot\)CO \(\rightarrow\) trans-HOCO reaction. It should be understood that the strict correlation between these processes is difficult to expect due to a number of additional channels. For example, some of the OH and CO fragments can be shortly separated in the matrix after photolysis and recombine upon annealing. Agglomeration of species upon annealing is another complicating factor. The probable reaction of the OH\(\cdot\cdot\cdot\)CO complex with H atoms can also change the temperature dependences. In this respect, we can mention that some increase of the amount of the H\(_2\)O\(\cdot\cdot\cdot\)CO complex is systematically observed after annealing. In the Xe matrix, the amount of OH\(\cdot\cdot\cdot\)CO is very small, and it is difficult to study this process in detail. However, this annealing allowed us to detect the OH fundamental of the OH\(\cdot\cdot\cdot\)CO complex in the Xe matrix (at 3520.0 cm\(^{-1}\)), which was otherwise masked by the absorption of residual FA (see Fig. 6). In Kr and Xe matrices, annealing at 35 and 45 K, respectively, also resulted in a slight decrease of the trans-HOCO bands (see the lower trace in Fig. 6). A similar behavior was observed previously and may indicate the reaction of trans-HOCO with mobile H atoms.\(^{56}\)

As to the case of the Ne matrix, a slow decay (on a timescale of more than 10 h) of the OH\(\cdot\cdot\cdot\)CO complex accompanied by the formation of trans-HOCO was observed even in the dark at 4.5 K (the lowest temperature of our experiment) (see Fig. 7). It is worth mentioning that no other products of OH\(\cdot\cdot\cdot\)CO decay (e.g. CO\(_2\)) were found in these experiments, except for small amounts of the H\(_2\)O\(\cdot\cdot\cdot\)CO complex. According to our kinetics measurements, the decay of the OH\(\cdot\cdot\cdot\)CO complex in the dark is not a single exponential but slows down in time, which is common for solid-state reactions.\(^{65}\) The decay of the OH\(\cdot\cdot\cdot\)CO complex is accelerated by temperature; however, the narrow temperature range of stability of the Ne matrix and the complicated decay curve prevented further studies on this matter. In addition, it was found that this process was accelerated by broadband IR light of the globar and selective excitation of the OH mode by narrowband radiation of OPO (3546.5 cm\(^{-1}\)). IR light seemed to decrease the trans-HOCO yield (compared to the process in the dark), but additional channels were not observed. It should be stressed that no dark OH\(\cdot\cdot\cdot\)CO \(\rightarrow\) trans-HOCO reaction was detected in other matrices at 4.5 K as well as there was no efficient effect of IR light.

Finally, we examined the photostability of the OH\(\cdot\cdot\cdot\)CO and trans-HOCO species in the Kr matrix. It was found that ~250 pulses at 193 nm decomposed trans-HOCO almost completely, whereas the OH\(\cdot\cdot\cdot\)CO bands remained virtually unchanged. The 193 nm photolysis of trans-HOCO yielded CO\(_2\), but the amount of CO monomer did not change.
Discussion

Light-induced decomposition of water is known to occur via the \( \text{H}_2\text{O} \rightarrow \text{H} + \text{OH} \) channel and the energy of Kr-lamp photons is enough to dissociate water in matrices. Therefore, one may expect the formation of the \( \text{OH} \cdots \text{CO} \) complex upon photolysis of the \( \text{H}_2\text{O} \cdots \text{CO} \) complex. In the present work, we observed two bands, correlating with the VUV-induced decomposition of \( \text{H}_2\text{O} \cdots \text{CO} \), which are assigned to the fundamental vibrations of the \( \text{OH} \cdots \text{CO} \) complex. The OH and CO absorption bands appear at 3546.5 (Ne), 3526.5 (Ar), 3521.9 (Kr), and 3520.0 \( \text{cm}^{-1} \) (Xe) and at 2159.8 (Ne), 2152.5 (Ar), 2147.9 (Kr), and 2145.0 \( \text{cm}^{-1} \) (Xe), respectively.

The available calculations predict two structures for this complex, which can be represented as \( \text{OH} \cdots \text{CO} \) and \( \text{OH} \cdots \text{OC} \) (both linear), the \( \text{OH} \cdots \text{CO} \) structure being energetically more favorable (by 140–180 \( \text{cm}^{-1} \)). According to the calculations, the experimentally observed complex has the \( \text{OH} \cdots \text{CO} \) structure, in which the hydrogen atom of OH interacts with the carbon atom of CO. Table 3 shows the experimental and calculated shifts of the \( \text{OH} \cdots \text{CO} \) bands with respect to the \( \text{OH} \) and CO monomers. The experimental values are in good agreement with the theory. We did not observe any candidates for the less stable \( \text{OH} \cdots \text{OC} \) structure. This species should have a blue-shifted OH absorption and a red-shifted CO one, i.e. the directions of the shifts are opposite in comparison with those of \( \text{OH} \cdots \text{CO} \). Thus, it seems that the less stable \( \text{OH} \cdots \text{OC} \) structure is not stabilized under our experimental conditions. It is worth noting that this result is in agreement with the studies in the gas-phase and He droplets, where only the \( \text{OH} \cdots \text{CO} \) structure was detected.
The decrease of the complexation-induced shift with the increase of the matrix dielectric constant is an interesting observation (see Table 3). This trend is presumably due to a weaker matrix effect on vibrations of the complex units compared to the monomers. It was previously discussed that the complexation-induced shift is worth counting from the monomer in a vacuum rather than from that in the matrix. A Ne matrix is presumably the best approximation of a vacuum among the practical noble gases and the very good agreement of the experiment in the Ne matrix with calculations of ref. 43 is remarkable.

trans-HOCO is another product observed upon VUV photolysis of the H2O – CO complex. The previous matrix-isolation studies have shown that this radical can be produced in different ways. First, it is known that trans-HOCO can be formed in low-temperature matrices via the OH + CO → trans-HOCO reaction. In this case, the CO molecule should be in close proximity to the species that served as a precursor of the OH radical. This reaction pathway has been demonstrated in a number of experimental works, where trans-HOCO was generated upon VUV photolysis of H2O in solid CO25,26 UV photolysis of the CO – H2O complex in noble-gas matrices,21 near-UV photolysis of the CO – HONO complex in a N2 matrix,19a and X-ray radiolysis of the H2O – CO2 complex in noble-gas matrices.51 Upon X-ray radiolysis of matrix-isolated FA, the direct dissociation channel HCOOH → HOCO + H occurs,56 which was not found previously in UV photolysis. In the present work, trans-HOCO was efficiently produced in the “two-color” photochemical experiments with FA/Ng matrices, i.e. when UV photolysis of the matrix was followed by VUV photolysis.

The previous works on UV photolysis of matrix-isolated FA showed only two primary channels, HCOOH → H2O + CO and HCOOH → H2 + CO2.14 The present results suggest the existence of additional channels. First, UV photolysis of matrix-isolated FA efficiently produces H atoms, which is evidenced by annealing-induced reactions. It follows that some radical products are formed under these conditions. Second, trans-HOCO is rapidly decomposed by UV radiation most probably yielding CO2 and H atoms. It is possible that the direct dissociation of FA to trans-HOCO and the H atom occurs upon UV photolysis, similarly to X-ray radiolysis,56 but trans-HOCO is not observed because of its very efficient photodecomposition. In addition, we cannot exclude the production of H atoms via the photodecomposition of HCO. Indeed, the reaction HCOOH → HCO + OH is a main channel in the gas-phase photolysis of FA.67

Table 3  Experimental and calculated shifts (in cm⁻¹) of the fundamental modes of the OH – CO complex with respect to OH and CO monomers

| Experiment (this work) | Theory⁶
|------------------------|------|
| Mode                  | Ne  | Ar  | Kr  | Xe  | Ref. 38⁺ | Ref. 43⁺ | Ref. 45⁺ |
| ν(OH)                 | −26.5 | −21.5 | −16.7 | −11.4 | −12 | −27 | −19 |
| ν(CO)                 | +18.9 | +14.0 | +12.4 | +12.0 | +16 | +20 | — |

a Experimental frequencies of the OH monomer in noble-gas matrices are taken from refs. 51 and 71. b For the more stable OH – CO structure. c Calculations at the CCSD(T)/cc-pVQZ level of theory. d Calculations at the CCSD(T)/Def2-TZVP level of theory.

In our experiments with VUV irradiation, trans-HOCO is mainly formed from the H2O – CO complex although the direct dissociation channel HCOOH → HOCO + H is also possible. The present results cannot directly prove whether the H2O – CO → trans-HOCO photoreaction (VUV) is a single-step process or it occurs via the OH – CO intermediate. It is difficult to distinguish these two channels based on the kinetic measurements because the VUV-induced degradation of both trans-HOCO and OH – CO (yielding CO2) significantly complicates this analysis. Nevertheless, the possibility of the two-step mechanism H2O – CO → OH – CO → trans-HOCO is indirectly supported by the observed transformation of OH – CO to trans-HOCO, and this process is discussed in more detail below.

The gas-phase reaction between OH and CO leading to trans-HOCO has been suggested to occur via the OH – CO complex.37,68,69 Our observations provide valuable information about the reactivity of the OH – CO complex. The annealing-induced decay of OH – CO occurring in Ar and Kr matrices at ~30 K correlates with the formation of trans-HOCO. As mentioned above, the lack of a strict correlation between these processes observed in the Ar matrix below 25 K (see Fig. 5b) features additional reactions. As suggested previously,51 the recombination of shortly-separated (non-complexed) pairs OH + CO → trans-HOCO may be responsible for the formation of trans-HOCO at temperatures between 10 and 25 K. The short-range recombination with H atoms recovering the H2O – CO complex can contribute to the decay of OH – CO at ~15 K. In the Ne matrix, the OH – CO decay in the dark is also accompanied by the formation of trans-HOCO. Thus, we conclude that trans-HOCO is the main product of decomposition of the OH – CO complex under our experimental conditions and an additional minor channel may be the OH – CO + H → H2 + CO2 reaction. The annealing-induced reaction OH – CO → trans-HOCO in Ng matrices (Ng = Ar, Kr, and Xe) can be an over-barrier process. Indeed, the Arrhenius equation yields the characteristic reaction time of ca. 10 s at 30 K and 2 × 1015 years at 10 K, for the reaction barrier of 665 cm⁻¹ and the pre-exponential factor of 7.4 × 1012 s⁻¹.‡

In the Ne matrix, the OH – CO decay and the formation of trans-HOCO occur in the dark even at 4.5 K. This observation can be considered as a signature of quantum tunneling because the over-barrier reaction at such a low temperature can be excluded. The OH – CO → trans-HOCO reaction induced by IR light also takes place in the Ne matrix. It is interesting that in other matrices, the OH – CO → trans-HOCO process was not found at 4.5 K. Concerning the possible tunneling mechanism, this difference may be connected with the details of the matrix.

‡ The calculated value of the barrier height was extracted from ref. 42c and the used pre-exponential factor corresponds to the experimental frequency for the intermolecular bending mode in the OH – CO complex (ref. 44b).
environment (solvation), in agreement with the known observations.\textsuperscript{70} It is more difficult to understand the lacking efficiency of the IR-induced process in other noble-gas matrices. We can speculate that the vibrational energy relaxation of OH···CO is faster for heavier matrix atoms, and the required reorganization of the complex does not occur.

Finally, we discuss the effects of the matrix material (see Fig. 2) and matrix annealing (see Fig. 4) on the branching ratio of the OH···CO and trans-HOCO channels of VUV photolysis of the H$_2$O···CO complex. First, this ratio sufficiently decreases in the Kr matrix as compared to Ar and Ne matrices. In the Ne matrix, the OH···CO formation is very inefficient. Second, the relative yield of the OH···CO production can be sufficiently increased by annealing of the matrices after initial UV photolysis (prior to VUV-photolysis). These trends qualitatively correlate with the matrix site splitting of the H$_2$O···CO absorptions. The ratio between the H$_2$O···CO amounts in the relaxed and unrelaxed matrix sites after UV photolysis of FA decreases from Ne to Xe. We believe that the bands of H$_2$O···CO in the Ne matrix correspond to the relaxed matrix site because they are narrow and unstructured. Matrix annealing stimulates conversion of the unrelaxed site to the relaxed one. (In general, annealing leads to relaxation of matrix morphology to a lower energy.) These correlations seem to show that VUV photolysis of the H$_2$O···CO complex in an unrelaxed environment produces mainly trans-HOCO. In contrast, a more efficient formation of the OH···CO complex occurs in a relaxed environment, e.g., after annealing of the matrix. The exact structure and energetics of these matrix sites are unknown.

In addition to matrix morphology, the geometry of the parent H$_2$O···CO complex can affect its VUV photoproducts. It is possible that the photochemical channels are different for the HOH···CO and HOH···OC structures. For example, the low yield of the OH···CO complex in the Xe matrix may be connected with the dominating HOH···OC structure of the precursor. However, to examine this effect, one needs to obtain matrices with different structures of the H$_2$O···CO complex (HOH···CO only and HOH···OC only). In the present work, we failed to find experimental conditions providing these matrices and this question remains unanswered.

Conclusions

In the present work, we have studied VUV photolysis (130–170 nm) of the H$_2$O···CO complexes in noble-gas matrices (Ne, Ar, Kr, and Xe). The H$_2$O···CO complexes were generated by UV photolysis (193 and 250 nm) of formic acid (FA) in noble-gas matrices. In agreement with the previous observations,\textsuperscript{14} the matrix material has a significant effect on both the yield and the geometry of the H$_2$O···CO complex. As a new finding, UV photolysis of FA is observed to produce considerable amounts of H atoms. The formation of H atoms possibly includes the photolysis of trans-HOCO and/or HCO directly produced from FA. This observation shows that UV photochemistry of FA in noble-gas matrices is not fully understood.

VUV photolysis of the H$_2$O···CO complex in noble-gas matrices leads to the formation of the OH···CO radical–molecule complex, in which the hydrogen atom of OH interacts with the carbon atom of CO. All fundamental absorptions of this complex were found in the four matrices. The red shifts of $-26.5$, $-21.5$, $-16.7$, and $-11.4$ cm$^{-1}$ (with respect to OH monomer) were observed for the OH stretching mode in Ne, Ar, Kr and Xe matrices, respectively, whereas the blue shifts of $+18.9$, $+14.5$, $+12.4$ and $+12.0$ cm$^{-1}$ were found for the corresponding CO stretching vibrations. The obtained data are in good agreement with the calculations reported previously.\textsuperscript{38,43,45} No evidence for the stabilization of the less stable OH···OC structure was found. The formation of the OH···CO complex is quite efficient in Ne and Ar matrices, and it is hardly visible in the Xe matrix. The yield of the OH···CO complex increased if the matrices containing the H$_2$O···CO complexes were subjected to annealing prior to VUV photolysis. These observations suggest that the local matrix morphology and possibly also the H$_2$O···CO complex geometry affect the photolysis pathways.

The trans-HOCO radicals are efficiently formed by VUV photolysis of the matrix-isolated H$_2$O···CO complexes. Several new assignments are suggested for this species. We have to note that the multi-step production of trans-HOCO from FA via the H$_2$O···CO complex is a promising approach for further matrix-isolation studies on this important species. It is worth noting that neither the OH···CO complexes nor the trans-HOCO radicals appear after UV photolysis of FA in the noble-gas matrices; thus, the VUV photolysis has a clear advantage in this case.

Finally, the intrinsic reactivity of the matrix-isolated OH···CO complex resulting in the formation of trans-HOCO is directly demonstrated. This reaction was observed in Ar and Kr matrices upon annealing at 30–35 K. These results confirm that the OH···CO complex can act as an intermediate in the OH + CO $\rightarrow$ HOCO reaction. The case of the Ne matrix is special because the formation of trans-HOCO from the OH···CO complex occurs in the dark even at the lowest experimental temperature (4.5 K), which is in contrast to other matrices. It is possible that quantum tunneling is involved in this process because the over-barrier reaction is improbable at such a low temperature. If it is true, this finding represents a strong matrix effect on the tunneling rate. IR light activates this reaction in the Ne matrix at 4.5 K, and again, this effect is not certainly found in the other matrices, which is not fully understood. The Ne matrix is the closest approximation of the gas phase among the noble-gas solids; thus, the tunneling and IR-induced reactions found in the Ne matrix may also occur in the gas phase.

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