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Cyclic mechanism in the trapping of carbonyl oxides with alcohols and carboxylic acids

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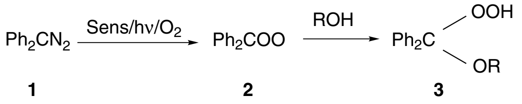
Abstract—The reaction of diphenylcarbonyl oxide with alcohols and carboxylic acids, which has been classified as a nucleophilic trapping, is shown to be in the reactivity order: $AcOH \gg MeOH > CF_3CH_2OH > EtOH \gg t\text{-}BuOH$. A laser-flash spectroscopy indicated that the reaction of carboxylic acids is very fast, that is, one-tenth of the diffusion rate. These results suggest that the hydroxyl compounds react as an acid and a nucleophile at the same time and the major reaction is via the seven- and five-membered cyclic mechanism for RCO_2H and ROH, respectively.

Carbonyl oxides and related species are known as a key intermediate in the ozonolysis of olefins[1] and have attracted much attention in the various fields such as synthetic, biological, mechanistic, and atmospheric chemistry.[2] Chemical property of the peroxidic species is significantly dependent on their substituents.[2a,3] For example, an unique reactivity has been known for a carbonyl oxide (CO) carrying a potent electron-withdrawing[4] or -donating group.[5] One of recent interests is a generation of hydroxyl radical from CO's in gas phase.[6] Typical reactions of CO's are the cycloaddition to aldehydes and the trapping with alcohols and carboxylic acids.[1,2] The latter reaction with hydroxyl compounds has been regarded as the evidence of CO intermediates in the ozonolysis of olefins[1] and classified as the nucleophilic trapping.[2b] We became interested in the trapping reaction and obtained unexpected results that the trapping proceeds by way of a cyclic mechanism, carboxylic acids being the most reactive as described in the following.

The reaction of diazo compounds with singlet oxygen is well known to produce the corresponding CO's.[7] Thus, the irradiation of diphenyldiazomethane (**1**) and Rose Bengal in acetonitrile at >400 nm under oxygen afforded benzophenone quantitatively, and the reaction in the presence of ROH resulted in the formation of α-alkoxyhydroperoxide (**3**),[7b] as shown in Eq. 1, as the trapped product from diphenylcarbonyl oxide (**2**), for example, 51% yield of **3** when R = Me.



$$\underset{\mathbf{1}}{Ph_2CN_2} \xrightarrow{Sens/h\nu/O_2} \underset{\mathbf{2}}{Ph_2COO} \xrightarrow{ROH} \underset{\mathbf{3}}{Ph_2C}\begin{matrix} OOH \\ OR \end{matrix} \qquad (1)$$

It is apparent that **2** was trapped efficiently since the selectivity for **2** from **1** and $^1O_2$ is known to be 50–60%.[8] Comparable yields (i.e., 40–65%) of **3** were resulted with ethyl alcohol (R = Et) and acetic acid (R = Ac), but no product was obtained from *t*-BuOH. Relative reactiviy of these hydroxyl compounds toward **2** were determined from the relative yields of **3** in their presence of 1:1 ratio in MeCN.[9] The resulting relative reactivity of AcOH–MeOH–CF_3CH_2OH–EtOH–*t*-BuOH are 50:5.0:1.4:1.0:<0.01; unexpectedly, acetic acid was shown to be the most reactive in trapping **2**. A different trapping ability has been reported to be $AcOH < t\text{-}BuOH < MeOH$,[10] but the order was estimated indirectly during an olefin ozonolysis.

In order to confirm whether carboxylic acids react with CO's facilely or not, the trapping reaction was studied by means of laser flash spectrophotometry.[11] Carbonyl oxide **2** is known to decay slowly according to second-order kinetics, yielding benzophenone ultimately.[12]

Keywords: Carbonyl oxides; Cycloadditions; Alcohols; Carboxylic acids and derivatives; Peroxides; Mechanisms.

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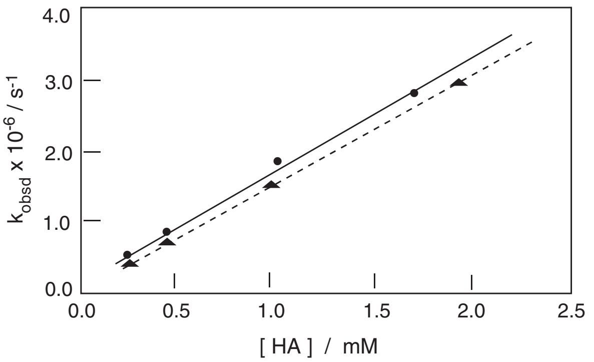


Figure 1. Effect of concentrations of HA on the decay rate of Ph_2COO (**2**) in acetonitrile at 20 °C: ●, AcOH; ▲, PhCOOH.

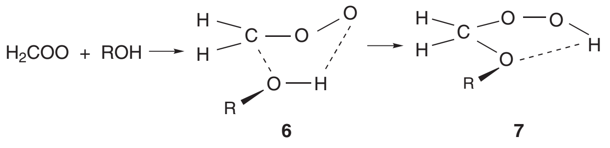
When acetic acid was added, CO **2** decayed rapidly according to the first-order dependence on [**2**] (e.g., the lifetime of 0.37 s in the presence of 1.0 mM AcOH). As shown in Figure 1, the decay rate is proportional to the acid concentrations, and the resulting second-order rate constant for AcOH is $k_2 = 1.61 \times 10^9\ M^{-1} s^{-1}$ (vs [**2**] and [AcOH]; see Fig. 1). The k_2 values of **2** for benzoic and *m*-chlorobenzoic acids are 1.56 and $1.40 \times 10^9\ M^{-1} s^{-1}$, respectively, and that of $(p\text{-}ClC_6H_4)_2COO$ with AcOH was $1.69 \times 10^9\ M^{-1} s^{-1}$. Apparently, the reaction of **2** with carboxylic acids is as fast as one-tenth of the diffusion rate and is independent of their acidity. For comparison, the k_2 value for the reaction of **2** and PhCHO was determined to be $5.6 \times 10^7\ M^{-1} s^{-1}$,[13] which is only 1/30 of the value with RCO_2H.

How about the rate of reaction between CO's with alcohols? For the case of $Ph(MeO_2C)COO$, a reactive CO, the k_2 value for MeOH is reported to be $3.4 \times 10^6\ M^{-1} s^{-1}$.[14] On the other hand, the reaction rate of **2** with alcohols has not been reported because the reaction is too slow for the accurate determination. The k_2 value of **2**, however, could be estimated from the initial decay in the presence of MeOH, affording the approximate one of $2.7 \times 10^4\ M^{-1} s^{-1}$. The estimation seems to be acceptable since **2** is trapped efficiently by MeOH.

These kinetic study on the trapping of **2** confirmed the interesting fact that the reactivity order is $RCO_2H \gg RCHO \gg ROH$. Although the reactions with hydroxyl compounds have been classified as 'nucleophilic trapping',[2b] the order of $RCO_2H \gg ROH$ clearly suggests that the trapping is not controlled by their nucleophilicity. Then pathway (a) or (b) is conceivable as the mechanism of trapping with hydroxyl compounds (Scheme 1). The assumption of hydrogen bonding between the outer oxygen of CO and hydroxyl compounds is reasonable since the oxygen is of minus charge and behaves as a nucleophilic oxidant.[2b,3,7b] The observed trapping reactivity of $RCO_2H \gg MeOH > CF_3CH_2OH > EtOH$ is not compatible with pathway (a) where the product selectivity would be dependent on the nucleophilicity of RCO_2H or ROH. Especially, the observed orders of $RCO_2H \gg ROH$ and of $CF_3CH_2OH > EtOH$[15] clearly deny pathway (a) since RCO_2H and CF_3CH_2OH is known to be less nucleophilic.

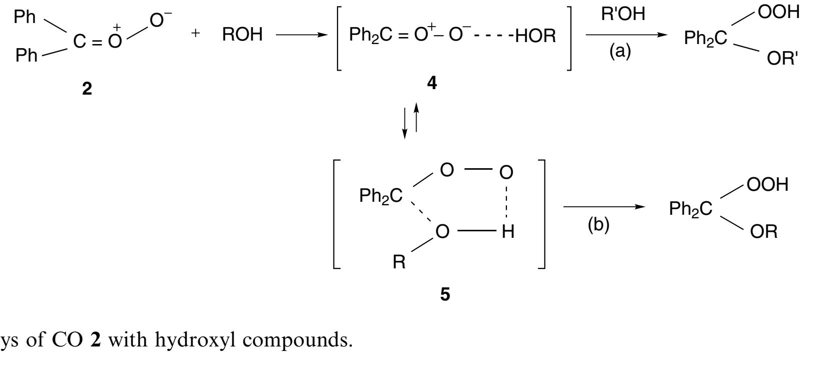
On the other hand, a cyclic mechanism such as path (b) may explain the trapping orders since the hydroxyl compounds could react as an acid and a nucleophile at the same time. The observed higher trapping reactivity of RCO_2H in comparison to alcohols could be explained only by cyclic mechanism involving a hydrogen bonded transition state such as **5**. According to the cyclic mechanism the trapping reactivity is governed by the hydrogen bonding ability and partially by their nucleophilicity. No reaction of *t*-BuOH is explicable by the steric hindrance between the bulky *tert*-butyl and two phenyl groups in **3** or **5**.

Suitability of the cyclic transition state (TS) **5** is considered according to the semi-empirical AM1 method by which the Criegee mechanism was successfully analyzed.[16] According to the method[17] a five-membered cyclic TS **6** could be calculated for the addition of ROH to parent H_2COO (Eq. 2). Resulting TS **6** (R = H) is of an envelope type and similar to that for the addition of $H_2C{=}O$.[16a]



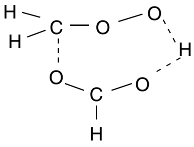
(2)

The heat of addition of H_2O to yield adduct **7** is calculated to be highly exothermic (i.e., −59 kcal/mol)[18] by



Scheme 1. Trapping pathways of CO **2** with hydroxyl compounds.

the AM1 method, but the activation energy to form TS **6** (R = H) is as high as 30.3 kcal/mol, indicating that the reactions of alcohols is not so facile.[19] The calculated activation energy for the addition of MeOH (R = Me, Eq. 2) is 32.4 kcal/mol, but that of formic acid (R = HCO) is as high as 43.5 kcal/mol. Thus, five-membered TS **6** cannot explain the observed fast reaction of carboxylic acids. For the case of acids, however, seven-membered TS **8** could be pictured.



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In fact, such TS **8** was suggested by the AM1 method, the activation energy being −48.0 (AM1) or −30.2 kcal/mol (a DFT).[20] The activation energy is predicted to be barrierless, which is consistent with the observed fast reaction of carboxylic acids. In order to examine the incorporation of hydrogen bonding, the deuterium isotope effect was determined in the reaction of **2** with AcOH and AcOD. The resulting small value of $k_H/k_D = 1.44$ (MeCN, 25 °C) is in a line with the hydrogen-bonded cyclic TS **8** in the fast reaction close to the diffusion rate.

Finally, some should be noted on the apparent discrepancy between the kinetic rate ratio and the competitive trapping reactivity. The rate ratio for the carboxylic acid and MeOH is $10^9:10^4$, that is, the 10^5-fold difference, while that from competitive trapping experiments was 10:1, that is, only 10-fold. The discrepancy suggests clearly that in the co-presence of RCO_2H and R′OH (see Scheme 1) the major reaction is pathway (b) but pathway (a) operates as a minor one (up to 10%).

In conclusion, the present paper on the reaction of CO's revealed experimentally that the addition of carboxylic acids proceeds very fast via seven-membered TS while that of alcohols by way of five-membered TS. So-called nucleophilic trapping of CO's is to be classified as the trapping via five- or seven-membered cyclic mechanism.

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9. Acetonitrile solution of **1** (7.5 mM), Rose Bengal (0.15 mM), ROH (0.615 M each) was irradiated for 1.5 h at >400 nm under oxygen. Product yields were determined by ^{1}H NMR measurement. $Ph_2C(OR)OOH$: **3a** (R = Me) δ_H ($CDCl_3$): 3.33 (s, 3H), 7.2–7.7 (m, 10H); **3b** (R = Et): 2.02 (t, 3H), 3.52 (q, 2H), 7.2–7.7 (m, 10H); **3c** (R = CH_2CF_3): 3.84 (s, 2H), 7.2–7.7 (m, 10H); **3d** (R = COMe): 2.16 (s, 3H), 6.8–7.5 (m, 10H).
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17. Spartan package: MACSPARTAN Plus 2.0, Wavefunction, Inc., Irvine, CA 92612.
18. Calculated heat of reaction of Eq. 2 are −59 and −52 kcal/mol for R = H and HCO, respectively. The high heat of reaction seems, when the reaction of CO's with water or carboxylic acid occurs in gas phase, to indicate the spontaneous homolysis of weak O–O bond in **7** leading to the formation of hydroxyl radical.
19. In contrast, the cycloaddition of $H_2C{=}O$ to H_2COO was shown to have a low activation energy of below 2 kcal/mol.[16a]
20. A DFT calculation: pBP/DN**(Spartan)/AM1.[17]