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Carboxylation of Cyclohexanone with Carbon Dioxide and Potassium Phenoxide. Dependence of the Reaction upon the Amount of Carbon Dioxide Complexed with Potassium Phenoxide

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The uptake of CO_2 by potassium phenoxide (PhOK) in *N*,*N*-dimethylformamide (DMF) was investigated in a vacuum system. Further, the carboxylation of cyclohexanone by various amounts of CO_2 complexed with PhOK was studied. The yield of the carboxylate at 30 s increased with increase of M.R. (molar ratio of CO_2 absorbed by PhOK to PhOK initially added) in the range of M.R. less than 0.41. However, in the range of M.R. above 0.60, it decreased with increase of M.R. The time required for completion of the reaction depended on the M.R., and three ranges were distinguishable. The ultimate yield of the carboxylate in the carboxylation increased proportionally to M.R. value. It is considered that the source of CO_2 for carboxylate formation was CO_2 complexed with PhOK rather than uncomplexed CO_2.

Keywords——carbon dioxide; potassium phenoxide; cyclohexanone; carbon dioxide–phenoxide complex; carboxylation

Sodium (or potassium) phenoxide is a useful reagent for the carboxylation of active methylene-containing compounds.[1)] We have investigated[2)] the carboxylation in the presence of substituted phenoxides in order to clarify the mechanism of this reaction, and we proposed[2b)] two possible reaction paths. One mechanism involves CO_2 transfer from CO_2–phenoxide complex to a substrate (RH), forming a carboxylate. In the other mechanism, carboxylation occurs between CO_2 and a substrate anion (R^-) which is formed by the reaction of the substrate with phenoxide.

In the carboxylation of cyclohexanone by potassium phenoxide and carbon dioxide, the dependence of the reaction rate upon the concentration of cyclohexanone is first order.[1b)] This result is consistent with both reaction mechanisms mentioned above. Potassium phenoxide and its substituted phenoxide derivatives were shown to absorb CO_2[2a)] in a vacuum system, the amount of CO_2 absorbed by potassium phenoxide depending on the CO_2 pressure. As mentioned above the complex formed by reaction between CO_2 and phenoxide may play an important role in the carboxylation reaction. Thus, significant information about the reaction mechanism might be obtained by studying the dependence of the reaction upon the concentration of the CO_2–phenoxide complex, that is, the amount of CO_2 absorbed by phenoxide.

The dependence of the carboxylation reaction upon the amount of CO_2 absorbed by potassium phenoxide (PhOK) was investigated in *N*,*N*-dimethylformamide (DMF) with cyclohexanone as the substrate at 0 °C. In this study, carboxylation was carried out after the uptake of CO_2 by PhOK in the vacuum system, and the time course of the reaction was followed.

Experimental

Materials and Glassware——The carboxylation involving PhOK is disturbed by even an extremely small amount of water, so great care was taken to exclude water from the reaction system. Cyclohexanone was distilled under atmospheric pressure. DMF was dried with CaH_2 for more than 2 d at room temperature, then distilled under nitrogen at reduced pressure. PhOK was prepared as follows. A methanol solution of phenol was mixed with aqueous potassium hydroxide solution. The solvents were evaporated off and the residue was dried at 150 °C under reduced pressure. Well-dried glassware was used for the measurement of CO_2 uptake and for the carboxylation.

The Uptake of CO_2 by PhOK——The uptake of CO_2 by PhOK was measured at 0 °C in the vacuum system. A DMF solution of PhOK (5 mmol PhOK in 50 ml of DMF) was degassed to a pressure corresponding to the vapor pressure of DMF at this temperature. Then CO_2 was introduced, and allowed to react with the DMF solution of PhOK until it was completely absorbed. Additional CO_2 was introduced into this solution, and the procedure was repeated. The amounts of CO_2 taken up by PhOK at various CO_2 pressures were calculated by subtracting the amount absorbed by DMF from the amounts taken up by the DMF solution of PhOK.

Carboxylation of Cyclohexanone——CO_2 was added to a DMF solution of PhOK (10 mmol PhOK in 98 ml of DMF) as described above at 0 °C, then N_2 gas was introduced until the total pressure (N_2 plus CO_2) reached atmospheric pressure. To this solution, cyclohexanone (10 mmol) was added in 2 ml of DMF. After an appropriate time interval, the reaction mixture was sampled. The sample was acidified with dilute hydrochloric acid and the carboxylic acid formed was extracted with ether. The ethereal layer was dried with sodium sulfate, and methylated with diazomethane. Methyl cyclohexanone-2-carboxylate thus formed was quantitatively analyzed by gas chromatography (15% DEGA on Uniport B; hydrogen flame ionization detector).

Results and Discussion

Figure 1 shows the solubility of CO_2 in 50 ml of DMF at 0 °C and at various CO_2 pressures. The solubility increased linearly with increase of CO_2 pressure (slope, 4.6×10^{-4} mmol/Torr·ml). Figure 2 shows the uptake of CO_2 by PhOK (about 0.1 M DMF solution) at various CO_2 pressures. The ordinate shows M.R., that is, the molar ratio of CO_2 absorbed by PhOK to PhOK initially added. The amounts of CO_2 taken up by PhOK were calculated by subtracting the amount of CO_2 dissolved in DMF alone (Fig. 1) from the observed values. As can be seen from Fig. 2, PhOK binds with CO_2 strongly, and consequently, considerable amounts of CO_2 are absorbed by PhOK even at low CO_2 pressure. Thus, in the solution with M.R. of less than about 0.5, CO_2 exists exclusively in the complexed form with PhOK.

Figures 3 and 4 show the time courses of the carboxylation of cyclohexanone in the initial period with various values of M.R. and at atmospheric CO_2 pressure. The yield of the carboxylate was calculated on the basis of the amount of cyclohexanone initially added (10 mmol). Table I lists the yields of the carboxylate at 30 s after the start of the reaction. In the range of M.R. from 0.11 to 0.41, the yield at 30 s increased with increase of M.R.

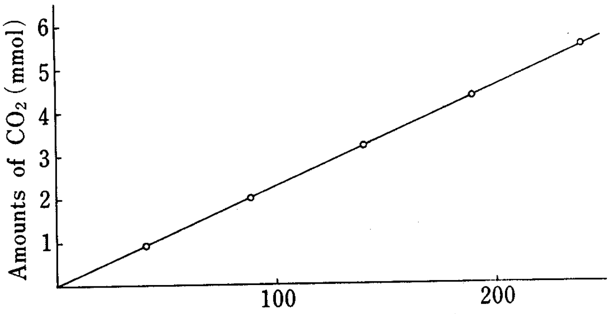

Fig. 1. The Solubility of CO_2 in 50 ml of DMF at Various CO_2 Pressures at 0 °C

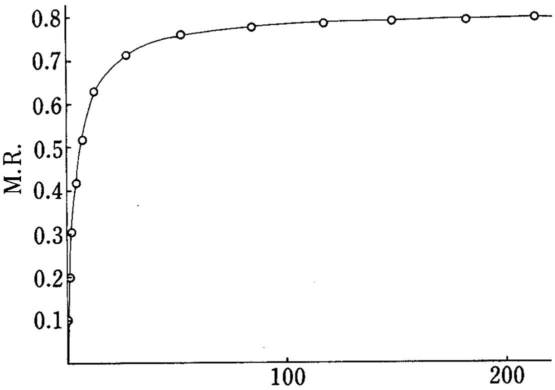

Fig. 2. The Uptake of CO_2 by PhOK in DMF Solution (0.1 M) at 0 °C

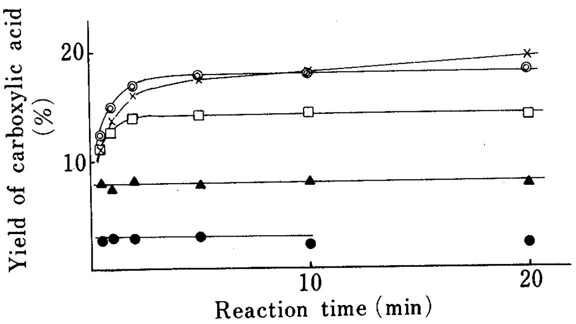

Fig. 3. Carboxylation of Cyclohexanone with M.R. $=0.11$—0.51

—●—, M.R. $=0.11$; —▲—, M.R. $=0.21$; —□—, M.R. $=0.32$; —◎—, M.R. $=0.41$; —×—, M.R. $=0.51$.

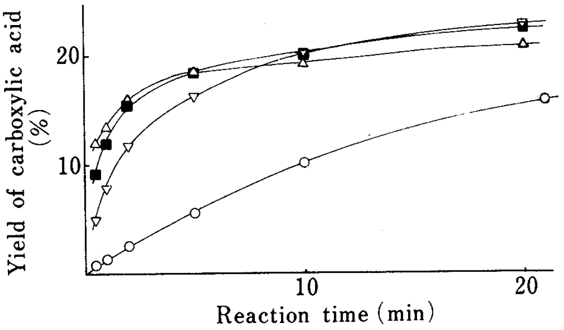

Fig. 4. Carboxylation of Cyclohexanone with M.R. $=0.60$—0.77 and at Atmospheric CO_2 Pressure

—△—, M.R. $=0.60$; —■—, M.R. $=0.70$; —▽—, M.R. $=0.77$; —○—, atmospheric CO_2 pressure.

TABLE I. The Yields of the Carboxylate at 30 s and the Ultimate Yields in Carboxylation with Various M.R. Values and at Atmospheric CO_2 Pressure

M.R.	Yield at 30 s (%)	Ultimate yield (%)
0.11	2.7	2.3
0.21	7.9	7.7
0.32	11	14
0.41	12	18
0.51	11	24
0.60	12	27
0.70	9.2	31
0.77	5.0	36
Atmospheric CO_2 pressure	0.8	42

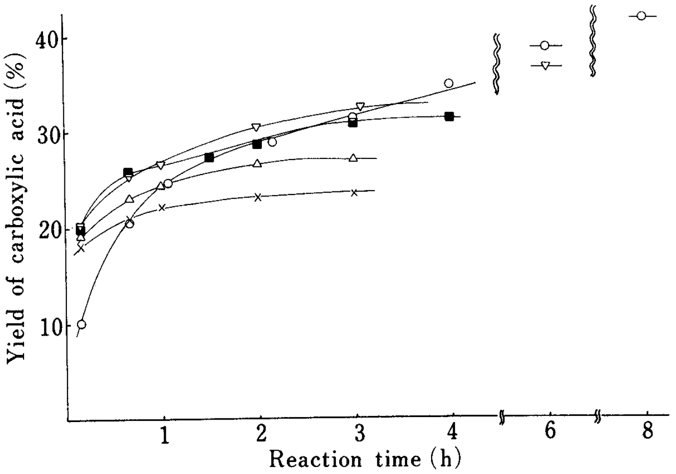

Fig. 5. Carboxylation of Cyclohexanone with M.R. $=0.51$—0.77 and at Atmospheric CO_2 Pressure (Later Period of the Reaction)

—×—, M.R. $=0.51$; —△—, M.R. $=0.60$; —■—, M.R. $=0.70$; —▽—, M.R. $=0.77$; —○—, atmospheric CO_2 pressure.

However, in the range of M.R. above 0.60, the yield at 30 s decreased with increase of M.R. and became very small at atmospheric CO_2 pressure, that is, at M.R. of almost unity.

In the carboxylation with M.R. $=0.11$ and 0.21, the reaction was very rapid and was completed in 30 s (Fig. 3). When carboxylation was done at M.R. $=0.32$ and 0.41, the reaction was completed in a few minutes (Fig. 3). Figure 5 shows the time courses of carboxylation at the later period with M.R. of more than 0.51 and atmospheric CO_2 pressure. In these cases, the times required for completion of the reaction were more than 1 h. Thus, the times for the reaction to go to completion were distinctly different at different M.R. values, and three ranges were distinguishable.

In the carboxylation with M.R. $=0.21$, the amount of CO_2 complexed with PhOK in the reaction solution is 2.1 mmol and that present in the uncomplexed form is 0.07 mmol, as calculated with the use of the slope shown in Fig. 1. On the other hand, the ultimate yield of the carboxylate in the carboxylation with M.R. $=0.21$ is about 8% (Table I), that is, 0.8 mmol of the carboxylate was produced. Thus, it seems that CO_2 complexed with PhOK acts as the CO_2 source for the carboxylate in this reaction. Table I also lists the ultimate yields of the carboxylate in the carboxylation with various M.R. values and at atmospheric CO_2 pressure. It is clear that the ultimate yield increased with increase of M.R., that is, the amount of CO_2 complexed with PhOK, suggesting that CO_2 complexed with PhOK is the reactive CO_2 source in the carboxylation.

With respect to the carboxylation of carbonyl compounds using sodium phenoxide in diglyme, Bottaccio *et al.*[3] proposed the reaction mechanism in which carboxylation occurs between CO_2 complexed with phenoxide and the anion of the substrate. As shown above, in

$$CO_2\ (\text{complexed}) + RNa \longrightarrow RCO_2Na$$

the carboxylation with potassium phenoxide in DMF, it also appears that the CO_2 complexed with phenoxide may act as the CO_2 source. By following the time course of the carboxylation, it was revealed that a very rapid reaction occurs in the range of small M.R. values. In the experiment on CO_2 uptake by PhOK, it was observed in the range of M.R. less than 0.4 that a precipitate formed and then disappeared on further addition of CO_2. These results suggest the presence of a CO_2 species other than $CO_2 \cdot PhOK$, and which is responsible for the rapid carboxylation.

The kinetic results obtained here are not in accordance with those reported by Bottaccio *et al.*[3] This difference may be ascribed to the difference in the reaction conditions, especially the metal of the phenoxide and the solvent. From this point of view, an investigation with lithium phenoxide or its substituted derivatives would be interesting, because it is suggested that lithium phenoxide forms a tetramer and lithium di-*tert*-butyl phenoxide forms a monomer or dimer in aprotic solvents.[4]

References

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