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Synthesis of Carboxylic Acid from Aryl Halide and Carbon Monoxide Catalyzed by Nickel Carbonyl

Mikitake NAKAYAMA and Tsutomu MIZOROKI

Government Chemical Industrial Research Institute, Tokyo, Meguro-ku, Tokyo

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In the reacion of aryl bromide with carbon monoxide in the presence of water and a catalytic amount of nickel carbonyl, it has been found that aromatic carboxylic acids (benzoic acid, polymethylbenzoic acid, α-naphthoic acid, *etc.*) are formed in very high yields when such salts of carboxylic acids as potassium acetate or sodium benzoate are added to the starting materials. The carbonylation reaction of aryl bromide is strongly inhibited by the hydrobromic acid formed, and the addition of the salt of carboxylic acid effectively decreases its concentration in the course of the reaction. When the amount of potassium acetate is larger than that of aryl bromide, the rate of the carbonylation reaction of bromobenzene to form benzoic acid is proportional to the amounts of bromobenzene, nickel tetracarbonyl, and water and to the reciprocal of the carbon monoxide pressure. From these kinetic data, the effect of the salts of carboxylic acids and the course of the reaction are discussed.

Many attempts to obtain aromatic carboxylic acids or their esters from the reactions of aryl halides with carbon monoxide using transition metal compounds as catalysts have been made. Nickel complexes have been demonstrated to be the most effective catalysts since the synthesis of benzoic acid from halobenzene with $Ni(CO)_2(Ph_3P)_2$[1) or a nickel(II) iodide catalyst[2) and that of phthalic anhydride from bromobenzene in the presence of sodium carbonate with a nickel tetracarbonyl catalyst[3) were published. The yields of aromatic carboxylic acids have, however, depended to a cansiderable degree on the nickel catalysts, the solvents, and the additives. On the other hand, it has been shown that the treatment of aryl iodide with a stoichiometric amount of nickel tetracarbonyl under milder reaction conditions results in forming an aryl carbonyl compound (carboxylic ester or diketone) in a high yield.[4) We expected that the low yields of aromatic carboxylic acids by the catalytic reactions of aryl halides with carbon monoxide would be caused by the inhibition of the hydrogen halides formed and have found that their yields really become very high when salts of carboxylic acids are added to the starting materials to decrease effectively the concentration of hydrogen halide during the reaction.[5)

This work has been undertaken to obtain substituted benzoic acids from the reactions of aryl bromides with carbon monoxide in the presence of potassium acetate and water using nickel tetracarbonyl, and to investigate their reaction rates.

Experimental

Apparatus. The same apparatus as has been described in a previous paper was used.[6) All the reactions were carried out in titanium-molybdenum alloy autoclaves (225 m*l* and 300 m*l* in volume). A titanium or a titanium-manganese alloy autoclave could not be used in these corrosive reactions. Aryl bromide, water, salt of carboxylic acid, and nickel(II) acetate were placed in the autoclave, and it was heated by a shaking-type electric furnance. The temperature of the autoclave was kept constant for about one hour before carbon monoxide was introduced from a pressure-accumulator vessel. Carbon monoxide was supplied to keep the reaction pressure constant during the reaction. After the reaction had been carried out for 90 min, both the heating and the supply of carbon monoxide were stopped and the autoclave was allowed to cool to room temperature.

Materials. 4-Bromo-*o*-xylene, 4-bromo-*m*-xylene, and 2-bromo-*p*-xylene were formed selectively from *o*-, *m*-, and *p*-xylenes respectively by the bromination of xylenes, using iodine as the catalyst according to

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1) H. J. Leibu, *Chem. Abstr.*, **48**, 5214 (1954); **49**, 14807 (1955); **50**, 10775 (1956).

2) K. Yamamoto and K. Sato, This Bulletin, **27**, 389 (1954).

3) W. W. Prichard, *J. Am. Chem. Soc.*, **78**, 6137 (1956).

4) N. L. Bauld, *Tetrahedron Letters*, **1963**, 1840; E. Yoshisato, M. Ryang and S. Tsutsumi, Preprint for the 19th Annual Meeting of the Chemical Society of Japan, Yokohama (April, 1966), III, p. 321.

5) T. Mizoroki and M. Nakayama, This Bulletin, **40**, 2203 (1967).

6) T. Mizoroki, M. Nakayama and M. Furumi, *Kogyo Kagaku Zasshi* (*J. Chem. Soc. Japan, Ind. Chem. Sect.*), **65**, 1054 (1962).

Wisansky method;[7] they were purified by distillation. 5-Bromo-pseudocumene was obtained by the bromination of pseudocumene[8] and recrystallized from ethanol (mp 73°C). 2-Bromo-mesitylene was prepared from mesitylene[9] and purified by distillation. The other aryl halides and salts of carboxylic acids were commercial product; their purities were checked by gas chromatography before use. Commercially-available nickel(II) acetate and nickel tetracarbonyl (made by Alfa Inorganic, Inc.) were used without further purification. The carbon monoxide was obtained from the decomposition of formic acid; its purity was more than 98%.

Analyses. The organic products were extracted by diethyl ether, and the aqueous phase was separated from the ether phase. Carboxylic acids present in the ethereal layer were extracted with an aqueous potassium hydroxide or sodium carbonate solution (2N) from the other organic compounds. The carboxylic acids were precipitated from a given amount of the aqueous solution with an aqueous hydrochloric acid solution. Before the white precipitates were filtrated and washed well with cold water, they had been cooled well in a freezer. The amounts of carboxylic acids were determined by titration with an aqueous potassium hydroxide solution. They were identified by gas chromatographies of their methyl esters or by means of their IR absorption spectra or melting points. The amounts of Br^- and Ni^{2+} present in the aqueous phase were determined by the Volhard method and by EDTA titration respectively, and those of carbon monoxide and carbon dioxide, by absorption methods.

Results

Reaction Conditions. The reaction rates of aryl halides with carbon monoxide catalyzed by nickel tetracarbonyl depend greatly on the temperature, the pressure of carbon monoxide, and the amounts of water and of a salt of carboxylic acid to be discussed later. The effect of the temperature, for example, is shown in Fig. 1. Most of the reactions with aryl bromides were carried out under 200 kg/cm² at 250°C for 90 min. Carbon monoxide was absorbed within 40—60 min under the reaction conditions. Preliminary experiments showed that no aryl bromide was hydrolyzed under the reaction conditions, although most of the alkyl halides were hydrolyzed into alcohols and potassium halides by adding potassium acetate,

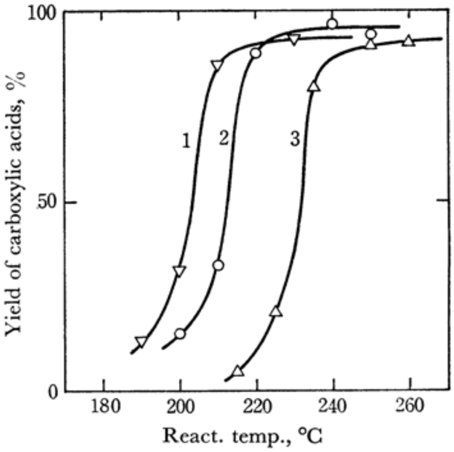

Fig. 1. Effect of temperature.
1. C_6H_5I (0.20 mol)
2. α-$C_{10}H_7Br$ (0.30 mol)
3. C_6H_5Br (0.30 mol)
Reaction conditions:
$AcOK$/aryl halide = 1.1 mol ratio
H_2O/aryl halide = 10 mol ratio
$Ni(AcO)_2 \cdot 4H_2O$/aryl halide = 0.01 mol ratio
Pressure 200 kg/cm², Time 90 min.

TABLE 1. SYNTHESIS OF POLYMETHYLBENZOIC ACIDS

Aryl bromide 0.30 mol, H_2O 3.00 mol, potassium acetate 0.33 mol, nickel(II)acetate 0.003 mol; temp. 250°C, press. 200 kg/cm², time 90 min

Aryl bromide	Acid formed			Br^-	
		mol	%	mol	%
o-Bromotoluene	*o*-Methylbenzoic acid	0.260	86.5	0.299	99.6
m-Bromotoluene	*m*-Methylbenzoic acid	0.298	99.5	0.304	101
p-Bromotoluene	*p*-Methylbenzoic acid	0.283	94.4	0.289	96.4
4-Bromo-*o*-xylene	3,4-Dimethylbenzoic acid	0.284	94.6	0.296	98.7
4-Bromo-*m*-xylene	2,4-Dimethylbenzoic acid	0.263	84.3	0.286	95.3
2-Bromo-*p*-xylene	2,5-Dimethylbenzoic aicd	0.285	95.0	0.300	100
5-Bromopseudocumene[a]	2,4,5-Trimethylbenzoic acid	0.157	78.5	0.190	95.0
Bromomesitylene	2,4,6-Trimethylbenzoic acid	0.0923	30.8	0.202	67.3

a) 5-Bromopseudocumene used was 0.20 mol.

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7) W. A. Wisansky and S. Ansbacher, "Organic Syntheses," Coll. Vol. III, p. 138, (1955).

8) J. Schramm, *Ber.*, **19**, 216 (1886).

9) L. I. Smith, "Organic Syntheses," Coll. Vol. II, p. 95 (1948).

without absorbing any carbon monoxide.

Syntheses of Substituted Benzoic Acids. The yields of polymethylbenzoic acids from the reactions with bromopolymethylbenzenes are described in Table 1. Carbon monoxide was absorbed almost quantitatively in the reactions of bromotoluenes (*o*-, *m*- and *p*-) or bromoxylenes (4-bromo-*o*-xylene, 4-bromo-*m*-xylene, and 2-bromo-*p*-xylene), and the corresponding benzoic acids were formed in very high yields. The amounts of Br^- described in Table 1 also show that bromotoluene and bromoxylene react quantitatively. In the reaction with bromobenzene, small amounts of benzene, phenol, and biphenyl were formed as by-products.[*1] The corresponding hydrocarbons and phenols were also detected in the products obtained from the reactions with bromopolymethylbenzene. This is the reason why the amounts of benzoic acids formed are smaller than those of Br^-. 2,4,5-Trimethylbenzoic acid was also formed quantitatively from the reaction with 5-bromopseudocumene, while 2,4,6-trimethylbenzoic acid could not be obtained in a high yield from the reaction with bromomesitylene, probably because of the steric hindrance of two ortho methyls.

Carbonylations of *p*-bromoanisole, *p*-bromoacetophenone, and *p*-bromobenzoic acid were tested under the same conditions. *p*-Bromoanisole was very reactive, but *p*-methoxybenzoic acid was not formed selectively and a lot of by-product (*p*-methoxyphenol and anisole) were found in the product. On the other hand, *p*-bromobenzoic acid was not so reactive. Either the reaction temperature or the amount of water had to be increased in order to obtain terephthalic acid in a high yield. The reactivity of aryl bromide in the carbonylation reaction seemed to increase when methyls (electron-releasing substituents) were introduced into the benzene ring, but it was difficult to know the effects of other substituents on this reaction because of the side reactions.

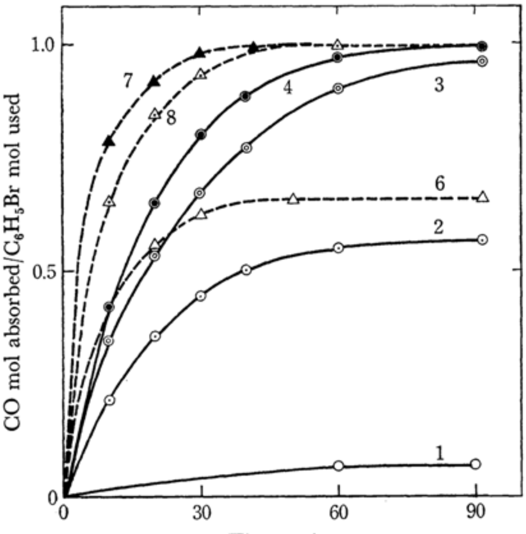

Fig. 2. Effect of potassium acetate on absorption rate of carbon monoxide.
Numbers in the figure are run No. in Table 2.

TABLE 2. EFFECT OF POTASSIUM ACETATE ADDED (at 250°C, 200 kg/cm²)

Run	Solvent	AcOK added (mol)	Convn.		Ni²⁺ (%)
			Acid or ester formed (%)	Br^- (%)	
1	H_2O[a)]	0.00	1.0	1.5	94.2
2		0.25	44.6	52.0	93.9
3		0.55	92.4	98.8	2.0
4		0.75	84.0	99.2	2.1
5	CH_3OH[b)]	0.00	0.0	0.0	89.4
6		0.15	48.0	52.0	88.2
7		0.33	89.6	100	5.7
8		0.45	90.1	98.7	7.7

a) Bromobenzene used was 0.50 mol.
b) Bromobenzene used was 0.30 mol.

Effect of Salt of Carboxylic Acid. The effect of potassium acetate on the reaction of bromobenzene in the presence of either water or methanol is represented in Table 2 and Fig. 2. Figure 2 shows how effectively the addition of potassium acetate increases the absorption rate of carbon monoxide. Practically no carbonylation reaction took place when no potassium acetate was added. When the amount of potassium acetate was half of the amount of bromobenzene, that of the carbon monoxide absorbed was also nearly a half of the amount calculated from bromobenzene. Carbon monoxide was not absorbed quantitatively unless the amount of potassium acetate reached that of bromobenzene. The absorption rate of carbon monoxide was larger in methanol than in water.

Most of the nickel(II) acetate used as a catalyst was present as Ni^{2+} in the product when the amount of potassium acetate was smaller than bromobenzene. Only a small amount of Ni^{2+} was, however, detected and most of the nickel was present as nickel tetracarbonyl when enough potassium acetate was added, as is shown in Table 2. This means that the addition of potassium acetate is favorable for the formation of nickel tetracarbonyl during the reaction as well as for the carbonylation of bromobenzene. Its effect on the formation of nickel tetracarbonyl from nickel(II) bromide ($NiBr_2+5CO+H_2O \rightarrow Ni(CO)_4+CO_2+2HBr$) was,

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[*1] Carbon monoxide was partly consumed to form formic acid, but the amount so consumed was only 5—10% of the amount of carbon monoxide absorbed.

therefore, examined separately. Without potassium acetate, no absorption of carbon monoxide to form nickel tetracarbonyl was observed under the same conditions as for the carbonylation reaction of bromobenzene, but rapid absorption took place when twice as much potassium acetate was added as the amount of nickel(II) bromide, and most of the nickel(II) bromide (more than 95%) was reduced into either nickel tetracarbonyl or metallic nickel. Amines, such as pyridine, triethylamine, and aniline,[*2] had nearly the same effect as salts of carboxylic acids, while the latter were more effective.

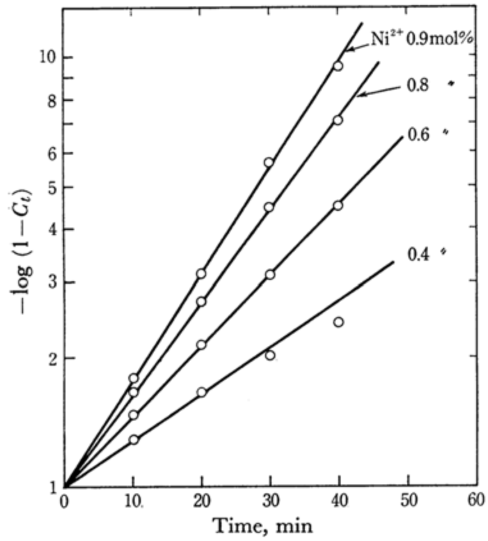

Fig. 3. Reaction rate of carbonylation of bromobenzene.
Reaction conditions: C_6H_5Br 0.50 mol, H_2O 3.00 mol, AcOK 0.55 mol, Temperature 250°C, Pressure 200 kg/cm^2

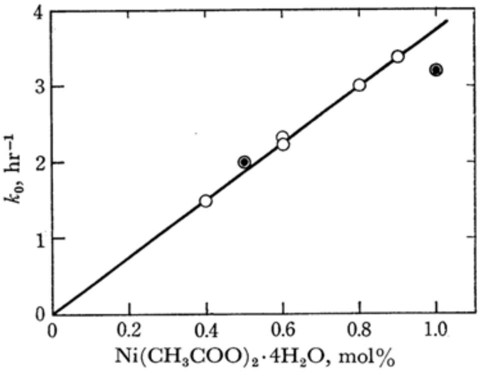

Fig. 4. Effect of nickel(II) acetate used as the catalyst on the reaction rate.
Reaction conditions: C_6H_5Br 0.50 mol, AcOK 0.55mol, H_2O 3.00 mol, Temperature 250°C, Pressure 200 kg/cm^2
◉: nickel tetracarbonyl used as the catalyst

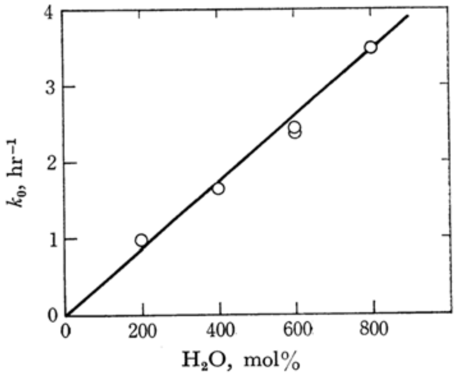

Fig. 5. Effect of water added.
Reaction conditions: C_6H_5Br 0.50 mol, AcOK 0.55 mol, $Ni(AcO)_2 \cdot 4H_2O$ 0.6 mol% (0.003 mol), Temperature 250°C, Pressure 200 kg/cm^2

Kinetic Study. The rate of the carbonylation reaction of bromobenzene in the presence of enough potassium acetate ($AcOK/C_6H_5Br = 1.1$ mol ratio) was investigated on the basis of the absorption rate of carbon monoxide. $-\log(1-C_t)$ are plotted against the reaction time (min) in Fig. 3, where C_t is the conversion of bromobenzene into benzoic acid calculated from the amount of carbon monoxide absorbed in t min. The rate was proportional to the amount of bromobenzene, and its rate constants could be obtained from the gradients of these linear plots. As is shown in Fig. 4, the rate was proportional to the amount (mol % based on bromobenzene) of nickel(II) acetate; in this figure the rate constants obtained in the case of introducing nickel tetracarbonyl[*3] are also plotted. No difference between nickel(II) acetate and nickel tetracarbonyl was observed in their catalytic activities. The effect of water is shown in Fig. 5. The rate was also proportional to the amount of water over the range of 2—8 times as much as bromobenzene. When the amount of water added was more than 8 times, the absorption rate of carbon monoxide became too large to take its rate constant. The pressure of carbon monoxide had a strong effect, as is shown in Fig. 6 and Table 3. The maximum reaction rate was observed at 150 kg/cm^2 under the reaction conditions described in the figure. Under pressures of carbon monoxide higher than 150 kg/cm^2, the rate was nearly proportional to the reciprocal of the pressure. Somewhat different kinetic behavior was observed in the absorption

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[*2] Besides benzoic acid, a lot of *N*-benzoylaniline was formed.

[*3] $Ni(CO)_4$ was introduced into the autoclave by carbon monoxide pressure when the temperature of the autoclave became 250°C.

TABLE 3. EFFECT OF CARBON MONOXIDE PRESSURE ON THE CARBONYLATION OF BROMOBENZENE

p_{CO} (kg/cm^2)	Convn. Acid (%)	Convn. Br^- (%)	Ni^{2+} (%)	k_0 (hr^{-1})	Purge gas Vol. (l)[a]	Purge gas CO_2 (vol%)	Purge gas CO (vol%)	Purge gas Others (vol%)
400	50	60	—	0.76	22.9	9.4	75.6	15.0
300	72	80	1.7	1.42	17.1	9.6	77.2	13.2
200	92	99	2.0	2.29	11.7	9.0	78.6	12.4
170	87	101	1.3	3.04	9.5	8.9	77.5	13.6
150	79	99	3.3	3.66	8.3	16.0	70.4	13.6
140	84	101	0.0	3.52	7.8	14.0	70.9	15.1
120	65	101	5.0	2.14	6.2	27.4	54.2	18.4
100	59	94	21.7	1.39	5.2	32.2	47.7	20.1

a) at 0°C, 1 atm.

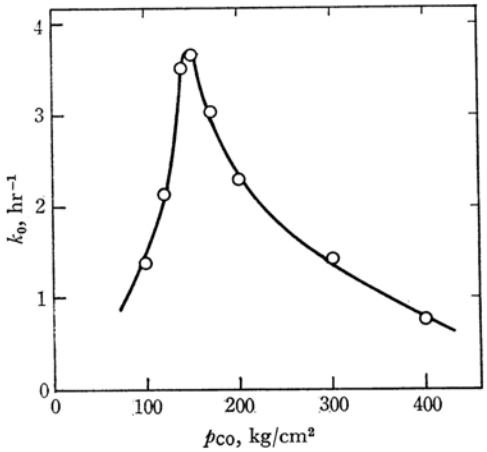

Fig. 6. Effect of carbon monoxide pressure on the reaction rate.
Reaction conditions: C_6H_5Br 0.50 mol, AcOK 0.55 mol, H_2O 3.00 mol, $Ni(AcO)_2 \cdot 4H_2O$ 0.6 mol-% (0.003 mol), Temperature 250°C

rates under lower pressures. However, it was difficult to obtain reliable data here, partly because the reaction was accompanied by side reactions (the formation of phenol and biphenyl) and benzoic acid was not selectively formed, as is shown in Table 3 (the difference between the amounts of benzoic acid and Br^- becomes large), and partly because the carbon monoxide pressure could not be assumed to be constant during the reaction as a result of the accumulations of carbon dioxide and hydrogen formed by a water-gas reaction in the autoclave.

Discussion

On the Effect of Salts of Carboxylic Acids. Figure 2 and Table 2 show that a strong protonic acid, HBr, strongly inhibits the carbonylation of bromobenzene, and that the inhibition can easily be removed by adding potassium acetate. From the facts that the equilibrium of the reaction of $RCOOK + HBr \rightleftarrows RCOOH + KBr$ ($R = CH_3-$, C_6H_5-, *etc.*) inclines much toward the right and that its reaction rate is very fast, it can be postulated that the hydrobromic acid formed from the carbonylation of bromobenzene is converted quantitatively into potassium bromide. The inhibition by hydrobromic acid can be explained as follows:

$$NiBr_2 + 5CO + H_2O \xrightarrow{r_1} Ni(CO)_4 + 2HBr + CO_2 \tag{1}$$

$$C_6H_5Br + Ni(CO)_4 \xrightarrow{r_2} (C_6H_5Br)Ni(CO)_n + (4-n)CO \tag{2}$$

$$(C_6H_5Br)Ni(CO)_n + H_2O \xrightarrow{r_2'} C_6H_5COOH + (HBr)Ni(CO)_{n-1} \tag{2'}$$

$$HBr + Ni(CO)_4 \xrightarrow{r_3} (HBr)Ni(CO)_n + (4-n)CO \tag{3}$$

$$HBr + (HBr)Ni(CO)_n \xrightarrow{r_4} NiBr_2 + H_2 + nCO \tag{4}$$

The reaction rate (r_3) of $Ni(CO)_4$ with HBr would be much larger than that (r_2) of $Ni(CO)_4$ with C_6H_5Br, and the reaction rate (r_4) represented by Eq. (4) would also be very fast. Nickel tetracarbonyl is, consequently, difficult to be reformed so as to keep its concentration high, while the effective decrease in the concentration of hydrobromic acid by adding potassium acetate results in controlling the reaction of (3) and (4), and the $(HBr)Ni(CO)_{n-1}$ formed from the reaction of (2′) can be reconverted into nickel tetracarbonyl without any accompanying water-gas reaction, as is represented by Eq. (5):

$$(HBr)Ni(CO)_{n-1} \xrightarrow[-RCOOH,\ -Br^-]{+RCOO^-} Ni(CO)_{n-1} \xrightarrow{+CO} Ni(CO)_4 \tag{5}$$

The catalytic carbonylation of bromobenzene, therefore, takes place smoothly.

On the Kinetic Study. The kinetic behavior of the reaction with aryl bromide catalyzed by $Ni(CO)_4$ is similar to an oxo reaction catalyzed by $Co_2(CO)_8$. The rate of the latter is proportional to the amounts of an olefin and dicobalt octacarbonyl, the partial pressure of hydrogen, and the reciprocal of the partial pressure of carbon monoxide.[10] The former in the presence of enough potassium acetate is proportional also to the amounts of bromobenzene, nickel tetracarbonyl, and water, and to the reciprocal of carbon monoxide pressure, as is shown in Figs. 3, 4, 5, and 6, when the pressure is more than 150 kg/cm^2. Consequently, a reaction scheme similar to that derived from the kinetic study of the oxo reaction can be given to the carbonylation of bromobenzene catalyzed by nickel tetracarbonyl.

$$C_6H_5Br + Ni(CO)_4 \overset{K}{\rightleftarrows} (C_6H_5Br)Ni(CO)_3 + CO \qquad (a)$$

$$(C_6H_5Br)Ni(CO)_3 + H_2O \xrightarrow{k} C_6H_5COOH + (HBr)Ni(CO)_2 \qquad (b)$$

$$(HBr)Ni(CO)_2 + 2CO + AcOK \xrightarrow{\text{fast}} Ni(CO)_4 + AcOH + KBr \qquad (c)$$

Assuming that nickel tetracarbonyl is reproduced sufficiently fast during the reaction and that the equilibrium of Eq. (a) is very small, the reaction rate, r, can be given by Eq. (d):

$$\begin{aligned} r &= K\cdot k\,\frac{[Ni(CO)_4][C_6H_5Br][H_2O]}{p_{CO}} \\ k_0 &= k\cdot K\,\frac{[Ni(CO)_4][H_2O]}{p_{CO}} \end{aligned} \qquad (d)$$

The $(k_0 \times p_{CO})$ values obtained from the k_0 of the reactions under pressures higher than 150 kg/cm^2, shown in Figs. 3, 4, 5, and 6, are plotted against $[Ni(CO)_4]\times[H_2O]$ in Fig. 7. The linear plot is in reasonable agreement with the rate Eq. (d). From these kinetic data alone, however, it was difficult to determine whether benzoic acid is formed by the attack of a water molecule or by a hydroxide ion in Eq. (b).

In the oxo reaction, hydrocobalt carbonyl was regenerated so rapidly that its concentration could be assumed to be constant during the reaction; otherwise, it is difficult to explain its kinetic behavior.[11] On the other hand, in the carbonylation of bromobenzene catalyzed by nickel tetracarbonyl, a σ-aryl nickel carbonyl could be formed by the oxidative addition of bromobenzene to nickel tetracarbonyl, as in a Grignard's reaction[12] or as in the carbonylation of aryl halide by the $Rh(Ph_3P)_2(CO)Cl$ catalyst.[13] This σ-aryl carbonyl would also be rapidly rearranged with carbon monoxide coordinated to nickel into an acyl nickel carbonyl, which would, then, be attacked by a water molecule or a hydroxide ion to form benzoic acid; it is essential that nickel tetracarbonyl itself be regenerated rapidly for a smooth catalytic recycling. Its kinetic behavior, nevertheless, is very similar to the oxo reaction as long as enough potassium acetate is added to regenerate the nickel tetracarbonyl sufficiently fast. This means that acyl metal carbonyls are relatively stable in the catalytic carbonylation of aryl bromides as well as in oxo reactions.

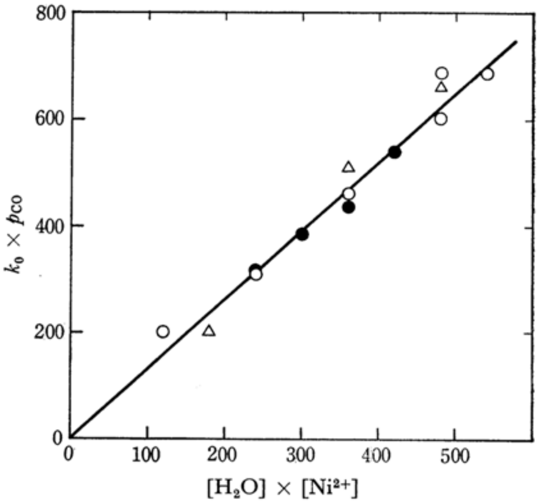

Fig. 7. Plots of k_0 according to the Eq. (d).
p_{CO}: ●, 300 kg/cm^2 ○, 200 kg/cm^2 △, 170 kg/cm^2

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[10] I. Wender, H. W. Sternberg and M. Orchin, "Catalysis," Vol. V, ed. by P. H. Emmett, Reinhold Publ. Co., New York (1957), p. 119.

[11] A. J. Chalk and J. F. Harrod, "Advances in Organometallic Chemistry," Vol. 6, ed. by F. G. A. Stone and R. West, Academic Press, New York (1968), p. 129.

[12] D. J. Cram and G. S. Hammond, "Organic Chemistry," McGraw-Hill Co., New York (1959), p. 219.

[13] J. Tsuji and K. Ohno, *Tetrahedron Letters*, **1966,** 4713.