Mechanisms of Double and Single Carbonylation Reactions of Aryl Iodides Catalyzed by Palladium Complexes To Give α-Keto Esters and Esters

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Various aryl iodides are converted into α-keto esters and esters on reactions with alcohols and Et_3N under CO pressure in the presence of catalytic amounts of palladium complexes. Detailed examination of factors controlling the selectivity for α-keto ester formation revealed the following characteristics of the reactions. (a) Use of palladium catalysts having bulkier tertiary phosphine ligands increases the selectivity for α-keto ester formation. (b) Secondary alcohols of moderate bulkiness and high basicity gave α-keto esters in high selectivity. (c) Addition of less polar solvents such as benzene and dichloromethane to the system improves the selectivity for α-keto ester formation. (d) Higher CO pressure is required to obtain α-keto esters in higher yields. NMR examination of the catalytic system containing PhI, alcohol, Et_3N, and $PdCl_2(PPh_3)_2$ revealed the presence of an aroylpalladium(II) complex as the predominant species. Model studies of the reactions of isolated phenyl- and benzoylpalladium(II) complexes toward alcohols, Et_3N, and carbon monoxide indicate that an aroylpalladium(II) intermediate generated by a rapid CO insertion into an arylpalladium(II) complex is responsible for both the ester and α-keto ester formations in the catalytic reactions. Alcohols of higher basicity show higher reactivity in the α-keto ester formation whereas more acidic alcohols give esters at higher reaction rates. A kinetic study on the ester formation indicates that the ester formation proceeds predominantly through a mechanism involving predissociation of a tertiary phosphine ligand. On the basis of the experimental results a mechanism comprising two catalytic cycles to produce α-keto ester and ester is proposed.

Introduction

Recently a novel catalytic process converting aryl and alkenyl halides into α-keto amides has been developed independently by two groups (eq 1).[1,2] This process

$$RX + 2CO + 2R'_2NH \xrightarrow{\text{Pd cat.}} RCOCONR'_2 + RCONR'_2 + R'_2NH_2X \quad (1)$$

R = aryl, alkenyl; X = Br, I; R′ = alkyl

provides a useful means for introducing two CO molecules into an organic compound in a single step and has potential utility in organic synthesis. In this process a variety of aryl and alkenyl bromides and iodides can be readily converted into corresponding α-keto amides under mild conditions. By proper choice of palladium catalysts having tertiary phosphine ligands and of secondary amines, formation of amides produced as the byproducts of the double carbonylation can be suppressed to give α-keto amides selectively at high yields. From α-keto acids derived by hydrolysis of the α-keto amides various useful organic compounds including α-amino acids, α-hydroxy acids, and heterocyclic compounds can be easily prepared.[3] However, the utility of the process is somewhat restricted when the α-keto amides thus prepared are resistant to hydrolysis. This problem can be circumvented if we can devise a double carbonylation process to give α-keto esters that are more readily hydrolizable. Synthesis of α-keto esters by the following process has been achieved by proper choice of alcohol and tertiary amine as well as of palladium catalyst having suitable tertiary phosphine ligands under CO pressure, again independently by the two groups (eq 2).[4,5]

$$ArI + 2CO + ROH + Et_3N \xrightarrow{\text{Pd cat.}} ArCOCOOR + ArCOOR + Et_3NHI \quad (2)$$

Ar = aryl; R = alkyl

The catalytic process 2 proceeds more slowly than process 1 that gives α-keto amides, and the experimental conditions for obtaining α-keto esters in high yields are limited. In our effort for improving the selectivity for formation of α-keto esters we have examined the mechanisms of the double and single carbonylations in depth by studying the actual catalytic systems as well as model systems containing organopalladium complexes assumed in the catalytic process. We now report full details of our studies on the double and single carbonylations. Although the single carbonylation process has been well-known,[6] there is still lack of information regarding the detailed mechanism.[6,7] In the first part of the paper we examine

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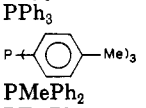
Table I. Effect of Tertiary Phosphine Ligands on the Catalytic Double Carbonylation of PhI and *sec*-BuOH in the Presence of Et_3N Promoted by $PdCl_2L_2$ Complexes[a]

run	L	θ,[b] deg	pK_a[c]	product ratio PhCOCOO-*sec*-Bu	product ratio PhCOO-*sec*-Bu	total yield, %/PhI
1	PCy_3[d]	170	9.05	77	23	51
2	PPh_3	145	3.04	55	45	73
3		145		43	57	75
4	$PMePh_2$	136	4.65	28	72	87
5	PEt_2Ph	136	6.78	43	57	66
6	PMe_3	118	7.85	24	76	6

[a] Reaction conditions: PhI (5 mmol), *sec*-BuOH (11 mmol), Et_3N (7.6 mmol), palladium catalyst ($PdCl_2L_2$) (0.1 mmol), in CH_2Cl_2 (2 mL), p(CO) = 70 atm (initial value measured at room temperature), at 70 °C. Reaction time: 120 h (runs 1, 4–6), 96 h (runs 2, 3). [b] Tolman's cone angle of L.[8] [c] Value of conjugate acid of L.[9] [d] Cy = cyclohexyl.

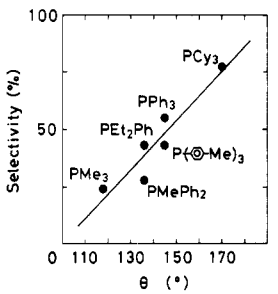


Figure 1. Plot of the selectivity for α-keto ester formation vs. Tolman's cone angle (θ) of tertiary phosphine ligand coordinated to palladium catalyst.

the catalytic systems themselves and in the second part properties of benzoylpalladium complexes existing as the main active species in the catalyst systems. The study has revealed that the single carbonylation giving esters proceeds by a different mechanism from the single carbonylation giving amides.

Results

A. Scope and Reaction Conditions. 1. Substrate. Various aryl iodides including iodides of aromatic heterocycles can be converted into α-keto esters in medium to good yields as reported in the preliminary form.[4] Vinyl iodides, however, gave α-keto esters in poor yields. Aryl bromides could be double-carbonylated to α-keto esters but only at much slower rates than those of corresponding aryl iodides. Alkyl iodides such as isopropyl iodide and benzyl iodide gave no carbonylation product.

2. Catalyst. Palladium chlorides having tertiary phosphine ligands are effective catalyst precursors for the double carbonylation. The palladium chlorides are transformed in reaction solutions to catalytically active species. The rate and selectivity of α-keto ester formation are markedly influenced by nature of the phosphine ligands. Table I summarizes catalytic activities of $PdCl_2L_2$-type complexes having various tertiary phosphine ligands (L). The steric influence is most important in determining the selectivity for α-keto ester formation as can be seen from the plot of Tolman's cone angles of tertiary phosphines vs. selectivities (Figure 1). The use of the least bulky trimethylphosphine caused a decrease not only in the selectivity but also in the reactivity of the palladium catalyst (run 6, Table I). On the basis of these results we have used triphenylphosphine and tricyclohexylphosphine as ligands in most of catalytic reactions.

The amount of tertiary phosphine ligands contained in the catalytic systems also is crucial in carrying out the double carbonylation process. Table II shows the effect of triphenylphosphine added to the catalytic system to convert phenyl iodide and *sec*-BuOH into the α-keto ester

Table II. Effect of Added Triphenylphosphine on the Palladium-Catalyzed Double Carbonylation of PhI and *sec*-BuOH in the Presence of Et_3N in CH_2Cl_2[a]

run	cat.	product ratio PhCOCOO-*sec*-Bu	product ratio PhCOO-*sec*-Bu	total yield, %/PhI
1	$PdCl_2(PhCN)_2$	14	86	85
2	$PdCl_2(PhCN)_2 + PPh_3$	21	79	83
3	$PdCl_2(PPh_3)_2$	37	63	57
4	$PdCl_2(PPh_3)_2 + PPh_3$	40	60	26
5	$PdCl_2(PPh_3)_2 + 2PPh_3$	42	58	19

[a] Reaction conditions: PhI (5 mmol), *sec*-BuOH (11 mmol), Et_3N (7.6 mmol), in CH_2Cl_2 (2 mL), palladium catalyst (0.05 mmol), p(CO) = 40 atm (initial value at room temperature), at 70 °C, for 48 h.

in the presence of triethylamine and palladium chlorides. It can be seen from the table that addition of the triphenylphosphine ligands up to 2 equiv/palladium causes improvement in the selectivity for the α-keto ester formation and further increase in the amount of the ligand added causes a decrease in the conversion without a significant increase in the selectivity. The results suggest that coordination of two PPh_3 ligands to palladium is important in maintaining the double carbonylation activity but the presence of excess ligand hinders both the double and single carbonylation processes.

The catalytic systems are sensitive to the presence of oxygen. Although the catalyst precursor $PdCl_2L_2$ itself is not readily attacked by air, introduction of air into the gas phase containing the catalyst system caused a considerable drop in selectivity for α-keto ester formation. As will be described later, formation of tertiary phosphine oxide was confirmed by examining the catalytic system with NMR spectroscopy. The decrease in the amount of the tertiary phosphine ligand by oxidation seems to cause a decrease in the catalytic species responsible for the double carbonylation and an increase in the species responsible for single carbonylation.

3. Reaction Course. The present carbonylation reaction is a relatively slow process, and a moderately high temperature (60–80 °C) is required to perform the reaction at a reasonable rate. Higher temperature, on the other hand, causes a decrease in selectivity for α-keto ester formation.

Figure 2 exhibits a typical time course in the reaction of phenyl iodide, 2-butanol, and triethylamine catalyzed by $PdCl_2(PPh_3)_2$ in CH_2Cl_2 carried out at 70 °C. GLC analysis of the reaction solution revealed formation of no other product than PhCOCOO-*sec*-Bu and PhCOO-*sec*-Bu. The system showed the selectivity over 50% at the early stage of the reaction, but the selectivity gradually decreased to about 40% after 25 h. A similar drop in selectivity with the progress of time was observed also in a

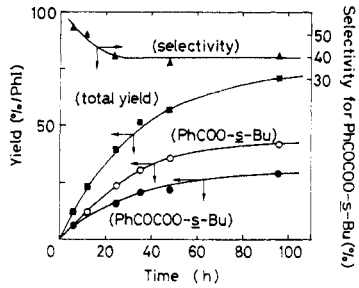


Figure 2. Time course of the double carbonylation reaction of PhI, *sec*-BuOH, and Et_3N catalyzed by $PdCl_2(PPh_3)_2$ under CO pressure. Reaction conditions: PhI (5 mmol), *sec*-BuOH (11 mmol), Et_3N (7.6 mmol), $PdCl_2(PPh_3)_2$ (0.05 mmol), in CH_2Cl_2 (2 mL), at 70 °C, $p(CO)$ = 40 atm (initial value at room temperature).

Table III. Effect of CO Pressure on the Catalytic Double Carbonylation of PhI and *sec*-BuOH in the Presence of Et_3N Promoted by $PdCl_2(PPh_3)_2$ Complex[a]

run	CO,[b] atm	product ratio: PhCOCOO-*sec*-Bu	product ratio: PhCOO-*sec*-Bu	total yield, %/PhI
1	20	24	76	58
2	40	37	63	57
3	60	51	49	58
4	80	56	44	57

[a] Reaction conditions: PhI (5 mmol), *sec*-BuOH (11 mmol), Et_3N (7.6 mmol), $PdCl_2(PPh_3)_2$ (0.05 mmol), in CH_2Cl_2 (2 mL), at 70 °C, for 48 h. [b] Initial value measured at room temperature.

system by using $PdCl_2(PCy_3)_2$ (Cy = cyclohexyl group) as the catalyst precursor.

4. Effect of CO Pressure. In the reaction of phenyl iodide, *sec*-BuOH, and Et_3N in the presence of $PdCl_2(PCy_3)_2$ as the catalyst precursor the reaction rate increased with an increase in CO pressure, while the selectivity for α-keto ester formation slightly decreased at higher CO pressures.[4] On the other hand, for a similar system but with $PdCl_2(PPh_3)_2$ as the catalyst precursor, higher CO pressure improved the selectivity for the α-keto ester without affecting the total yield of carbonylation products (Table III).

5. Effect of Alcohol. In the reaction of phenyl iodide with various alcohols in the presence of Et_3N and $PdCl_2(PCy_3)_2$, secondary alcohols of moderate bulkiness gave α-keto esters in high selectivity, whereas primary alcohols such as methanol and ethanol gave mainly single carbonylation products.[4] The sterically more demanding *tert*-butyl alcohol in the reaction with PhI, CO (70 atm), and Et_3N catalyzed by $PdCl_2(PCy_3)_2$ gave *tert*-butyl benzoylformate along with phenyl benzoylformate as the main products.

6. Effect of Tertiary Amine. Addition of a tertiary amine such as Et_3N is essential for carrying out the synthesis of α-keto esters. The prime role of the amine is to remove hydrogen iodide generated in the reaction system. Among the tertiary amines examined triethylamine usually gave the most satisfactory results. Use of more compact amines such as trimethylamine or bulkier amines like triisobutylamine instead of Et_3N decreased the selectivity for α-keto ester formation. The highly basic amine 1,8-diazabicyclo[5.4.0]-7-undecene gave mostly the single carbonylation product. Less basic amines such as Ph_3N and pyridine afforded only the single carbonylation product in low yields (see Table II in ref 4). These results indicate that employment of a tertiary amine of appropriate basicity and bulkiness is effective for producing α-keto esters in high yields. Reactions with metal alkoxides such as *sec*-BuONa and *i*-PrONa predominantly gave esters.

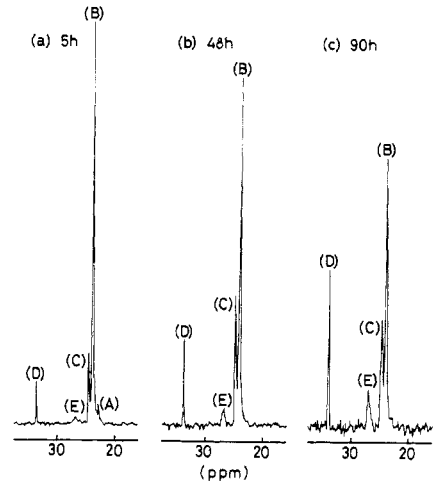


Figure 3. $^{31}P\{^1H\}$ NMR spectroscopic change of the catalytic double carbonylation system. Reaction conditions: PhI (1 mmol), *sec*-BuOH (2.2 mmol), Et_3N (1.4 mmol), $PdCl_2(PPh_3)_2$ (0.02 mmol), in CD_2Cl_2 (0.4 mL), under CO pressure (20 atm), at 50 °C. The NMR spectra (40 MHz) were measured at room temperature.

7. Effect of Solvent. The present double carbonylation reaction was markedly influenced by the nature of the solvent.[4] The reactions carried out in less polar solvents such as CH_2Cl_2 and benzene afforded α-keto esters in good selectivity whereas addition of polar solvents such as acetone and *N,N*-dimethylformamide to the system decreased the selectivity.

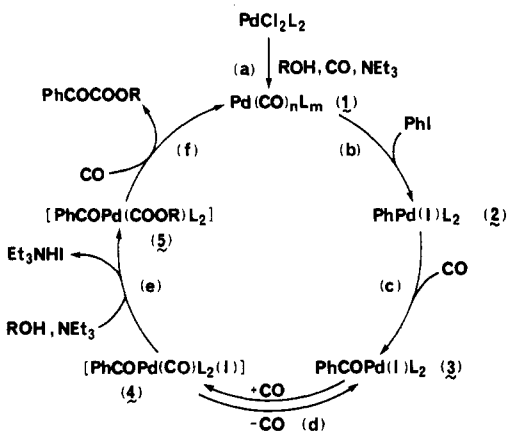
B. NMR Studies of the Catalytic Systems. Since the present catalytic double and single carbonylation reactions are slow processes, we thought that we might observe the catalytic species involved in the reaction by means of NMR spectroscopy under the catalytic conditions. Figure 3 shows the change of a $^{31}P\{^1H\}$ NMR spectrum with time of a CD_2Cl_2 solution containing $PdCl_2(PPh_3)_2$, *sec*-BuOH, and Et_3N under CO pressure (20 atm) kept at 50 °C. In preparation of the NMR sample the initially insoluble $PdCl_2(PPh_3)_2$ dissolved in 15 min at 50 °C to give first a homogeneous red solution which later changed to yellow with deposition of white crystals of Et_3NHI. The spectrum taken after 5 h showed the formation of *trans*-$Pd(COPh)I(PPh_3)_2$ (**3a**) as the predominant species (marked B in Figure 3) as characterized by comparison with the authentic sample separately prepared. Besides peak B, another peak marked D in Figure 3 was identified to arise from triphenylphosphine oxide which was produced by oxidation of part of the ligand by oxygen contained in the CO gas. The other small peaks A and C were not identified.[10] The intensities of peaks A and B gradually decreased with time with an increase in peaks C and D. Furthermore, a broad signal, E, probably due to a Pd(0) species having PPh_3 and CO ligands, appeared and grew as the reaction progressed.

Yields of the α-keto ester and ester formed in a catalytic system containing the same contents with the solution for the NMR study were measured independently. The selectivity for α-keto ester formation showed a similar trend to that observed in Figure 2: i.e., the selectivity for α-keto ester decreased with time.[11] The NMR result together

(10) It has been confirmed that signals A, C, and E correspond to neither $PdCl_2(PPh_3)_2$ (29.5 ppm) nor *trans*-$PdPh(I)(PPh_3)_2$ (28.7 ppm).

(11) Selectivities of PhCOCOO-*s*-Bu and conversions of PhI in the reaction systems of Figure 3 are as follows (select, % (convn, %)): a, 71 (3); b, 52 (19); c, 42 (36).

Scheme I



with other evidence to be discussed later suggests that removal of part of the two PPh_3 ligands attached to the active species as triphenylphosphine oxide causes a decrease in the concentration of an active species that is responsible for α-keto ester formation.

C. Examination of Behavior of Organopalladium Complexes Assumed To Be Involved in the Catalytic Reaction. For obtaining further information regarding the mechanism of the double carbonylation, we have examined the behavior of *trans*-benzoyliodobis(tertiary phosphine)palladium(II) (**3**) which was identified as the predominant species in the catalytic system. As represented in Scheme I the benzoylpalladium complex is considered to be formed by the CO insertion reaction into a Pd–Ph bond of a phenylpalladium complex (**2**) produced by oxidative addition of PhI to a Pd(0) species (**1**), which may be generated from the catalytic precursor $PdCl_2L_2$.[7a-c] A part of Scheme I, i.e., processes a–c, is identical with that proposed for explaining the α-keto amide formation.[1,12] The part represented on the left-hand side of Scheme I is now examined to account for the α-keto ester formation. The most important steps in the catalytic cycle are formation of a CO-coordinated benzoylpalladium complex (**4**) from the preceding benzoylpalladium complex **3** and the subsequent nucleophilic attack of alcohol aided by Et_3N on the coordinated CO ligand to give a benzoyl(alkoxycarbonyl)palladium complex (**5**) that liberates the product, the α-keto ester on reductive elimination.

1. IR Study. In the previous study regarding the mechanism of α-keto amide formation[1a] we have obtained some evidence supporting the CO-coordinated species **4** by an infrared study under CO pressure. Reversible formation of the CO-coordinated species **4** from **3** was deduced by observing the appearance of the terminal ν(CO) band at 2137 cm^{-1} when *trans*-Pd(COPh)I($PMePh_2$)$_2$ (**3c**) dissolved in a CH_2Cl_2–MeOH solution was treated with CO under pressure and its disappearance when CO was purged from the system. In the present study we extended the previous IR investigation and examined the effect of ligands with five different benzoylpalladium complexes having tertiary phosphine ligands of different basicities and steric bulkiness.

The results summarized in Table IV show the influence of the tertiary phosphine ligands on equilibrium d in Scheme I between **3** and **4** under CO pressure. In the IR spectra of complexes **3a–c** containing bulky tertiary phosphine ligands, the terminal ν(CO) band was observed at 2137 (for **3a** and **3c**) and 2135 cm^{-1} (for **3b**).[13] The IR spectra were observed in CH_2Cl_2–MeOH mixtures. In contrast, no terminal ν(CO) band was observed in neat CH_2Cl_2. The relative intensity of the terminal ν(CO) band to the benzoyl ν(CO) band diminished with a decrease in Tolman's cone angle for the tertiary phosphine ligand. For the benzoyl complexes with less bulky (and basic) tertiary phosphine ligands (PMe_3 and PMe_2Ph) no terminal ν(CO) band was observed. The results indicate that the CO ligand can coordinate to the benzoylpalladium complexes in polar solvents when the tertiary phosphine ligands are bulky.

Table IV. IR Data for *trans*-Pd(COPh)I(L)$_2$ Complexes in CH_2Cl_2–CH_3OH (4:1) under CO Pressure (20 atm) at Room Temperature[a]

L (θ, deg)[b]	$\nu(CO)_{terminal}$	$\nu(CO)_{benzoyl}$	ratio of absorbance (terminal/benzoyl)
PCy_3, **3b** (170)	2135	1635	0.96
PPh_3, **3a** (145)	2137	1650	0.81
$PMePh_2$, **3c** (136)	2137	1650	0.57
PMe_2Ph (122)	*c*	1635	0.00
PMe_3 (118)	*c*	1635	0.00

[a] In cm^{-1}. [b] See ref 8. [c] Not observed.

2. NMR Study. The infrared study, however, does not provide the information concerning the structure of the CO-coordinated benzoylpalladium complex **4**. It does not tell if the tertiary phosphine ligands remain attached to palladium or are dissociated in solution. Thus we examined the NMR spectra of complexes **3a–c** and benzoyl complexes having the benzoyl group labeled with the ^{13}C carbon, *trans*-Pd(^{13}COPh)IL$_2$ (L = PPh_3 (**3a**–^{13}C), PCy_3 (**3b**–^{13}C), $PMePh_2$ (**3c**–^{13}C)), under CO pressure.

The ^1H NMR spectrum of *trans*-Pd(COPh)I($PMePh_2$)$_2$ (**3c**) observed in a CD_2Cl_2–CD_3OD mixture (4:1 in volume ratio) under CO pressure (20 atm) at room temperature exhibited methyl protons of the $PMePh_2$ ligands at δ 2.08[14] as a triplet (J = 3.3 Hz) due to the virtual coupling[15] of the two $PMePh_2$ ligands. The result clearly indicates that the trans configuration is retained without significant dissociation of the $PMePh_2$ ligands in solution under CO pressure.

The $^{31}P\{^1H\}$ NMR spectrum of **3c** under CO pressure showed a singlet peak at 7.05 ppm (downfield from external PPh_3 reference), which is slightly shifted to a higher field than the chemical shift of **3c** itself measured in vacuo (7.02 ppm). The singlet peak of **3c** was split into a doublet in the spectrum of **3c**-^{13}C under CO pressure due to coupling to the ^{13}C carbon in the benzoyl group (J_{P-C} = 4 Hz). The splitting of the $^{31}P\{^1H\}$ NMR spectrum of **3c** arising from coupling to the coordinated CO ligand was not observed even when carbon monoxide gas containing 10% of ^{13}CO was used at 20 atm. The result suggests that complex **3c** exists in the solution under CO pressure in a rapid equilibrium with the CO-coordinated benzoylpalladium complex **4c**.

In the $^{13}C\{^1H\}$ NMR spectrum of **3c**-^{13}C the benzoyl carbon showed a triplet at δ 234.3 with J_{P-C} = 4 Hz. In addition to the triplet a sharp singlet was observed at δ

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(13) The ν(CO) frequencies of CO ligands observed (2135–2137 cm^{-1}) are comparable to the reported ν(CO) values (2130–2147 cm^{-1}) for *trans*-[Pd(C_6F_5)(CO)(PR_3)$_2$]$^+ClO_4^-$ and *trans*-[PdCl(CO)(PEt_3)$_2$]$^+BF_4^-$ complexes: Uson, R.; Fornies, J.; Martinez, F. *J. Organomet. Chem.* **1976**, *112*, 105. Clark, H. C.; Dixon, K. R. *J. Am. Chem. Soc.* **1969**, *91*, 596.

(14) The chemical shift was slightly higher than that of **3c** observed under vacuum (δ 2.12 (t, J = 3.5 Hz)).

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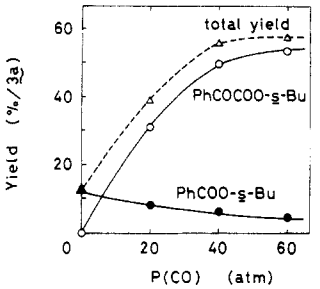


Figure 4. Effect of CO pressure on the reaction of *trans*-Pd(COPh)I(PPh_3)$_2$ (**3a**) with *sec*-BuOH and Et_3N. Reaction conditions: **3a** (0.025 mmol), *sec*-BuOH (0.5 mL), Et_3N (0.5 mL), solvent (CH_2Cl_2 (1 mL) + PhCl (0.28 mL)), at 70 °C, for 1 h.

184.2 which can be assigned to a coalesced peak of the coordinated and free CO signals. No broadening or splitting of the peak was observed on cooling the sample below −30 °C. These NMR observations indicate that the two $PMePh_2$ ligands are retained in complex **4c** under CO pressure in mutually trans positions and cis to the benzoyl group, and the CO-coordinated **4c** is in rapid equilibrium with the free CO and **3c**.

The NMR spectra of **3a**-^{13}C and **3b**-^{13}C observed under CO pressure in CD_2Cl_2–CD_3OD (4:1) mixtures also revealed the absence of dissociation of tertiary phosphine ligands on an NMR time scale and the occurrence of a rapid CO-coordination equilibrium between the benzoyl complexes **3** and the CO-coordinated benzoyl complexes **4** with retention of the trans geometry.[16]

In our previous IR spectroscopic study of *trans*-Pd(COPh)I($PMePh_2$)$_2$ (**3c**) and *trans*-[Pd(COPh)(CO)($PMePh_2$)$_2$]$^+ClO_4^-$ under CO pressure,[1a] we assumed the formation of an ionic CO-coordinated species, *trans*-[Pd(COPh)(CO)($PMePh_2$)$_2$]$^+I^-$, in solution under pressurized CO from comparison of the IR spectrum of **3c** under CO with that of *trans*-[Pd(COPh)(CO)($PMePh_2$)$_2$]$^+ClO_4^-$. The assumption of the CO-coordinated ionic species was based also on the observation of the marked effect of polar solvent on the development of the terminal ν(CO) peak under CO pressure at a frequency close to that of the ν(CO) peak of the perchlorate salt. However, according to the present study the $^{31}P\{^1H\}$ NMR signal arising from the coordinated $PMePh_2$ ligands in **3c** under CO pressure was observed at a considerably higher field (7.05 ppm) than that of *trans*-[Pd(COPh)(CO)($PMePh_2$)$_2$]$^+ClO_4^-$ (8.07 ppm), and the chemical shift of **3c** under CO pressure differed little from that of **3c** in vacuo (7.02 ppm). Therefore, the iodide ligand in **3c** under CO pressure may not be completely ionized as we previously assumed, and the I^- ion may be retained in the neighborhood of the palladium center. The effect of bulky tertiary phosphine ligands favoring the formation of the CO-coordinated complexes (Table IV) may be taken as indication that the bulkier tertiary phosphine ligands assist the CO coordination to palladium by pushing the iodide ligand away from palladium. The presently available evidence precludes from further characterization of the CO-coordinated complex **4** whether it is square pyramid or trigonal bipyramid.

3. Effect of CO Pressure on Reactions of the Benzoyliodopalladium(II) Complexes with Alcohols and Et_3N.

In the previous mechanistic study on the double carbonylation of aryl halides to give α-keto amides we have established that the CO-coordinated aroylpalladium complexes undergo nucleophilic attack of secondary amines to give α-keto amides whereas CO-coordinated arylpalladium complexes afford amides on reaction with secondary amines.[1a] On the other hand, in the present reactions of aroylpalladium complexes with alcohols in the presence of Et_3N, both esters and α-keto esters are formed in varying yields depending on reaction conditions. Figure 4 shows the effect of CO pressure on the yields of the α-keto ester and ester in the reaction of *trans*-Pd(COPh)I(PPh_3)$_2$ (**3a**) with *sec*-BuOH and Et_3N carried out at 70 °C for a limited time (1 h). A mixture of CH_2Cl_2 and chlorobenzene was employed as the solvent. Chlorobenzene that does not react with palladium complexes under the reaction conditions was added to make the environment of the system close to that of the catalytic one.

In the absence of CO only the ester is obtained whereas the α-keto ester becomes the major product upon an increase in CO pressure. The relative yield of the α-keto ester to ester ([KE]/[E]) was found to increase linearly with an increase in the CO pressure (Figure 5). A similar trend was observed when *trans*-Pd(COPh)I(PCy_3)$_2$ (**3b**) was used instead of **3a**.

When ethanol was used in place of *sec*-BuOH under otherwise similar conditions, similar enhancement in selectivity for α-keto ester formation with an increase in CO pressure was observed. However, the effect of CO pressure on the total yield of α-keto ester and ester varied depending on solvent. When *N*,*N*-dimethylformamide

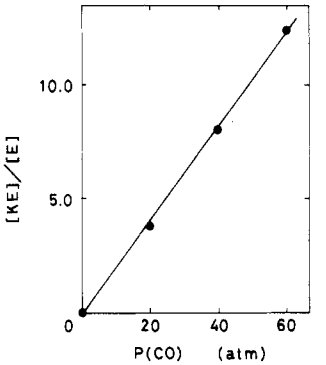


Figure 5. Plot of [KE]/[E] vs. p(CO) for the reaction of *trans*-Pd(COPh)I(PPh_3)$_2$ (**3a**) with *s*-BuOH and Et_3N in CH_2Cl_2–PhCl at 70 °C.

Table V. Effect of Solvent on the Reaction of *trans*-Pd(COPh)I(PPh_3)$_2$ (3a) with Alcohol and Et_3N under CO Pressure[a]

run	alcohol	solv	product ratio: α-keto ester	product ratio: ester	total yield, %/Pd
1	*sec*-BuOH	CH_2Cl_2	89	11	56
2		benzene	80	20	51
3		DMF	60	40	51
4		*t*-BuOH[b]	44	56	12[c]
5	EtOH	CH_2Cl_2	82	18	61
6		benzene	84	16	55
7		DMF	59	41	59

[a] Reaction conditions: **3a** (0.025–0.05 mmol), alcohol (*sec*-BuOH (0.5 mL), EtOH (0.2 mL)), Et_3N (0.5 mL), solvent (1 mL), p(CO) = 40 atm (initial value at room temperature), at 70 °C (for tuns 1–4) or 50 °C (for runs 5–7), for 1 h. [b] Since reactivity of *t*-BuOH was much less lower than that of *sec*-BuOH, no carbonylation product originated from *t*-BuOH was formed. [c] The reaction proceeded in a heterogeneous system due to poor solubility of **3a** in the reaction solution.

(16) $^{31}P\{^1H\}$ and $^{13}C\{^1H\}$ NMR data of *trans*-Pd(^{13}COPh)IL_2 (L = PPh_3 (**3a**-^{13}C), PCy_3 (**3b**-^{13}C)) in CD_2Cl_2–CD_3OD (4:1) under CO pressure (20 atm) at room temperature. $^{31}P\{^1H\}$ NMR (40 MHz): **3a**-^{13}C, 24.1 ppm (d, J_{P-C} = 5 Hz); **3b**-^{13}C, 23.5 ppm (d, J_{P-C} = 5 Hz). $^{13}C\{^1H\}$ NMR (25 MHz): **3a**-^{13}C, δ 232.6 (t, J_{P-C} = 5 Hz, Pd–COPh), 184.4 (s, Pd–CO and free CO); **3b**-^{13}C, δ 232.7 (t, J_{P-C} = 5 Hz, Pd–COPh), 183.5 (s, Pd–CO and free CO).

Table VI. Competitive Reactions of Alcohols toward *trans*-Pd(COPh)I(PPh_3)$_2$ (3a) in the Presence of Et_3N under CO Pressure[a]

	alcohol pair		product ratio			
run	R^1OH	R^2OH	$PhCOCOOR^1$	$PhCOCOOR^2$	$PhCOOR^1$	$PhCOOR^2$
1	MeOH	$ClCH_2OH$	0.17	0	0.23	0.59
2	MeOH	$MeOCH_2CH_2OH$	0.27	0	0.38	0.35
3	MeOH	EtOH	0.29	0.30	0.30	0.10
4	EtOH	*n*-PrOH	0.34	0.40	0.16	0.10
5	EtOH	*i*-PrOH	0.55	0.20	0.23	0.016
6	*n*-PrOH	*i*-PrOH	0.59	0.11	0.27	0.030
7	*i*-PrOH	*sec*-BuOH	0.47	0.43	0.055	0.043

[a] Reaction conditions: **3a** (0.025 mmol), R^1OH (3.8 mmol), R^2OH (3.8 mmol), Et_3N (7.9 mmol), solvent (CH_2Cl_2 (1.5 mL) + PhCl (0.28 mL)), p(CO) = 40 atm (initial value at room temperature), at 70 °C, for 1–5 h. The reactions gave total yields of the esters and α-keto esters over 80%.

(DMF) was used as the solvent, the total yield decreased upon an increase in CO pressure, whereas it remained almost constant when CH_2Cl_2 was used.

The effect of solvent on the selectivity for α-keto ester formation is summarized in Table V. Higher selectivity for the α-keto ester formation was observed in less polar solvents such as CH_2Cl_2 and benzene than in more polar solvents such as DMF and *t*-BuOH. The trend is similar to the effect of solvent observed in the catalytic systems.

4. Effect of Alcohols. For further examination of the effect of alcohols we have carried out competitive reactions of equimolar mixtures of various combinations of alcohols with **3a** in the presence of Et_3N under CO pressure.

$$\underset{\textbf{3a}}{trans\text{-}Pd(COPh)I(PPh_3)_2} + R^1OH + R^2OH + Et_3N + \underset{40\ atm}{CO} \xrightarrow[CH_2Cl_2\text{-}PhCl,\ 70\ °C]{-Et_3NHI} PhCOCOOR^1 + PhCOCOOR^2 + PhCOOR^1 + PhCOOR^2 \quad (3)$$

Table VI summarizes the relative product ratios of α-keto esters and esters formed from reactions using respective pairs of alcohols. On the basis of the data in Table VI relative reactivities of seven alcohols giving α-keto esters (r_{KE}) and esters (r_E) in reference to ethanol were obtained. The r_E values decreased in the order $ClCH_2CH_2OH$ (7.7) > MeOH (3.0) > $MeOCH_2CH_2OH$ (2.8) > EtOH (1.0) > *n*-PrOH (0.63) > *i*-PrOH (0.070) > *s*-BuOH (0.055). On the other hand, the r_{KE} diminished in the order *n*-PrOH (1.2) > EtOH (1.0) > MeOH (0.97) > *i*-PrOH (0.36) > *s*-BuOH (0.33) > $MeOCH_2CH_2OH$ (0.0) ≈ $ClCH_2CH_2OH$ (0.0). The selectivity orders of alcohols in ester and α-keto ester formations indicate the importance of electronic factors in their reactions with the palladium complex. The involvement of steric factors also is seen when the reactivities of *n*-PrOH, *i*-PrOH, and *sec*-BuOH are compared, the reactivity decreasing with an increase in the steric bulkiness of the alcohol. Furthermore, it is noted that in ester formation alcohols having electron-withdrawing alkyl groups show higher reactivities whereas more basic alcohols generally have higher reactivities in α-keto ester formation where steric factors are not involved.

5. Comparison of Relative Reactivities of Phenyl- and Benzoylpalladium Complexes with Alcohol and Et_3N under CO Pressure. In the previous paper on the reactions of aryl halides with CO and secondary amines to give α-keto amides and amides, we concluded that amides were formed catalytically by attack of the secondary amines on CO-coordinated arylpalladium species to give an arylcarbamoylpalladium intermediate from which amides are liberated by reductive elimination of the aryl and carbamoyl groups. In that case the reaction of a phenylpalladium complex with a reactive secondary amine such as piperidine under CO pressure predominatly gave amide whereas the benzoylpalladium complex exclusively gave the α-keto amide on treatment with the same secondary amine under the same reaction conditions. To see if the mechanism similar to that for amide formation is operative also for the present ester formation we compared the reactivities of phenylpalladium iodides (**2**) and benzoylpalladium iodides (**3**) having PPh_3 and PCy_3 ligands.

Table VII. Comparison of Reactivities of Benzoyl- and Phenylpalladium Complexes toward *sec*-BuOH, Et_3N, and CO[a]

			product ratio		
run	complex[b]	CO,[c] atm	PhCO-COO-*sec*-Bu	PhCOO-*sec*-Bu	total yield, %/Pd
1	**2a**	20	77	23	42
2	**3a**	20	79	21	39
3	**2a**	60	93	7	58
4	**3a**	60	93	7	58
5	**2b**	20	73	27	28
6	**3b**	20	79	21	22
7	**2b**	60	93	7	32
8	**3b**	60	97	3	33

[a] Reaction conditions: complex (0.025 mmol), *sec*-BuOH (0.5 mL), Et_3N (0.5 mL), solvent (CH_2Cl_2 (1.0 mL) + PhCl (0.28 mL)), at 70 °C, for 1 h (runs 1–4) and 2 h (runs 5–8). [b] **2a**, *trans*-PdPh(I)(PPh_3)$_2$; **3a**, *trans*-Pd(COPh)I(PPh_3)$_2$; **2b**, *trans*-PdPh(I)(PCy_3)$_2$; **3b**, *trans*-Pd(COPh)I(PCy_3)$_2$. [c] Initial value at room temperature.

The results summarized in Table VII indicate that the phenylpalladium iodides and benzoylpalladium iodides have essentially the same reactivity toward *sec*-BuOH in the presence of Et_3N under CO pressure. The results suggest that the benzoylpalladium intermediate generated by CO insertion into phenylpalladium complex is responsible for the ester as well as for the α-keto ester formation and that the CO insertion is faster than the subsequent reactions to give esters or α-keto esters.

6. Kinetic Studies on Ester Formation. Therefore, we carried out kinetic studies on the reaction of *trans*-Pd(COPh)I(PPh_3)$_2$ (**3a**) with EtOH and Et_3N under argon atmosphere, focusing on the ester formation. The rate of formation of ethyl benzoate in the reaction solution containing dimethyl maleate (dmm) was followed by means of GLC. The olefin was added to trap the [Pd(PPh_3)$_2$] species generated in the system after formation of ethyl benzoate. In the absence of dmm the system was gradually darkened with progress of the reaction that stopped at ca. 65% conversion of **3a**. In the presence of dmm the reaction proceeded cleanly to 100% conversion probably because the stabilized Pd(dmm)(PPh_3)$_2$ does not liberate free PPh_3[17] that retards the ester formation. The ester for-

$$\underset{\textbf{3a}}{trans\text{-}Pd(COPh)I(PPh_3)_2} + EtOH + Et_3N \xrightarrow[\text{under argon}]{dmm} PhCOOEt + Et_3NHI + Pd(dmm)(PPh_3)_2 \quad (4)$$

Table VIII. Pseudo-First-Order Rate Constants for the Reactions of *trans*-Pd(COPh)I(PPh_3)$_2$ (3a) with EtOH and Et_3N under Various Reaction Conditions[a]

run	solv	temp, °C	[dmm], M	[EtOH], M	[Et_3N], M	[PPh_3], M	10^4k_{obsd}, s^{-1}
1	DMF	55	0.08	0.71	0.80	0	3.9
2	DMF	55	0.16	0.71	0.80	0	3.8
3	DMF	55	0.32	0.71	0.80	0	3.7
4	DMF	55	0.16	0.44	0.80	0	2.1
5	DMF	55	0.16	0.88	0.80	0	4.4
6	DMF	55	0.16	1.05	0.80	0	5.1
7	DMF	55	0.16	0.71	0.32	0	1.4
8	DMF	55	0.16	0.71	0.61	0	2.8
9	DMF	55	0.16	0.71	1.00	0	4.7
10	DMF	55	0.16	0.71	0.80	0.0064	1.6
11	DMF	55	0.16	0.71	0.80	0.013	0.93
12	DMF	55	0.16	0.71	0.80	0.026	0.61
13	DMF	55	0.16	0.71	0.80	0.051	0.42
14	DMF	40	0.16	0.71	0.80	0	1.1
15	DMF	50	0.16	0.71	0.80	0	2.3
16	DMF	60	0.16	0.71	0.80	0	5.1
17	DMF	65	0.16	0.71	0.80	0	7.5
18	benzene	55	0.16	0.71	0.80	0	0.29
19	PhCl	55	0.16	0.71	0.80	0	0.51
20	Me_2SO	55	0.16	0.71	0.80	0	>10

[a] [3a] = 0.030–0.040 M.

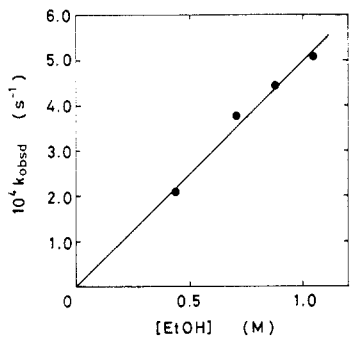


Figure 6. Plot of k_{obsd} vs. [EtOH].

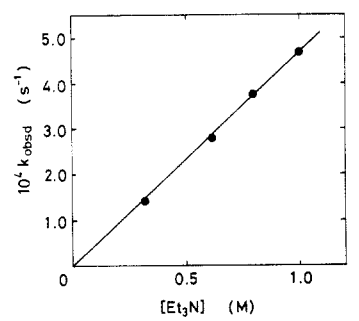


Figure 7. Plot of k_{obsd} vs. [Et_3N].

mation obeyed the pseudo-first-order rate law in the concentration of **3a** up to ca. 80% conversion. The pseudo-first-order rate constants, k_{obsd}, measured under various reaction conditions are listed in Table VIII. The reaction rate is nearly independent of the concentrations of dmm (runs 1–3) but is proportional to the concentrations of Et_3N as well as EtOH as can be seen from Figures 6 and 7. The third-order rate constant, 6.3×10^{-4} s^{-1} M^{-2}, derived by dividing the slope of the straight line in Figure 6 by the concentration of Et_3N was in agreement with the value of 6.5×10^{-4} s^{-1} M^{-2} obtained by dividing the slope of the straight line in Figure 7 by the concentration of EtOH.

The ester formation is effectively retarded by addition of free PPh_3 to the system (runs 2, 10–13 in Table VIII). Plot of the k_{obsd} against $1/[PPh_3]$ values gave a straight line as shown in Figure 8. The result indicates the involvement of predissociation of a part of the PPh_3 ligands from **3a** in the ester formation on its reaction with ethanol and Et_3N.

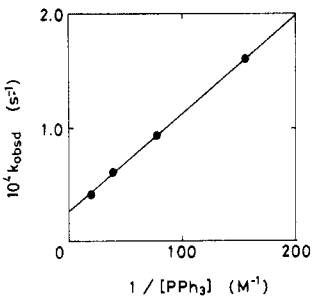


Figure 8. Plot of k_{obsd} vs. $1/[PPh_3]$.

From the k_{obsd} values measured at five different temperatures (runs 2, 14–17) the following activation parameters for the ester formation were estimated: $\Delta H^{\ddagger} = 15.1 \pm 0.5$ kcal mol^{-1}; $\Delta S^{\ddagger} = -27.1 \pm 1.0$ eu; $\Delta G^{\ddagger} = 24.4 \pm 0.5$ kcal mol^{-1} at 55 °C.

A quite distinct solvent effect was noted. The rates in polar *N,N*-dimethylformamide (DMF) and dimethyl sulfoxide (Me_2SO) solvents were much higher than those in less polar solvents such as benzene and chlorobenzene (runs 2, 18–20 in Table VIII).

In the addition to the kinetic study of reaction of *trans*-Pd(COPh)X(PPh_3)$_2$ (X = I) with EtOH and Et_3N under argon we measured the reaction rates of the corresponding bromide and chloride. The pseudo-first-order rate constant, k_{obsd}, decreased slightly in the order X = I (10^4k_{obsd} = 3.75) > X = Br (3.46) X = Cl (3.25). The order may reflect the slight decrease in the trend for dissociation of PPh_3 from the benzoylpalladium halides in the order I > Br > Cl.

The relative reactivities of nine kinds of alcohols toward **3a** in the presence of Et_3N were measured under argon atmosphere and compared with the results of the reactions performed under CO pressure. The results of the competitive reactions using a range of pairs of alcohols are listed in Table IX. The relative reactivities of alcohols,

$$\textit{trans}\text{-Pd(COPh)I(PPh}_3\text{)}_2 + R^1OH + R^2OH + Et_3N \xrightarrow[\text{under argon}]{\overset{\textbf{3a}}{\text{DMF, dmm}}} PhCOOR^1 + PhCOOR^2 + Et_3NHI \quad (5)$$

(17) Takahashi, S.; Hagihara, N. *J. Chem. Soc. Jpn.* **1967**, *88*, 1306. Minematsu, H.; Nonaka, Y.; Takahashi, S.; Hagihara, N. *J. Organomet. Chem.* **1973**, *59*, 395.

Table IX. Competitive Reactions of Alcohols toward *trans*-Pd(COPh)I(PPh_3)$_2$ (3a) in the Presence of Et_3N under Argon Atmosphere[a]

	alcohol pair		product ratio[b]	
run	R^1OH	R^2OH	$PhCOOR^1$	$PhCOOR^2$
1	MeOH	EtOH	3.3	1
2	*n*-PrOH	EtOH	0.78	1
3	*n*-BuOH	EtOH	0.75	1
4	$MeOCH_2CH_2OH$	MeOH	0.84	1
5	$ClCH_2CH_2OH$	MeOH	8.7	1
6	$NCCH_2CH_2OH$	$MeOCH_2CH_2OH$	10.6	1
7	*n*-BuOH	*i*-PrOH	7.1	1
8	*n*-BuOH	*sec*-BuOH	10.4	1

[a] Reaction conditions: **3a** (0.075 mmol), R^1OH (1.7 mmol), R^2OH (1.7 mmol), Et_3N (1.9 mmol), in DMF (2 mL) containing dimethyl maleate (0.38 mmol), at 50 °C, for 13–20 h, under argon atmosphere. [b] The summed yields of esters obtained were over 90% as determined by GLC.

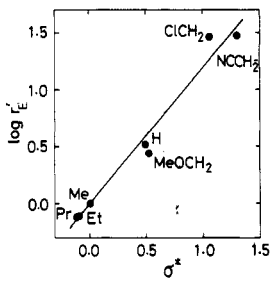


Figure 9. Plot of the relative reactivities (r_E') of various substituted methanols (RCH_2OH) vs. Taft σ^* values of R groups for the reactions with *trans*-Pd(COPh)I(PPh_3)$_2$ (**3a**) in the presence of Et_3N in DMF at 50 °C.

r_E', derived from the table decrease in the order $NCCH_2CH_2OH$ (29.7) > $ClCH_2CH_2OH$ (28.7) > MeOH (3.3) > $MeOCH_2CH_2OH$ (2.8) > EtOH (1.0) > *n*-PrOH (0.78) > *n*-BuOH (0.75) > *i*-PrOH (0.11) > *sec*-BuOH (0.072). The order and magnitudes of the r_E' values obtained here are in general agreement with those of the r_E values (vide supra) estimated in the reactions carried out under CO pressure.

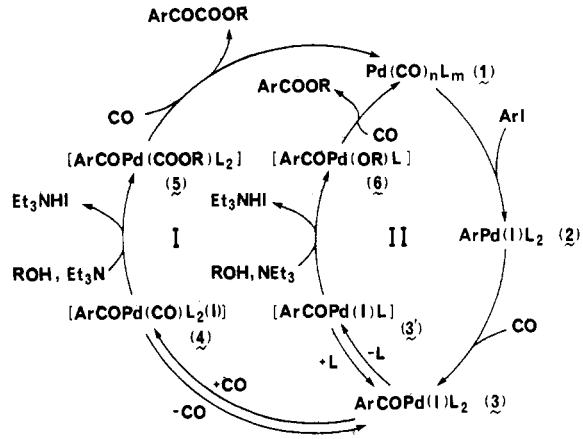
Plot of logarithms of the r_E' values against the Taft σ^* values of R groups attached to methanol (RCH_2OH) gave a straight line with a ρ^* value of 1.2 (Figure 9). Since pK_a values of the substituted methanols are known to be linearly correlated with the σ^* values of R groups ($\rho^* = 1.4$),[18] the present results clearly indicate that the more acidic alcohol gives the ester at the higher rate.

Discussion

The mechanisms for the double and single carbonylation reactions of aryl iodides to give α-keto esters and esters can be represented by Scheme II. The scheme consists of cycle I, giving α-keto esters, and cycle II, affording esters. The essential pattern of cycle I is similar to that proposed for formation of the α-keto amide.[1a] The catalyst precursor $PdCl_2L_2$ is reduced in the presence of CO, alcohol, and Et_3N to a zerovalent species represented as $Pd(CO)_nL_m$ (**1**), which oxidatively adds ArI to give *trans*-$PdAr(I)L_2$ (**2**). The insertion of CO into the Ar–Pd bond in **2** gives *trans*-Pd(COAr)IL_2 (**3**). Complex **3** has been identified by NMR study as the predominant species to be present in a rapid equilibrium with the CO-coordinated aroylpalladium complex **4**, which was proved to retain tertiary phosphine ligands in mutually trans positions. Attack of alcohol promoted by Et_3N on the coordinated CO ligand

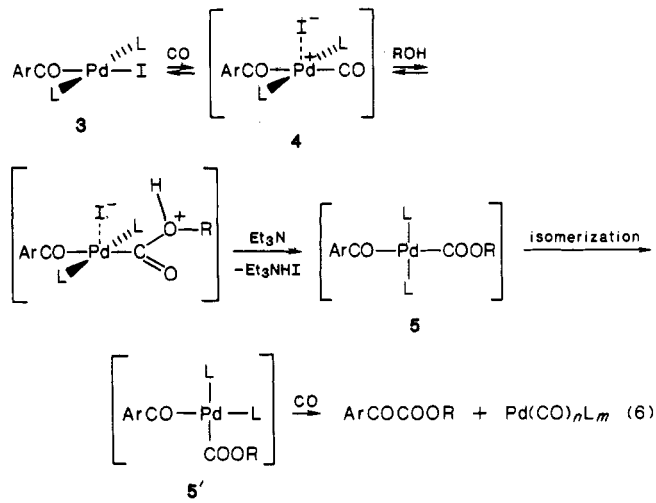
(18) Ballinger, P.; Long, F. A. *J. Am. Chem. Soc.* **1960**, *82*, 795.

Scheme II. Proposed Mechanism for the Catalytic Double and Single Carbonylations of Aryl Iodides Promoted by Palladium Complexes Having Tertiary Phosphine Ligands (L)



in **4** provides the aroyl(alkoxycarbonyl)palladium species **5**, which on reductive elimination liberates the α-keto ester with regeneration of **1** as a carrier of the further catalytic cycle.

Studies of reactions of alcohols and Et_3N under CO pressure with isolated *trans*-benzoylpalladium compleces **3a** and **3b** in fact established that α-keto esters are produced in high selectivity. The relative reactivity order of alcohols for α-keto ester formation (r_{KE}) estimated from the data on competitive reactions (Table VI) suggests that the more basic alcohol produces the α-keto ester at a higher rate when the difference in steric influence of the alcohol is ignored. Thus the following sequence of processes involving nucleophilic attack of alcohol on the coordinated CO may be envisaged.[19,20]



The square-pyramidal presentation for the CO-coordinated aroylpalladium complex **4** is a tentative one, and it may have a trigonal-bipyramid configuration. Since alcohol is a weak base, the nucleophilic attack of alcohol on

(19) A similar process for formation of alkoxycarbonylmetal moieties has been reported for the reactions of carbonylplatinum(II) and -palladium(II) chloride complexes with alcohols: Byrd, J. F.; Halpern, J. *J. Am. Chem. Soc.* **1971**, *93*, 1634. Yoshida, T.; Ueda, Y.; Otsuka, S. *Ibid.* **1978**, *100*, 3941. Clark, H. C.; Dixon, K. R.; Jacobs, W. J. *Ibid.* **1969**, *91*, 1346. Dobrzynski, E.; Angelici, R. *Inorg. Chem.* **1975**, *14*, 59. Rivetti, F.; Romano, U. *J. Organomet. Chem.* **1978**, *154*, 323.

(20) It has been established that the benzoylplatinum(II) carbonyl complex *trans*-$[Pt(COPh)(CO)(PPh_3)_2]^+ClO_4^-$ forms *trans*-Pt(PhCO)(COOMe)$(PPh_3)_2$ on the reaction with MeOH and Et_3N: Ozawa, F.; Huang, L.; Yamamoto, A., unpublished results. A similar result was reported independently: ref 12d.

the coordinated CO does not proceed readily in the absence of a base. In fact, when a competitive reaction of ethanol and more basic diethylamine was carried out under CO, the α-keto amide was obtained as the sole product (eq 7).

$$\underset{\mathbf{3c}}{\textit{trans}\text{-Pd(COPh)I(PMePh}_2)_2} + \underset{1}{\text{EtOH}} + \underset{1}{\text{Et}_2\text{NH}} \xrightarrow[(30\ \text{atm})]{\text{CO}} \text{PhCOCONEt}_2 \quad (7)$$

The aroyl(alkoxycarbonyl)palladium complex **5** generated by nucleophilic attack of alcohol on the coordinated CO ligand in **4** will have a trans configuration, which is not suitable for direct reductive elimination of the aroyl and alkoxycarbonyl groups. Therefore, a trans to cis isomerization (**5** → **5′**) must be involved prior to the reductive elimination.[21]

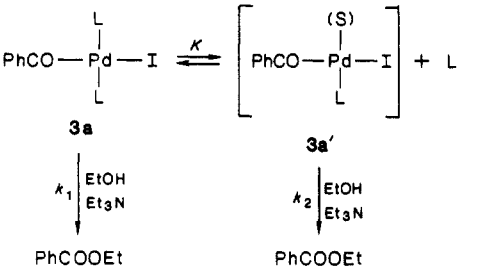
The remaining problem is the examination of the mechanism for producing esters. The experimental results indicate that it is reasonable to assume the aroylpalladium complex **3** as the common intermediate for both the double and single carbonylations. The selectivity increase for the α-keto ester formation at higher CO pressures (Figures 4 and 5) suggests that both the α-keto ester and ester are formed from the common aroylpalladium intermediate[22] and the equilibrium between **3** and **4** is in favor of **4** at higher CO pressures to produce the α-keto ester in higher selectivities.

Despite previous extensive studies on the palladium-catalyzed ester formation,[7] the most essential part in the catalytic reaction regarding the ester formation from the acylpalladium intermediate on reaction with alcohol and tertiary amine has remained unsolved and usually nucleophilic attack of alcohol on the acylcarbonyl group has been implicitly assumed. The results of the present kinetic studies on the reactions of the benzoylpalladium complexes with alcohols and Et_3N provide data incompatible with the assumption of direct nucleophilic attack of alcohol on the acyl group on the following basis. First, the more acidic alcohol gives the ester at the higher rate. Second, a competitive reaction of a 1:1 mixture of EtOH and more nucleophilic Et_2NH with **3c** carried out in the absence of CO gave only PhCOOEt, and no $PhCONEt_2$ was formed. The

$$\underset{\mathbf{3c}}{\textit{trans}\text{-Pd(COPh)I(PMePh}_2)_2} + \underset{1}{\text{EtOH}} + \underset{1}{\text{Et}_2\text{NH}} \xrightarrow[\text{in vacuo}]{} \text{PhCOOEt} \quad (8)$$

exclusive formation of the ester in eq 8 is in sharp contrast with the formation of only the α-keto amide when the reaction was carried out under CO pressure (eq 7). These results exclude the possibility of direct nucleophilic attack on the acyl group.

Scheme III



According to the results of kinetic studies on the reaction of **3a** with EtOH and Et_3N in the absence of CO to give the ester, the rate of ester formation was first-order, respectively, in the concentrations of [**3a**], [EtOH], and [Et_3N], and the reaction was severely hindered by the addition of PPh_3 (Figure 8). The results are compatible with Scheme III involving the partial dissociation of the PPh_3 ligands from **3a**. The rate of formation of PhCOOEt in this scheme may be expressed by eq 9. Since [**3a**] and

$$\frac{d[\text{PhCOOEt}]}{dt} = (k_1[\mathbf{3a}] + k_2[\mathbf{3a}'])[\text{EtOH}][\text{Et}_3\text{N}] \quad (9)$$

[**3a′**] can be expressed by

$$[\mathbf{3a}] = [\text{L}][\text{PhCOPd}]_{\text{total}}/([\text{L}] + K)$$

$$[\mathbf{3a}'] = K[\text{PhCOPd}]_{\text{total}}/([\text{L}] + K)$$

where [**3a**] + [**3a′**] = $[\text{PhCOPd}]_{\text{total}}$ and $K = [\mathbf{3a}'][\text{L}]/[\mathbf{3a}]$, the following rate expression (10) can be derived. If

$$\frac{d[\text{PhCOOEt}]}{dt} = \frac{k_1[\text{L}] + k_2K}{[\text{L}] + K}[\text{EtOH}][\text{Et}_3\text{N}][\text{PhCOPd}]_{\text{total}} \quad (10)$$

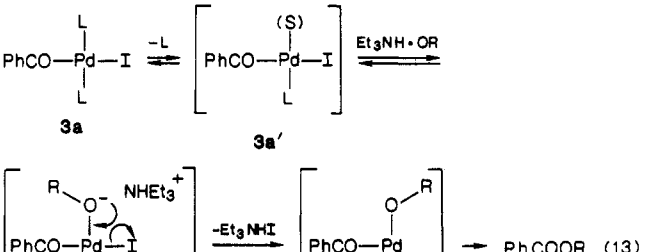
$[PPh_3] \gg K$ holds when free PPh_3 was added, k_{obsd} can be expressed by eq 11. Equation 11 is in agreement with

$$k_{\text{obsd}} = (k_1 + (k_2K/[\text{L}]))[\text{EtOH}][\text{Et}_3\text{N}] \quad (11)$$

the experimental results represented by Figures 6–8.

As for the reaction mechanism of alcohol and Et_3N with the benzoylpalladium iodide complex **3**, two routes are conceivable (eq 13 and 14). One involves nucleophilic attack of an alkoxide, formed from alcohol and Et_3N,[6a] on the three-coordinate intermediate **3a′** produced by partial dissociation of the PPh_3 ligands from **3a**.

$$\text{ROH} + \text{Et}_3\text{N} \rightleftarrows \text{Et}_3\text{NH}^+\text{OR}^- \quad (12)$$

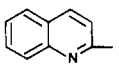
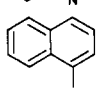


The experimental observation that the more acidic alcohol gives the ester at the higher rate is consistent with the favorable formation of the alkoxide from the more acidic alcohol in eq 12. In fact employment of sodium ethoxide (0.06 M) in DMF in a reaction with **3a** in place of the combination of ethanol and Et_3N gave ethyl ben-

(21) (a) Yamamoto, A. *Organotransition Metal Chemistry-Fundamental Concepts and Applications*; Wiley: New York, 1986. (b) Stille, J. K. In *The Chemistry of the Metal-Carbon Bond. Vol. 2. The Nature and Cleavage of Metal-Carbon Bonds*; Hartley, F. R., Patai, S., Eds.; Wiley: New York, 1985; p 625. (c) Yamamoto, A.; Yamamoto, T.; Komiya, S.; Ozawa, F. *Pure Appl. Chem.* **1984**, *56*, 1621 and references cited therein.

(22) Note that in the previous paper[1a] the attack of amine on the CO ligand coordinated to *arylpalladium* complex was assumed to account for formation of the amide, the single carbonylation product. The prime reason for the difference in the single carbonylation mechanisms for giving the ester and amide, respectively, is that the secondary amines have in general much higher nucleophilicity than alcohols. (For the difference in nucleophilicity see: Pearson, R. G.; Sobel, H.; Songstad, J. *J. Am. Chem. Soc.* **1968**, *90*, 319.) Thus in the ester formation the nucleophilic attack on the CO ligand coordinated to an arylpalladium complex is too slow to allow the CO insertion giving the aroylpalladium species, whereas amines having higher nucleophilicities attack the coordinated CO ligand attached to the arylpalladium species prior to the CO insertion into the aryl–palladium bond.

Table X. IR and Mass Spectroscopic Data of α-Keto Esters

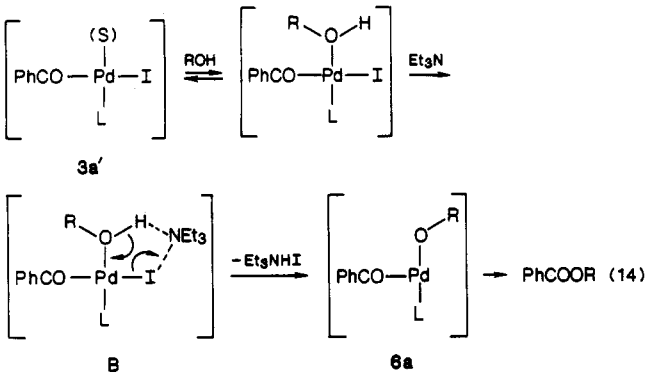
ArCOCOOR		IR,[a] ν(CO)		mass, m/e (relative intensity)[b]				
Ar	R	α-keto CO	ester CO	M^+	$ArCO^+$	Ar^+	R^+	yield,[d] %/ArI
Ph	Me	1739	1693	164 (1.0)	105 (100)	77 (43)	15 (9)	
Ph	Et	1736	1689	178 (0.8)	105 (100)	77 (38)	29 (6)	
Ph	Pr	1736	1690	192 (0.6)	105 (100)	77 (26)	43 (4)	
Ph	*i*-Pr	1732	1691	192 (0.2)	105 (100)	77 (28)	43 (20)	
Ph	*sec*-Bu	1732	1690	206 (0.05)	105 (100)	77 (28)	57 (24)	49
Ph	$CHEt_2$	1732	1691	230 (0.01)	105 (100)	77 (46)	71 (32)	
Ph	$CHPr_2$	1732	1691	*c*	105 (100)	77 (44)	99 (5)	
Ph	2-octyl	1732	1691	*c*	105 (100)	77 (38)	*c*	
Ph	cyclohexyl	1732	1691	232 (0.01)	105 (100)	77 (42)	83 (84)	
p-MeC_6H_5	*sec*-Bu	1731	1684	220 (0.4)	119 (100)	91 (30)	57 (18)	57
p-$MeOC_6H_5$	*sec*-Bu	1729	1677	236 (1.5)	135 (100)	107 (7)	57 (9)	47
p-NCC_6H_5	*sec*-Bu	1733	1705	231 (0.3)	130 (74)	102 (32)	57 (100)	47
	*sec*-Bu	1728	1667	212 (1.0)	111 (100)	83 (6)	57 (57)	61
	*sec*-Bu	1737	1712	256 (2.4)	156 (31)	128 (100)	57 (58)	22
	*sec*-Bu	1730	1678	256 (4.7)	155 (100)	127 (79)	57 (46)	42

[a] In cm^{-1}. [b] 70 eV. [c] Not observed. [d] GLC yields in the catalytic reactions carried out under the following reaction conditions: ArI (5 mmol), *sec*-BuOH (11 mmol), Et_3N (7.6 mmol), $PdCl_2(PCy_3)_2$ (0.1 mmol), $p(CO)$ = 70 atm (at room temperature), in CH_2Cl_2 (2 mL), at 70 °C, for 72–112 h.

zoate at a much faster rate ($k_{obsd} > 10^{-2}$ s^{-1} at 55 °C). Furthermore, the higher reaction rate in the ester formation in the more polar solvent may be associated with the ease of formation of the alkoxide in a solvent with a higher dielectric constant.

After removal of Et_3NHI from the supposed intermediate A in eq 13 a three-coordinate benzoylpalladium alkoxide (**6a**) will be generated. Formation of ester from an acylpalladium alkoxide through a three-coordinate species like **6a** has been previously established.[23]

Another possible route is initial coordination of the alcohol to the three-coordinate benzoylpalladium species **3a′** followed by abstraction of the alcoholic proton on interaction with NEt_3 to form **6a** and Et_3NHI (eq 14).



This mechanism is consistent with the considerably large negative entropy of activation. Furthermore, the fact that usage of bulky tertiary amines greatly affects the rates and selectivity in catalytic single and double carbonylations (see section A.6 above and Table II in ref 4) may be taken as an indication that the tertiary amine participates in the deprotonation of the alcohol coordinated to the palladium.

The experimental results obtained in the present study are consistent with mechanisms shown in Scheme II where oxidative addition of ArI and the subsequent CO insertion are rapid processes and attack of the alcohol and Et_3N on the aroylpalladium species and its CO adduct is rate-determining. The scheme is also compatible with the NMR observation of **3** as the predominant species under catalytic conditions. However, the possibility that a nonobservable species, by NMR spectroscopy, albeit minor, is responsible for the catalytic reaction cannot be excluded.

Experimental Section

Infrared spectra were measured on a Hitachi 295 or a JASCO IR-810 spectrometer by using KBr pellets for solid and KBr plates for liquid materials. IR spectra of benzoylpalladium complexes in solution under CO pressure were obtained on a JASCO FT/IR-3 spectrometer. NMR spectra were measured on a JEOL FX-100 spectrometer by Dr. Y. Nakamura and Ms. R. Ito of our laboratory. ^1H and $^{13}C\{^1H\}$ NMR signals are referenced to Me_4Si as an internal standard. $^{31}P\{^1H\}$ NMR signals are referenced to PPh_3 as an external standard (downfield positive). Mass spectra were measured on a Hitachi M-80 GC–mass spectrometer. Microanalyses (C, H, N, and halogen) were carried out by Mr. T. Saito and Dr. M. Tanaka of our laboratory using Yanagimoto CHN Autocorder Type MT-2 and Yazawa Halogen Analyzer.

Solvents, amines, alcohols, and aryl halides were dried in the usual manner, distilled, and stored under an argon atmosphere. Carbon monoxide was used as purchased (Nippon Sanso) without further purification. Dichlorobis(tertiary phosphine)palladium(II) complexes were prepared by the reactions of $PdCl_2(PhCN)_2$ with corresponding tertiary phosphines.

Preparation of Phenyl- and Benzoylpalladium(II) Complexes. The complexes *trans*-$PdPh(I)(PPh_3)_2$ (**2a**), *trans*-Pd(COPh)$I(PPh_3)_2$ (**3a**), *trans*-Pd(COPh)$Cl(PPh_3)_2$, and *trans*-Pd(COPh)$Br(PPh_3)_2$ were prepared by literature methods[7d,24] and identified by means of elemental analysis and IR and NMR spectroscopy. The complexes *trans*-Pd(COPh)$I(PMePh_2)_2$ (**3c**), *trans*-Pd(^{13}COPh)$I(PMePh_2)_2$ (**3c**-^{13}C), and *trans*-[Pd(COPh)(CO)$(PMePh_2)_2$]$^+ClO_4^-$ were prepared according to the methods described previously.[1a,12a]

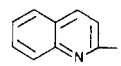
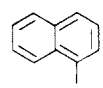
(a) Preparation of *trans*-PdPh(I)$(PCy_3)_2$ (2b). To a heterogeneous white mixture of $Pd(PCy_3)_2$[25] (1.5 g, 2.2 mmol) and benzene (10 mL) was added PhI (3.5 mL, 31 mmol) under nitrogen atmosphere at 5 °C. When the system was stirred at 30 °C, the heterogeneous mixture turned to a yellow homogeneous solution, from which white precipitate was gradually formed. The resulting

(23) It has been reported that acylphenoxopalladium complexes are readily decomposed in solution to give an ester: Komiya, S.; Akai, Y.; Tanaka, K.; Yamamoto, T.; Yamamoto, A. *Organometallics* **1985**, *4*, 1130.

(24) Fitton, P.; Johnson, M. P.; McKeon, J. E. *Chem. Commun.* **1968**, 6. Rick, E. A.; Fitton, P. *J. Organomet. Chem.* **1971**, *28*, 287.

(25) Otsuka, S.; Yoshida, T.; Matsumoto, M.; Nakatsu, K. *J. Am. Chem. Soc.* **1976**, *98*, 5850.

Table XI. ^{1}H NMR Data of α-Keto Esters[a]

ArCOCOOR				ArCOCOOR			
Ar	R	R	Ar	Ar	R	R	Ar
Ph	Me	3.90 (s, 3 H, CH_3)	7.4–7.7 (m, 3 H, *m,p*-Ph) 7.8–8.1 (m, 2 H, *o*-Ph)	*p*-MeC_6H_5	*sec*-Bu	0.98 (t, J = 7 Hz, 3 H, CH_2CH_3)	2.43 (s, 3 H, CH_3)
Ph	Et	1.36 (t, J = 7 Hz, 3 H, CH_3) 1.46 (q, J = 7 Hz, 2 H, CH_2)	7.5–7.8 (m, 3 H, *m,p*-Ph) 8.0–8.3 (m, 2 H, *o*-Ph)			1.38 (d, J = 6 Hz, 3 H, $CHCH_3$) 1.6–1.8 (m, 2 H, CH_2)	7.31 (d, J = 7 Hz, 2 H, *m*-Ph) 7.89 (d, J = 7 Hz, 2 H, *o*-Ph)
Ph	Pr	1.00 (t, J = 7 Hz, 3 H, CH_3) 1.6–2.0 (m, 2 H, CH_2) 4.40 (t, J = 6 Hz, 2 H, CH_2)	7.3–7.8 (m, 3 H, *m,p*-Ph) 7.9–8.1 (m, 2 H, *o*-Ph)	*p*-$MeOC_6H_5$	*sec*-Bu	5.17 (d, J = 6 Hz, 1 H, CH) 0.98 (t, J = 7 Hz, 3 H, CH_2CH_3) 1.38 (d, J = 6 Hz, 3 H, $CHCH_3$)	 3.88 (s, 3 H, CH_3) 6.97 (d, J = 9 Hz, 2 H, *m*-Ph)
Ph	*i*-Pr	1.41 (d, J = 6 Hz, 6 H, CH_3) 5.36 (qui, J = 6 Hz, 1 H, CH)	7.3–7.8 (m, 3 H, *m,p*-Ph) 7.9–8.1 (m, 2 H, *o*-Ph)			1.6–1.9 (m, 2 H, CH_2) 5.15 (se, J = 6 Hz, 1 H, CH)	7.97 (d, J = 9 Hz, 2 H, *o*-Ph)
Ph	*sec*-Bu	0.98 (t, J = 7 Hz, 3 H, CH_2CH_3) 1.39 (d, J = 6 Hz, 3 H, $CHCH_3$) 1.6–1.9 (m, 2 H, CH_2) 5.18 (se, J = 6 Hz, 1 H, CH)	7.4–7.8 (m, 3 H, *m,p*-Ph) 7.9–8.1 (m, 2 H, *o*-Ph)	*p*-NCC_6H_5	*sec*-Bu	0.98 (t, J = 7 Hz, 3 H, CH_2CH_3) 1.40 (d, J = 6 Hz, 3 H, $CHCH_3$) 1.6–1.9 (m, 2 H, CH_2) 5.18 (se, J = 6 Hz, 1 H, CH)	7.83 (d, J = 9 Hz, 2 H, *o*-Ph) 8.15 (d, J = 9 Hz, 2 H, *m*-Ph)
Ph	$CHEt_2$	0.99 (t, J = 7 Hz, 6 H, CH_3) 1.73 (m, 4 H, CH_2) 5.09 (qui, J = 6 Hz, 1 H, CH)	7.4–7.8 (m, 3 H, *m,p*-Ph) 7.9–8.1 (m, 2 H, *o*-Ph)		*sec*-Bu	0.98 (t, J = 8 Hz, 3 H, CH_2CH_3) 1.38 (d, J = 6 Hz, 3 H, $CHCH_3$) 1.5–1.9 (m, 2 H, CH_2) 5.12 (se, J = 6 Hz, 1 H, CH)	7.20 (dd, J = 5 and 4 Hz, 1 H) 7.83 (dd, J = 5 and 1 Hz, 1 H) 8.09 (dd, J = 4 and 1 Hz, 1 H)
Ph	$CHPr_2$	0.95 (t, J = 7 Hz, 6 H, CH_3) 1.2–1.8 (m, 8 H, CH_2) 5.20 (qui, J = 6 Hz, 1 H, CH)	7.3–7.7 (m, 3 H, *m,p*-Ph) 7.9–8.1 (m, 2 H, *o*-Ph)		*sec*-Bu	1.08 (t, J = 7 Hz, CH_2CH_3)	7.5–8.4 (m, 6 H)
Ph	2-octyl	0.88 (br, 3 H, CH_2CH_3) 1.1–1.5 (br, 8 H, CH_2) 1.5–1.9 (br, 2 H, $CHCH_2$) 1.39 (d, J = 6 Hz, 3 H, $CHCH_3$) 5.20 (se, J = 6 Hz, 1 H, CH)	7.4–7.8 (m, 3 H, *m,p*-Ph) 7.9–8.1 (m, 2 H, *o*-Ph)		*sec*-Bu	1.45 (d, J = 6 Hz, $CHCH_3$) 1.6–1.9 (m, 2 H, CH_2) 5.32 (se, J = 6 Hz, 1 H, CH) 0.98 (t, J = 7 Hz, 3 H, CH_2CH_3)	 7.4–8.1 (m, 6 H)
Ph	cyclohexyl	1.2–2.2 (m, 10 H, CH_2) 4.9–5.3 (m, 1 H, CH)	7.4–7.8 (m, 3 H, *m,p*-Ph) 7.9–8.1 (m, 2 H, *o*-Ph)			1.39 (d, J = 6 Hz, 3 H, $CHCH_3$) 1.6–1.9 (m, 2 H, CH_2) 5.19 (se, J = 6 Hz, 1 H, CH)	9.0–9.1 (m, 1 H)

[a] 100 MHz, in $CDCl_3$ at room temperature. Chemical shifts are in δ. Multiplicity abbreviations: s, singlet; d, doublet; t, triplet; q, quartet; qui, quintet; m, multiplet; dd, doublet of doublets; br, broad; se, sextet.

precipitate was filtered, washed with ether and hexane, and dried in vacuo. The crude product was recrystallized from CH_2Cl_2–Et_2O to yield white crystals of **2b** (1.3 g, 68%). Anal. Calcd for $C_{42}H_{71}IP_2Pd$: C, 57.9; H, 8.2; I. 14.6. Found: C, 57.5; H, 8.6; I, 15.2.

(b) Preparation of *trans*-Pd(COPh)I(PCy_3)$_2$ (3b). To a 100-mL glass-made pressure bottle containing *trans*-PdPh(I)-(PCy_3)$_2$ (**2b**; 1.1 g, 1.3 mmol) was added 10 mL of CH_2Cl_2 under nitrogen atmosphere. After the system was evacuated by pumping, 10 atm of CO gas was introduced. When the heterogeneous white mixture was stirred at room temperature, the system smoothly turned to a reddish yellow homogeneous solution. After the system was stirred for 2 h, the CO gas was purged and the solvent was removed under reduced pressure. The resulting yellow precipitate was washed with Et_2O and recrystallized from CH_2Cl_2–Et_2O to yield yellow crystals of **3b** (0.94 g, 83%). Anal. Calcd for $C_{43}H_{71}IOP_2Pd$: C, 57.3; H, 8.0; I, 14.1. Found: C, 56.9; H, 8.1; I. 14.2. IR (KBr): ν(CO) 1638 cm^{-1}.

(c) Preparation of *trans*-Pd(COPh)I(PMe_2Ph)$_2$. To a heterogeneous mixture of *trans*-Pd(COPh)I(PPh_3)$_2$ (**3a**; 1.1 g, 1.3 mmol) and CH_2Cl_2 (15 mL) was added PMe_2Ph (464 μL, 3.3 mmol) under nitrogen atmosphere at −30 °C. The reaction mixture was stirred at room temperature to allow it to turn into a homogeneous red solution. The solution was concentrated to ca. 5 mL under reduced pressure, and 15 mL of hexane was added to the system. The resulting orange precipitate was filtered, washed with hexane (5 mL × 3), and dried in vacuo. The crude product was purified by column chromatography (silica–hexane–Et_2O) to yield a yellow powder of *trans*-Pd(COPh)I(PMe_2Ph)$_2$ (0.34 g, 50%). Anal. Calcd for $C_{23}H_{27}IOP_2Pd$: C, 44.9; H, 4.4; I, 20.6. Found: C, 45.6; H, 4.6; I, 20.9. IR (KBr): ν(CO) 1640 cm^{-1}.

Similarly prepared was *trans*-Pd(COPh)I(PMe_3)$_2$ by using PMe_3 in place of PMe_2Ph (70%). Anal. Calcd for $C_{13}H_{23}IOP_2Pd$: C, 31.8; H, 4.7; I, 25.9. Found: C, 31.6; H, 4.7; I, 25.0. IR (KBr): ν(CO) 1650 cm^{-1}.

(d) Preparation of *trans*-Pd(^{13}COPh)(PPh_3)$_2$ (3a-^{13}*C*). To a Schlenk tube containing *trans*-PdPh(I)(PPh_3)$_2$ (**2a**; 0.27 g, 0.33 mmol) was added 3 mL of CH_2Cl_2 under argon atmosphere. After the system was evacuated by pumping, an atmospheric pressure of ^{13}CO gas (99% isotopic purity) was introduced. When the

heterogeneous white mixture was stirred at room temperature, the system smoothly turned into a reddish yellow solution. After the system was stirred for 2 h, the CO gas was purged and the solution was concentrated to ca. 1 mL. Addition of 10 mL of Et_2O to the system formed yellow precipitate, which was filtered and recrystallized from CH_2Cl_2–Et_2O to yield crystals of **3a**-^{13}C (0.19 g, 68%). IR (KBr): $\nu(^{13}C{=}O)$ 1605 cm^{-1} (cf. $\nu(^{12}C{=}O)$ 1637 cm^{-1}).

Similarly prepared was *trans*-$Pd(^{13}COPh)I(PCy_3)_2$ (**3b**-^{13}CO) by using **2b** in place of **2a**. The reaction of **2b** with ^{13}CO proceeded much more slowly than that of **2a** and required ca. 12 h to complete. IR (KBr): $\nu(^{13}C{=}O)$ 1606 cm^{-1} (cf. $\nu(^{12}C{=}O)$ 1638 cm^{-1}).

Catalytic Double Carbonylation of Aryl Halides. As a typical procedure (Table I, run 2), PhI (1.01 g, 5.0 mmol), *sec*-BuOH (0.82 g, 11 mmol), Et_3N (0.77 g, 7.6 mmol), and CH_2Cl_2 (2.0 mL) were added to a 100-mL stainless-steel pressure bottle containing $PdCl_2(PPh_3)_2$ (0.070 g, 0.10 mmol) under argon atmosphere. After the system was evacuated by pumping, 70 atm of CO gas was introduced at room temperature and the mixture was magnetically stirred at 70 °C for 96 h. After the CO gas was purged, the mixture was extracted with Et_2O (10 mL × 2) and analyzed by means of GLC (Shimadzu GC-6A; column, PEG-HT 20 M, 1 m) by using Ph_2O as an internal standard. The GLC analysis revealed the formation of PhCOCOO-*sec*-Bu (40%/PhI) and PhCOO-*sec*-Bu (33%) with 73% conversion of PhI. The α-keto ester and ester produced were isolated by column chromatography (silica–hexane–Et_2O) after removal of palladium complex by bulb-to-bulb distillation (Shibata GTO-250R).

Identification of α-keto esters and esters isolated from the catalytic double carbonylation systems were performed by means of IR and ^1H NMR spectroscopy and mass spectrometry. IR, ^1H NMR, and mass spectroscopic data of α-keto esters prepared in the present and previous[4] studies are given in Tables X and XI.

NMR Studies of the Catalytic System (Figure 3). A mixture of PhI (0.20 g, 1.0 mmol), *sec*-BuOH (200 μL, 2.2 mmol), Et_3N (200 μL, 1.4 mmol), and CD_2Cl_2 (400 μL) was added to a pressurizable NMR sample tube containing $PdCl_2(PPh_3)_2$ (0.014 g, 0.020 mmol) under argon atmosphere. After the system was evacuated by pumping, CO gas (20 atm) was introduced at room temperature. The same tube was placed in a thermostated oil bath controlled at 50 ± 1 °C. At intervals, the sample tube was removed and cooled to room temperature, and the reaction solution was examined by $^{31}P\{^1H\}$ NMR spectroscopy at room temperature. After the NMR measurement the sample tube was again placed in the oil bath and the reaction was resumed. Assignments of the signals observed in the NMR spectra were performed by comparing with the spectra of authentic samples measured under the similar conditions.

The yields of α-keto ester and ester at each time were confirmed independently by GLC analysis of samples containing the same contents with the solution for the NMR study.

Stoichiometric Reactions of Phenyl- and Benzoylpalladium Complexes with Alcohols and Et_3N under CO Pressure. A typical example (Table VII, run 2) is as follows. To a stainless-steel pressure bottle containing *trans*-Pd(COPh)I(PPh_3)$_2$ (**3a**; 0.022 g, 0.025 mmol) were added *sec*-BuOH (0.5 mL, 5.5 mmol), Et_3N (0.5 mL, 3.5 mmol), PhCl (0.28 mL), and CH_2Cl_2 (1.0 mL) under argon atmosphere. After the system was evacuated by pumping, CO gas (20 atm) was introduced at room temperature and the bottle was placed in an oil bath controlled at 70 ± 1 °C. After the system was magnetically stirred for 1 h, CO gas was purged and the reaction products were analyzed by GLC using Ph_2O as an internal reference. The GLC analysis revealed the formation of 31%/**3a** of PhCOCOO-*sec*-Bu and 8% of PhCOO-*sec*-Bu.

Competitive Reactions of Various Alcohols with *trans*-Pd(COPh)I(PPh_3)$_2$ (3a) under CO Pressure (Table VI). For example, to a stainless-steel pressure bottle containing *trans*-Pd(COPh)I(PPh_3)$_2$ (**3a**; 0.021 g, 0.024 mmol) were added MeOH (154 μL, 3.8 mmol), EtOH (220 μL, 3.8 mmol), Et_3N (1.1 mL, 7.9 mmol), and CH_2Cl_2 (1.5 mL) under argon atmosphere. After the system was evacuated, 40 atm of CO gas was introduced and the bottle was placed in an oil bath controlled at 70 ± 1 °C. After 1 h, formation of PhCOCOOMe (0.0058 mmol), PhCOCOOEt (0.0060 mmol), PhCOOMe (0.0060 mmol), and PhCOOEt (0.0020 mmol) (total yield 83%/**3a**) was confirmed by GLC analysis of the reaction solution. On the basis of the yields of α-keto esters and esters and the amounts of alcohols fed to the system, the relative reactivities were determined as MeOH/EtOH = 0.97 for α-keto ester formation and 3.0 for ester formation.

Kinetic Study on the Ester Formation. A 30-mL Schlenk tube containing a solution (2.5 mL) of the complex (0.030–0.040 M), reactants (EtOH and Et_3N), and additives (dimethyl maleate and/or PPh_3) was placed in a thermostated bath (HAAKE F2) controlled to ±0.1 °C. The amount of ethyl benzoate produced with time was measured by means of GLC. The systems with *N,N*-dimethylformamide and dimethyl sulfoxide as solvents were homogeneous throughout the reactions, whereas the reactions carried out in benzene and phenyl chloride gradually formed a white precipitate of Et_3NHI as the reactions progressed.

Competitive Reactions of Various Alcohols with *trans*-Pd(COPh)I(PPh_3)$_2$ (3a) in the Presence of Et_3N under Argon Atmosphere (Table IX). To a Schlenk tube containing *N,N*-dimethylformamide solution (2 mL) of **3a** (0.066 g, 0.076 mmol) were added methanol (70 μL, 1.7 mmol), ethanol (100 μL, 1.7 mmol), Et_3N (279 μL, 1.9 mmol), and dimethyl maleate (48 μL, 0.38 mmol) under argon atmosphere. After the system was stirred at 50 °C for 16 h, the reaction solution was analyzed by means of GLC. The GLC analysis revealed formation of PhCOOMe (0.053 mmol) and PhCOOEt (0.016 mmol) (total yield 91%/**3a**). On the basis of the yields of esters, the relative reactivity of methanol to ethanol was determined as 3.3.

Competitive Reaction of EtOH and Et_2NH with *trans*-Pd(COPh)I($PMePh_2$)$_2$ (3c). (a) Under CO Pressure. To a stainless-steel pressure bottle containing **3c** (0.030 g, 0.040 mmol) were added EtOH (86 μL, 1.5 mmol), Et_2NH (150 μL, 1.4 mmol), dimethyl maleate (48 μL, 0.38 mmol), and CH_2Cl_2 (2 mL) under nitrogen atmosphere at −30 °C. After the system was evacuated by pumping, 30 atm of CO gas was introduced. After the system was stirred for 20 h at room temperature, the reaction solution was analyzed by means of GLC to reveal formation of 92%/**3c** of $PhCOCONEt_2$.

(b) Under Vacuum. A CH_2Cl_2 solution containing the same contents as those in reaction (a) was stirred at room temperature in vacuo for 20 h. A GLC analysis of the reaction solution revealed formation of 11%/**3c** of PhCOOEt.

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Registry No. **2a**, 18115-61-2; **2b**, 108818-35-5; **3a**, 50417-71-5; **3a**-^{13}CO, 108818-38-8; **3b**, 108818-36-6; **3b**-^{13}CO, 108818-39-9; **3c**, 68391-88-8; *trans*-Pd(COPh)I(PMe_2Ph)$_2$, 108818-37-7; *trans*-Pd(COPh)I(PMe_3)$_2$, 68391-85-5; $PdCl_2(PCy_3)_2$, 29934-17-6; $PdCl_2(P(p\text{-}CH_3C_6H_4)_3)_2$, 50525-39-8; $PdCl_2(PEt_2Ph)_2$, 40791-49-9; PhCOCOO-*i*-Pr, 31197-66-7; PhCOCOO-*i*-C_6H_{11}, 61598-01-4; *p*-MeC_6H_4COCOO-*sec*-Bu, 100556-46-5; *p*-$MeOC_6H_4$COCOO-*sec*-Bu, 100556-47-6; *p*-NCC_6H_4COCOO-*sec*-Bu, 100556-48-7; PhCOCOOMe, 15206-55-0; PhCOCOOEt, 1603-79-8; PhCOCOOPr, 31197-63-4; PhCOCOO-*sec*-Bu, 95653-53-5; $PhCOCOOCHEt_2$, 96606-35-8; $PhCOCOOCH(CH_3)(CH_2)_5CH_3$, 93163-81-6; PhI, 591-50-4; *p*-MeC_6H_4I, 624-31-7; *p*-$MeOC_6H_4I$, 696-62-8; *p*-NCC_6H_4I, 3058-39-7; MeOH, 67-56-1; EtOH, 64-17-5; PrOH, 71-23-8; *i*-PrOH, 67-63-0; *sec*-BuOH, 78-92-2; Et_2CHOH, 584-02-1; Pr_2CHOH, 589-55-9; $CH_3(CH_2)_5CH(CH_3)OH$, 123-96-6; *c*-$C_6H_{11}OH$, 108-93-0; *n*-BuOH, 71-36-3; $MeOCH_2CH_2OH$, 109-86-4; $ClCH_2CH_2OH$, 107-07-3; $NCCH_2CH_2OH$, 109-78-4; $PdCl_2(PhCN)_2$, 14220-64-5; $PdCl_2(PPh_3)_2$, 13965-03-2; $PdPh_3$, 603-35-0; $PdCl_2(P(p\text{-}CH_3C_6H_4)_3)_2$, 50525-39-8; $PdCl_2(PMe_3)_2$, 25892-38-0; PhCOO-*sec*-Bu, 3306-36-3; $Pd(PCy_3)_2$, 33309-88-5; PMe_2Ph, 672-66-2; PMe_3, 594-09-2; 2-iodoquinoline, 6560-83-4; 1-iodonaphthalene, 90-14-2; *sec*-butyl thiophenoylformate, 100556-49-8; *tert*-butyl 2-quinolinoylformate, 108818-34-4; *sec*-butyl 1-naphthalenoylformate, 106484-06-4; 2-iodothiophene, 3437-95-4.