Regioselective Hydroesterification and Hydrocarboxylation of 3,3,3-Trifluoropropene and Pentafluorostyrene Catalyzed by Phosphine-Palladium Complex

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The hydroesterification and hydrocarboxylation of 3,3,3-trifluoropropene (TFP) and pentafluorostyrene (PFS) catalyzed by phosphine–palladium complexes were studied. It was found that the efficiency and the product distribution of the reaction depended markedly on the nature of nucleophile, i.e., water or alcohol, the structures of olefin and phosphine ligand, and other reaction variables such as solvent, temperature, and carbon monoxide pressure. Under optimal conditions either unbranched products or branched products were obtained in high yields with high regioselectivities. For example, 4,4,4-trifluorobutyric acid (**5a**) was obtained in 93% yield with 99% regioselectivity by using $PdCl_2$(dppf)–$SnCl_2$ as the catalyst in the hydrocarboxylation of TFP while ethyl 2-methyl-3,3,3-trifluoropropionate (**2a**) was obtained in 96% yield with 79% regioselectivity in the hydroesterification of TFP by using $PdCl_2(PPh_3)_2$ as the catalyst. Similarly, 3-(pentafluorophenyl)propionic acid (**5b**) was obtained in 93% yield with 99% regioselectivity in the hydrocarboxylation of PFS catalyzed by $PdCl_2$(dppf), and methyl 2-(pentafluorophenyl)propionate (**2b**) was obtained in 89% yield with 95% regioselectivity in the hydroesterification of PFS catalyzed by $PdCl_2(PPh_3)_2$. Possible mechanisms of the present reactions are discussed. The hydrocarboxylations of TFP and PFS may involve (hydroxycarbonyl)palladium(II) intermediates while the hydroesterifications of TFP and PFS may proceed via alkylpalladium(II) and acylpalladium(II) intermediates.

It is known that the hydrocarbonylations of olefins serve as a convenient device for the production of the corresponding esters and carboxylic acids.[1] Although mechanistic studies as well as applications of the reactions to organic syntheses have been extensively studied, little is known about the reactions of olefins bearing perfluoroalkyl and perfluoroaryl substituents.[2] Recently, it has been shown that unique physiological activities are often obtained by introducing a trifluoromethyl or pentafluorophenyl group into a biologically active compound.[3] As 3,3,3-trifluoropropene (TFP) and pentafluorostyrene (PFS) are important fundamental building blocks, we have been studying the functionalizations of these compounds, e.g., arylation,[4] Diels–Alder reactions,[5] ureidocarbonylation,[6] hydrosilylation,[7] and hydroformylation.[8] In the hydroformylation of TFP and PFS, we found that the regioselectivity of the reaction was unusually high and dependent markedly upon the catalyst metal species employed; e.g., the rhodium complex catalyzed reaction of TFP gave branched aldehyde in more than 95% selectivity while the cobalt carbonyl catalyzed reaction gave unbranched aldehyde in 93% selectivity.[8] The results make a sharp contrast to those of ordinary olefins such as propene, hexene, styrene, ethyl acrylate, etc.[1] These findings compelled us to examine other hydrocarbonylations of TFP and PFS. Now, we describe here the hydroesterification and hydrocarboxylation of TFP and PFS catalyzed by phosphine–palladium complexes, in which the former reaction gives branched esters whereas the latter gives unbranched carboxylic acids with high selectivities.

Results and Discussion

Hydroesterification of TFP and PFS. First, we examined the catalytic activities of typical transition-metal complexes such as $Co_2(CO)_8$, $Rh_6(CO)_{16}$, H_2PtCl_6/$SnCl_2$–acetone, and $PdCl_2(PPh_3)_2$ toward the hydroesterification of TFP and PFS with methanol and carbon monoxide at 100 °C and 110 atm, and it was found that only $PdCl_2(PPh_3)_2$ showed the catalytic activity enough to promote the reaction under the given reaction conditions. Thus, we decided to employ palladium complexes with phosphine ligands for the present study (see eq 1).

$$R_fCH{=}CH_2 + CO + ROH \xrightarrow{[Pd]} \underset{\text{Me}}{\overset{R_f}{\diagdown}}\!\!>\!CHCOOR + R_fCH_2CH_2COOR \quad (1)$$

1a, $R_f = CF_3$
b, $R_f = C_6F_5$

2a-(a), $R_f = CF_3$; $R = C_2H_5$
2a-(b), $R_f = CF_3$; $R = CH_3$
2a-(c), $R_f = CF_3$; $R = i\text{-}C_3H_7$
2b, $R_f = C_6F_5$; $R = CH_3$

3a-(a), $R_f = CF_3$; $R = C_2H_5$
3a-(b), $R_f = CF_3$; $R = CH_3$
3a-(c), $R_f = CF_3$; $R = i\text{-}C_3H_7$
3b, $R_f = C_6F_5$; $R = CH_3$

Next, we looked at the effects of reaction variables on the conversion and regioselectivity of the reaction. Table I summarizes the effects of the ratio of triphenylphosphine to palladium and the solvent effects on the reaction of TFP. As Table I indicates, (i) a PPh_3/Pd ratio of 2 gave the best yield (entry 2), (ii) existence of triphenylphosphine is a requisite,[9] but large excess of it decreases the catalytic activity (entry 4), and (iii) the PPh_3/Pd ratio exerts an

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(9) When the reaction was carried out with 10 mmol of TFP, 3 mL of ethanol, and 0.10 mmol of $PdCl_2$ in 10 mL of acetone at 100 °C and 110 atm of carbon monoxide, the yield of the esters was only 3%.

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Table I. Hydroesterification of TFP[a]

entry	catalyst	alcohol	solvent	conditions: temp, °C	conditions: time, h	yield, %	branched (2a)/unbranched (3a) ratio
1	$PdCl_2 + PPh_3$	EtOH	acetone	100	70	29	46/54
2	$PdCl_2 + 2PPh_3$	EtOH	acetone	100	70	62	49/51
3	$PdCl_2 + 4PPh_3$	EtOH	acetone	100	70	59	43/57
4	$PdCl_2 + 10PPh_3$	EtOH	acetone	100	70	23	31/69
5	$PdCl_2(PPh_3)_2$	EtOH	EtOH	100	62	74	49/51
6	$PdCl_2(PPh_3)_2$	EtOH	acetone	100	62	82	52/48
7	$PdCl_2(PPh_3)_2$	EtOH	tetrahydrofuran	100	62	93	71/29
8	$PdCl_2(PPh_3)_2$	EtOH	toluene	100	62	96	77/23
9	$PdCl_2(PPh_3)_2$	EtOH	benzene	100	62	95	79/21
10	$PdCl_2(PPh_3)_2$	EtOH	acetonitrile	100	62	96	79/21
11	$PdCl_2(PPh_3)_2$	EtOH	triethylamine	100	40	0	
12	$PdCl_2(PPh_3)_2$	EtOH	NaOAc[c]/EtOH	100	40	0	
13	$PdCl_2(PPh_3)_2 + 5SnCl_2$	EtOH	benzene	100	30	6	
14	$PdCl_2$(dppb)[d]	EtOH	acetone	120	53	12	<1/99
15	$PdCl_2$(dppb)[d]	EtOH	benzene	120	66	13	1/99
16	$PdCl_2$(dppf)[e]	EtOH	acetone	120	83	16	11/89
17	$PdCl_2$(dppf)[e]	EtOH	benzene	120	66	50	23/77
18	$PdCl_2(PPh_3)_2$	MeOH	benzene	100	62	95	72/28[f]
19	$PdCl_2(PPh_3)_2$	*i*-PrOH	benzene	100	62	93	79/21

[a] All reactions were run with 10 mmol of TFP, 3 mL of alcohol, and 0.10 mmol of palladium catalyst in 10 mL of solvent in a 50-mL stainless steel autoclave. [b] There was an initial pressure at room temperature of 110 atm of CO in all cases. [c] With addition of 10 mmol of NaOAc. [d] dppb = 1,4-bis(diphenylphosphino)butane. [e] dppf = 1,1′-bis(diphenylphosphino)ferrocene. [f] Ratio was determined by ^{19}F NMR.

Table II. Hydroesterification of PFS with Methanol[a]

entry	catalyst	solvent	CO press,[b] atm	temp, °C	time, h	conversion, %	yield, %	branched (2b)/unbranched (3b) ratio
1	$PdCl_2(PPh_3)_2 + 5SnCl_2$	acetone	70	100	60	11	10	22/78
2	$PdCl_2(PPh_3)_2$	acetone	70	100	60	88	71	93/7
3	$PdCl_2(PPh_3)_2$	acetone	120	100	60	92	76	93/7
4	$PdCl_2(PPh_3)_2$	benzene	120	100	60	90	89	95/5
5	$PdCl_2(PPh_3)_2$	acetone	70	125	24	77	25	79/21
6	$PdCl_2$(dppb)[c]	acetone	100	125	24	53	5	
7	$PdCl_2$(dppb)[c]	acetone	120	100	60	9	0	

[a] All reactions were run with 3.0 mmol of PFS, 1 mL of methanol, and 0.03 mmol of palladium catalyst in 4 mL of solvent in a 50-mL stainless steel autoclave. [b] Initial pressure at room temperature. [c] dppb = 1,4-bis(diphenylphosphino)-butane.

Table III. Hydrocarboxylation of TFP[a]

entry[b]	catalyst	yield, %	branched (4a)/unbranched (5a) ratio
1	$PdCl_2(PPh_3)_2$	35	35/65
2	$PdCl_2(PPh_3)_2 + 5SnCl_2$	7	
3	$PdCl_2$(dppb)[c]	36	<1/99
4	$PdCl_2$(dppb)[c] + $5SnCl_2$	43	<1/99
5	$PdCl_2$(dppb)[c] + $10SnCl_2$	56	<1/99
6	$PdCl_2$(dppf)[d]	64	7/93
7	$PdCl_2$(dppf)[d] + $2SnCl_2$	79	3/97
8	$PdCl_2$(dppf)[d] + $5SnCl_2$	93	1/99
9	$PdCl_2$(dppf)[d] + $10SnCl_2$	92	6/94

[a] All reactions were run with 10 mmol of TFP, 1.0 mL of water, and 0.10 mmol of palladium catalyst in 10 mL acetic acid in a 50-mL stainless steel autoclave. [b] The reaction conditions in all cases were as follows: initial pressure at room temperature of 110 atm of CO, 125 °C, and 70 h. [c] dppb = 1,4-bis(diphenylphosphino)butane. [d] dppf = 1,1′-bis(diphenylphosphino)ferrocene.

appreciable influence on branched/unbranched ratio. It is also shown that the regioselectivity depends considerably upon the nature of the solvent used, and a good branched/unbranched ratio as well as a high yield was obtained when benzene, toluene, or acetonitrile was used as the solvent; e.g., $CF_3(CH_3)CHCOOC_2H_5$ [**2a**-(a)] was obtained in 96% yield with 79% regioselectivity (entry 10). In triethylamine or in the presence of sodium acetate, the reaction did not proceed at all. When cis-chelating diphosphines such as 1,4-bis(diphenylphosphino)butane (dppb) or 1,1′-bis(diphenylphosphino)ferrocene (dppf) was employed as a ligand, which forms a cis-chelate with palladium, the yield of the product was decreased, and the unbranched ester [**3a**-(a)], $CF_3CH_2CH_2COOC_2H_5$, became predominant. The bulkiness of the alcohols does not have significant influence on the regioselectivity (entries 9, 18, 19).

Table II summarizes the results of the hydroesterification of PFS. As Table II shows, the type of phosphine ligands, the addition of stannous chloride, and the reaction temperature exert a marked influence upon both the yield and regioselectivity of the reaction. Namely, the branched product **2b** ($C_6F_5(CH_3)CHCOOCH_3$) was obtained in 89% yield with 95% selectivity by using triphenylphosphine as the ligand (entry 4) whereas the yields of the products were very low (i) when cis-chelating ligands were employed (entries 6, 7) and (ii) when stannous chloride was added (entry 1), and the unbranched product **3b** ($C_6F_5CH_2CH_2COOCH_3$) was the predominant one. A decrease in both the yield and the branched/unbranched ratio was observed on raising the reaction temperature to 125 °C (entry 5).

Hydrocarboxylation of TFP and PFS. The hydrocarboxylation of TFP and PFS was found to be effected

Table IV. Hydrocarboxylation of PFS[a]

entry	catalyst	conditions[b] temp, °C	time, h	conversion, %	yield, %	branched (4b)/unbranched (5b) ratio
1	$PdCl_2(PPh_3)_2$	125	24	100	90	27/73
2	$PdCl_2$(dppb)[c]	125	24	100	90	4/96
3	$PdCl_2$(dppb)[c]	100	48	100	90	<1/99
4	$PdCl_2$(dppf)[d]	125	24	100	89	1/99
5	$PdCl_2$(dppf)[d]	100	48	100	93	1/99
6	$PdCl_2$(dppb)[c] + $10SnCl_2$	100	18	40	25	<1/99
7	$PdCl_2$(dppf)[d] + $10SnCl_2$	100	18	32	29	1/99

[a] All reactions were run with 3.0 mmol of PFS, 0.3 mL of water, and 0.03 mmol of palladium catalyst in 4 mL of acetic acid in a 50-mL stainless steel autoclave. [b] There was an initial pressure at room temperature of 100 atm of CO in all cases. [c] dppb = 1,4-bis(diphenylphosphino)butane. [d] dppf = 1,1′-bis(diphenylphosphino)ferrocene.

also by phosphine–palladium complexes. It turned out that the nature of the solvent was a crucial factor for the promotion of this carbonylation; viz., the reaction readily proceeded in acetic acid under 110 atm of carbon monoxide at 125 °C whereas no reaction took place at all in tetrahydrofuran or acetone under similar conditions (at 125 °C and 110 atm of CO). Typical results on the hydrocarboxylation of TFP are summarized in Table III, and those of PFS are listed in Table IV (see eq 2).

$$R_fCH{=}CH_2 + CO + H_2O \xrightarrow[AcOH]{[Pd]}$$

1a, $R_f = CF_3$
b, $R_f = C_6F_5$

$$\underset{\text{4a, } R_f = CF_3;\ \text{b, } R_f = C_6F_5}{R_f(CH_3)CHCOOH} + \underset{\text{5a, } R_f = CF_3;\ \text{b, } R_f = C_6F_5}{R_fCH_2CH_2COOH} \quad (2)$$

As Table III shows, the palladium complexes with cis-chelating diphosphines, e.g., dppb and dppf, bring about good results, and an addition of stannous chloride to these catalyst systems considerably accelerates the reaction. These results form a sharp contrast with those obtained in the corresponding hydroesterification. By using $PdCl_2$(dppf)–$SnCl_2$ as the catalyst, the unbranched product **5a** ($CF_3CH_2CH_2COOH$) was obtained in 93% yield with 99% regioselectivity (entry 8).

As Table IV shows, the hydrocarboxylation of PFS proceeded much faster than that of TFP to give the unbranched acid **5b** selectively. In this case, the palladium complexes bearing cis-chelating diphosphine realize much higher regioselectivity (up to 96%) than $PdCl_2(PPh_3)_2$ does. An addition of stannous chloride decreases the reaction rate in this case (entries 6, 7).

Possible Mechanisms of the Hydroesterification and Hydrocarboxylation. The mechanisms of hydroesterification and hydrocarboxylation catalyzed by transition-metal complexes have been extensively studied,[1] and two kinds of mechanism have been proposed; viz., one mechanism involves hydridometal and acylmetal intermediates followed by solvolysis (eq 3),[10]

$$\text{H-[M]} \underset{}{\overset{RCH{=}CH_2}{\rightleftharpoons}} RCH_2CH_2\text{-[M]} \overset{CO}{\rightleftharpoons} RCH_2CH_2CO\text{-[M]} \xrightarrow{HOR'} RCH_2CH_2COOR' \quad (3)$$

$$\text{[M]-COOR'} \overset{RCH{=}CH_2}{\rightleftharpoons} \text{[M]-C(R)HCH}_2\text{COOR'} \overset{H^+}{\rightleftharpoons} RCH_2CH_2COOR' \quad (4)$$

and the other one involves (alkoxycarbonyl)- or (hydroxycarbonyl)metal and [β-(alkoxycarbonyl)alkyl]- or [β-(hydroxycarbonyl)alkyl]metal intermediates followed by acid cleavage of the palladium–alkyl bond (eq 4).[10]

One of the characteristic features of the present reactions compared with the previously reported works is that the regioselectivity of the reaction dramatically changes when hydrogen donor is changed from alcohol to water; e.g., when $PdCl_2(PPh_3)_2$ is used as a catalyst and PFS as the substrate, the branched/unbranched ratio observed in the hydroesterification is 79/21 to 95/5 (entries 2–5 in Table II) whereas that in the hydrocarboxylation is reversed to 27/73 (entry 1 in Table IV). In addition to this, the catalytic activity of palladium complexes bearing cis-chelating ligands, e.g., $PdCl_2$(dppb), is by far lower than that of $PdCl_2(PPh_3)_2$ in the hydroesterification whereas the catalytic activities of these palladium complexes are comparable with each other in the hydrocarboxylation.

We propose here possible mechanisms of the present hydroesterification and hydrocarboxylation, which can accommodate the characteristic features of the reactions mentioned above.

As for the possible mechanism of the hydrocarboxylation of TFP and PFS, the one involving (hydroxycarbonyl)-palladium(II) compound **6** and β-[(hydroxycarbonyl)alkyl]palladium(II) intermediate **7** can well explain the observed regioselectivities (Scheme I, cycle a). As it is reasonable to assume that a partial negative charge is developing at the α-carbon of the palladium–alkyl bond,[11] [α-R_f-β-(hydroxycarbonyl)ethyl]palladium(II) (**7a**) should be the favorable intermediate rather than **7b** since an electron-withdrawing R_f group stabilizes the partially developing negative charge in the transition state (t-**7a**) which leads to the formation of **7a**. Thus, the insertion of R_f-$CH{=}CH_2$ to **6** should be the regiodetermining step.[12]

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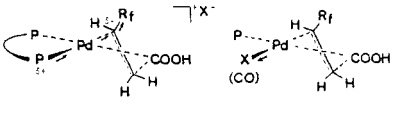
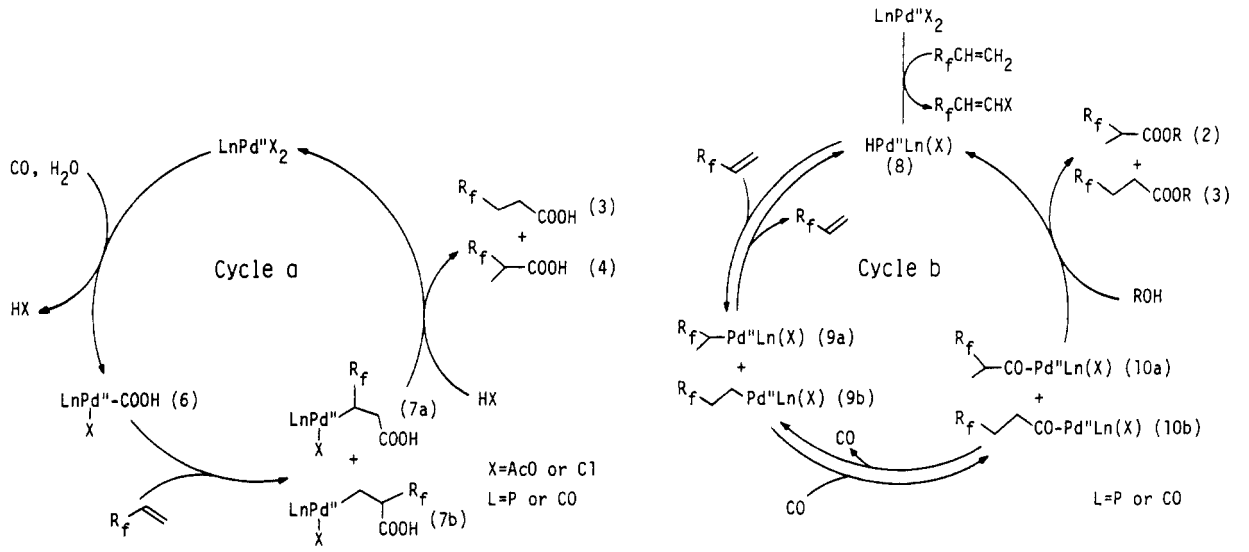
(12) As for the difference between the regioselectivity achieved by the palladium catalysts with cis-chelating diphosphines and that by $PdCl_2(PPh_3)_2$, it is suggested that cis-chelating diphosphine behaves as bidentate ligand throughout the catalytic cycle while the two triphenylphosphines behave as trans ligands and probably liberate one triphenylphosphine to give a monophosphine complex.

Because of the strong trans effect of the phosphine ligand, the transition state leading to **7a** (t-**7a**) would become much more favorable than that to **7b** (t-**7b**) especially in the case of the cis-chelating diphosphine complex (t-**7a**-A) since the electron-withdrawing R_f group is attached to the α-carbon in t-**7a**-A and a cationic species would be generated. On the other hand, the difference in the preference between the two transition states, t-**7a** and t-**7b**, would be much smaller for the triphenylphosphine complex since the trans effect of the phosphine ligand cannot necessarily be expected because of the ambiguity of the position of phosphine ligand in the coordinatiofn sphere (t-**7a**-B). This would be the reason why excellent unbranched/branched ratios are achieved by using cis-chelating diphosphines dppb and dppf.



t-7a-A t-7a-B

Scheme I. Possible Mechanisms for Hydrocarbonylations



Similar regioselectivities were observed in the oxidative carbonylation[13] and dicarbonylation[14] of olefins bearing electron-withdrawing groups such as styrenes and α,β-unsaturated carbonyl compounds.

In the hydroesterification of TFP and PFS, the mechanism involving [β-(alkoxycarbonyl)ethyl]palladium(II) intermediate **7** could also be operative. However, the protonative cleavage of the [β-(alkoxycarbonyl)ethyl]-palladium(II) intermediate **7** should be very slow because of the absence of acid as a solvent. Accordingly, the other mechanism involving hydridopalladium(II) (**8**) and acylpalladium(II) (**10**) intermediates is possible (Scheme I, cycle b). The regioselectivity of the reaction would be governed by the relative preference between the two alkylpalladium(II) intermediates **9a** and **9b**. Since a partial negative charge develops on the α-carbon of the alkyl–palladium bond and since the electron-withdrawing group on the α-carbon stabilizes the intermediate, **9a** is more favorable than **9b**, and thus the branched ester **2** should be produced selectively.[15] Actually, the results obtained for the reaction of PFS (Table II) are well accommodated by taking into account the strong inductive and resonance stabilizing effects of the α-perfluorophenyl group in **9a**. The results obtained for the reaction of TFP (Table I) are rather complicated. The observed considerably large solvent effects on the regioselectivity may be due to the change in the preference of the two competitive catalytic cycles a and b.[16]

Experimental Section

Measurements. NMR spectra (chemical shifts in parts per million from internal tetramethylsilane for ^1H and from internal fluorotrichloromethane for ^{19}F; δ is positive for downfield shifts in all cases) were recorded on a Varian EM-390 for ^1H and on a Varian XL-100-15A for ^{19}F. Mass spectra were recorded on a Hitachi RMU-6MG spectrometer at 70 eV. IR spectra were measured with a JASCO A-202 spectrometer. GLC analyses were carried out with a Shimadzu GC-7A instrument with a glass column (1.2 × 0.3 mm) packed with silicone SE-30 (30%) and DC-550 (30%) on Uniport B. A Varian Aerograph Model 920 gas chromatograph was used for separation of the products.

Materials. 3,3,3-Trifluoropropene (TFP) and pentafluorostyrene (PFS) were purchased from PCR Inc. and Aldrich Chem. Co., respectively, and used without further purification. Triphenylphosphine, 1,4-bis(diphenylphosphino)butane (dppb), and 1,1′-bis(diphenylphosphino)ferrocene (dppf) were used as purchased from Strem Chemicals, Inc. Palladium(II)–phosphine complexes $PdCl_2(PPh_3)_2$,[17] $PdCl_2$(dppb),[18] and $PdCl_2$(dppf)[19] were prepared in accordance with the literature methods. Other materials and solvents were used as received.

Hydroesterification and Hydrocarboxylation of 3,3,3-Trifluoropropene (TFP). The following procedure is typical. A 50-mL stainless steel autoclave fitted with a magnetic stirring bar was charged with a palladium catalyst (0.1 mmol), either degassed alcohol (3 mL) or water (1 mL), and a degassed solvent (10 mL). The autoclave was cooled with dry ice–acetone and evacuated. Then, gaseous TFP (0.96 g, 10 mmol) was introduced, and the autoclave was pressured with carbon monoxide up to 110 atm (at room temperature). The autoclave was heated to 100–125 °C and stirred for the necessary period of time at this temperature. Then, the apparatus was rapidly cooled with ice–water, and carbon monoxide was carefully purged out. The reaction mixture was submitted to quantitative GLC analysis for the determination of the product distribution and yields. Nonane was used as the internal standard for **2a**-(b), **3a**-(b), **2a**-(c), **3a**-(c), **4a**, and **5a**, and decane was used for **2a**-(a) and **3a**-(a). The structures of the products isolated by preparative GLC were determined on the basis of their spectral data and microanalyses. Results are summarized in Tables I and III.

Ethyl 2-methyl-3,3,3-trifluoropropionate [2a-(a)]: ^1H NMR ($CDCl_3$) δ 1.30 (t, J = 7.5 Hz, 3 H), 1.40 (d, J = 6.0 Hz, 3 H), 3.20 (m, 1 H), 4.22 (q, J = 7.5 Hz, 2 H); ^{19}F NMR ($CDCl_3$) δ −70.7 (d,

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(15) On the basis of the fact that the palladium complexes bearing cis-chelating diphosphines do not show any appreciable catalytic activity, it is strongly suggested that the active catalyst species of $PdCl_2(PPh_3)_2$ has only one triphenylphosphine, which should ease the coordination of carbon monoxide and thus accelerate the formation of acylpalladium(II) intermediate (**10**) while the alkylpalladium(II) intermediate (**9**) bearing cis-chelating diphosphine could hardly undergo the insertion of carbon monoxide into alkylpalladium bond because of the lack of effective coordination site. In fact, an addition of stannous chloride to $PdCl_2(PPh_3)_2$ or employment of a cis-chelating diphosphine seems to distrub the formation of the acylpalladium(II) intermediate and thus rather favor the (alkoxycarbonyl)palladium route which is essentially the same as the catalytic cycle a in Scheme I, and, as a result, the unbranched ester **3** is produced selectively but in very low yield.
(16) Namely, the acylpalladium(II) route (cycle b) is favorable in benzene, toluene, or tetrahydrofuran while the two mechanisms may be almost equally operative in ethanol or acetone. The fact that trifluoromethyl only has a purely inductive effect, and thus, is a much weaker stabilizing ability than perfluorophenyl, may be another reason why the highest branched/unbranched ratio attained in TFP (79/21) is much lower than that realized in the case of PFS (95/5).
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J = 8.5 Hz); IR (neat) 1750 cm^{-1} (C=O); mass spectrum, m/e 170 (M^+). Anal. Calcd for $C_6H_9F_3O_2$: C, 42.36; H, 5.33. Found: C, 42.44; H, 5.34.

Methyl 2-methyl-3,3,3-trifluoropropionate [2a-(b)]:[20] ^1H NMR (C_6D_6) δ 1.05 (d, J = 7.0 Hz, 3 H), 2.76 (m, 1 H), 3.26 (s, 3 H); ^{19}F NMR (C_6D_6) δ -69.8 (d, J = 8.0 Hz).

Isopropyl 2-methyl-3,3,3-trifluoropropionate [2a-(c)]: ^1H NMR ($CDCl_3$) δ 1.27 (d, J = 7.0 Hz, 6 H), 1.38 (d, J = 7.0 Hz, 3 H), 3.12 (septet, J = 7.0 Hz, 1 H), 5.05 (septet, J = 7.0 Hz, 1 H); ^{19}F NMR ($CDCl_3$) δ -70.3 (d, J = 7.0 Hz); IR (neat) 1745 cm^{-1} (C=O); mass spectrum, m/e 184 (M^+). Anal. Calcd for $C_7H_{11}F_3O_2$: C, 45.65; H, 6.02. Found: C, 45.68; H, 5.92.

Ethyl 4,4,4-trifluorobutyrate [3a-(a)]:[22] ^1H NMR ($CDCl_3$) δ 1.27 (t, J = 6.6 Hz, 3 H), 2.1-2.7 (m, 4 H), 4.15 (q, J = 6.6 Hz, 2 H); ^{19}F NMR ($CDCl_3$) δ -67.7 (t, J = 10.5 Hz); IR (neat) 1740 cm^{-1} (C=O); mass spectrum, m/e 170 (M^+).

Methyl 4,4,4-trifluorobutyrate [3a-(b)]:[21] ^1H NMR (C_6D_6) δ 1.7-2.3 (m, 4 H), 3.26 (s, 3 H); ^{19}F NMR (C_6D_6) δ -66.8 (t, J = 10.0 Hz).

Isopropyl 4,4,4-trifluorobutyrate [3a-(c)]: ^1H NMR ($CDCl_3$) δ 1.25 (d, J = 7.0 Hz, 6 H), 2.3-2.7 (m, 4 H), 5.0 (septet, J = 7.0 Hz, 1 H); ^{19}F NMR ($CDCl_3$) δ -67.3 (t, J = 10.0 Hz); IR (neat) 1740 cm^{-1} (C=O); mass spectrum, m/e 184 (M^+). Anal. Calcd for $C_7H_{11}F_3O_2$: C, 45.65; H, 6.02. Found: C, 45.40; H, 5.79.

2-Methyl-3,3,3-trifluoropropionic acid (4a):[20] ^1H NMR ($CDCl_3$) δ 1.48 (d, J = 7.2 Hz, 3 H), 3.28 (m, 1 H), 10.18 (br s, 1 H); ^{19}F NMR ($CDCl_3$) δ -70.6 (d, J = 8.1 Hz); IR (neat) 1725 cm^{-1} (C=O); mass spectrum, m/e 142 (M^+).

4,4,4-Trifluorobutyric acid (5a):[22,23] ^1H NMR ($CDCl_3$) δ 2.1-2.8 (m, 4 H), 9.10 (br s, 1 H); ^{19}F NMR ($CDCl_3$) δ -67.7 (t, J = 10.2 Hz); IR (neat) 1725 cm^{-1} (C=O); mass spectrum, m/e 142 (M^+).

Hydroesterification and Hydrocarboxylation of Pentafluorostyrene (PFS). The following procedure is typical. A 50-mL stainless steel autoclave fitted with a magnetic stirring bar was charged with a palladium catalyst (3×10^{-2} mmol), PFS (582 mg, 3 mmol), and either alcohol (1 mL) in acetone (4 mL) or water (0.3 mL) in acetic acid (4 mL), sealed up, and then purged by filling (20 atm) and releasing twice with carbon monoxide. The autoclave was pressurized with carbon monoxide up to the desired pressure, and then heating and stirring were started. After the reaction was run for the necessary period of time, the autoclave was cooled to room temperature and carefully depressurized. The reaction mixture was submitted to quantitative GLC analysis by using decane as the internal standard, and the products were isolated by preparative GLC. The structures of the products were determined on the basis of their spectral data and elemental analyses. Results are summarized in Tables II and IV.

Methyl 2-(pentafluorophenyl)propionate (2b): ^1H NMR ($CDCl_3$) δ 1.55 (d, J = 7.0 Hz, 3 H), 3.71 (s, 3 H), 4.05 (q, J = 7.0 Hz, 1 H); ^{19}F NMR ($CDCl_3$) δ -143.4 (m, 2 F), -156.4 (t, J = 20.0 Hz, 1 F), -162.6 (m, 2 F); IR (neat) 1750 cm^{-1} (C=O); mass spectrum, m/e 254 (M^+). Anal. Calcd for $C_{10}H_7F_5O_2$: C, 47.27; H, 2.76. Found: C, 47.17; H, 2.78.

Methyl 3-(pentafluorophenyl)propionate (3b): ^1H NMR ($CDCl_3$) δ 2.60 (t, J = 7.0 Hz, 2 H), 3.03 (t, J = 7.0 Hz, 2 H), 3.68 (s, 3 H); ^{19}F NMR ($CDCl_3$) δ -144.0 (m, 2 F), -157.3 (t, J = 20.0 Hz, 1 F), -163.0 (m, 2 F); IR (neat) 1750 cm^{-1} (C=O); mass spectrum, m/e 254 (M^+). Anal. Calcd for $C_{10}H_7F_5O_2$: C, 47.27; H, 2.76. Found: C, 47.24; H, 2.81.

2-(Pentafluorophenyl)propionic acid (4b): mp 91-92 °C; ^1H NMR ($CDCl_3$) δ 1.55 (d, J = 7.0 Hz, 3 H), 4.11 (q, J = 7.0 Hz, 1 H), 11.45 (br s, 1 H); ^{19}F NMR ($CDCl_3$) δ -142.9 (m, 2 F), -155.9 (t, J = 21.0 Hz, 1 F), -162.5 (m, 2 F); IR (KBr) 1720 cm^{-1} (C=O); mass spectrum, m/e 240 (M^+). Anal. Calcd for $C_9H_5F_5O_2$: C, 45.02; H, 2.10. Found: C, 45.00; H, 2.23.

3-(Pentafluorophenyl)propionic acid (5b): mp 95-96 °C; ^1H NMR ($CDCl_3$) δ 2.6-2.9 (m, 2 H), 2.9-3.3 (m, 2 H), 10.86 (br s, 1 H); ^{19}F NMR ($CDCl_3$) δ -144.1 (m, 2 F), -157.1 (t, J = 20.0 Hz, 1 F), -162.9 (m, 2 F); IR (KBr) 1715 cm^{-1} (C=O); mass spectrum, m/e 240 (M^+). Anal. Calcd for $C_9H_5F_5O_2$: C, 45.02; H, 2.10. Found: C, 45.11; H, 2.14.

Registry No. **1a**, 677-21-4; **2a**, 653-34-9; **2a**-(a), 56354-75-7; **2a**-(b), 339-17-3; **2a**-(c), 86994-26-5; **2b**, 86994-28-7; **3a**-(a), 371-26-6; **3a**-(b), 2365-82-4; **3a**-(c), 86994-27-6; **3b**, 86994-29-8; **4a**, 381-97-5; **4b**, 719-30-2; **5a**, 406-93-9; **5b**, 2002-92-8; $PdCl_2$, 7647-10-1; PPh_3, 603-35-0; $PdCl_2(PPh_3)_2$, 13965-03-2; $PdCl_2$(dppb), 29964-62-3; $PdCl_2$(dppf), 72287-26-4; $SnCl_2$, 7772-99-8.

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Notes

Regioselectivity of 1,3-Dipolar Cycloadditions of (Phenylsulfinyl)- and (Phenylsulfonyl)alkenes

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In a previous paper[2] two of us have reported the cycloaddition of nitrilimines to unsymmetrical disubstituted electron-deficient alkenes, with $PhSO_2$ as a substituent group. Here we examine the chemical behavior of nitrilimine **1** and nitrile oxide **2** toward both sulfinyl- and sulfonylalkenes **3** and **4**, respectively. The aim of our work is to get a better understanding of the influence of PhSO and $PhSO_2$ groups on the regioselectivity of the cycloaddition reactions of alkene dipolarophiles. Up to now the use of α,β-unsaturated sulfoxides and sulfones as dipolarophiles in 1,3-dipolar cycloaddition reactions is quite limited.[3]

A perturbation molecular orbital treatment has been performed in order to rationalize the experimental results.

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