Bull. Chem. Soc. Jpn., *72*, 2345—2350 (1999)

Palladium-Catalyzed Cross-Coupling of Benzyl Ketones and *α*,*β*-Unsaturated Carbonyl and Phenolic Compounds with *o*-Dibromobenzenes to Produce Cyclic Products

Yoshito Terao, Tetsuya Satoh, Masahiro Miura,* and Masakatsu Nomura

Department of Applied Chemistry, Faculty of Engineering, Osaka University, Suita, Osaka 565-0871

(Received May 17, 1999)

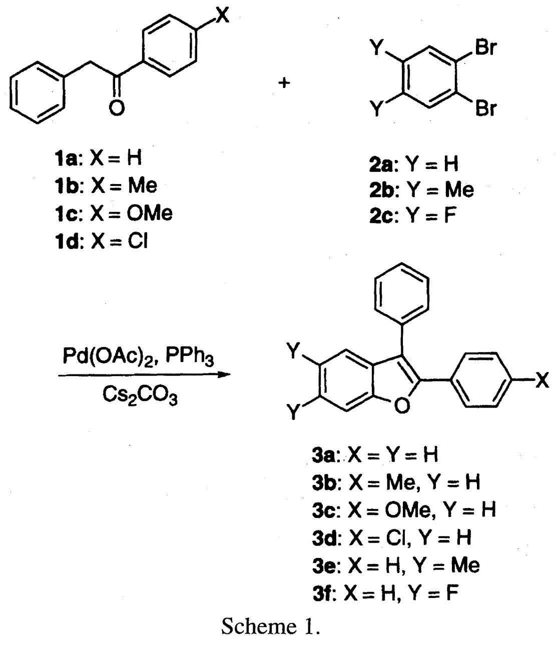
A number of carbonyl and phenolic compounds efficiently couple with *o*-dibromobenzenes in the presence of a palladium catalyst and a base to give the corresponding oxygen-containing heterocycles or carbocyclic compounds. Thus, from the reactions of benzyl phenyl ketones, 1-naphthols, and *α*,*β*-unsaturated aldehydes and ketones, benzofuran, benzopyran, benzocyclobutane, and indene derivatives, respectively, are produced selectively via the successive formation of C–C and C–O bonds or of two C–C bonds.

The palladium-catalyzed substitution reaction of aryl halides is now recognized to be of genuine synthetic utility. For example, the Heck reaction with alkenes and the Suzuki and Stille coupling reactions with organoboronates and organostannanes, respectively, are often employed for the preparation of substituted aromatic compounds.[1] Meanwhile, we have recently reported that benzyl ketones,[2a,2b] phenylacetic acid derivatives,[2b] 4-alkylnitrobenzenes,[2c] *α*,*β*-unsaturated aldehydes and ketones,[2d] and phenolic compounds[2a,2b,2e] can effectively undergo intermolecular arylation under conditions similar to those for the Heck reaction. In these reactions, a hydrogen existing on benzylic, allylic, or aromatic carbon is directly substituted by an aryl group without stoichiometric metalation. Such inter-[3,4a,4b] and intramolecular[5] arylation reactions of ketones, including aliphatic ones as well as amides,[4c] have also been described by Buchwald, Hartwig, and Muratake. It may be reasonable to consider that, when *o*-dibromobenzenes are used as arylation reagents for the above substrates, certain cyclic products can be directly obtained even in the intermolecular cases. Consequently, we investigated the catalytic reaction with the bromides.[6] As a result, benzofuran, benzopyran, benzocyclobutane, and indene derivatives have been found to be selectively obtained from the reactions of benzyl phenyl ketones, 1-naphthols, and *α*,*β*-unsaturated aldehydes and ketones, respectively. While the methods for the construction of these nuclei by means of palladium catalysis have been reported,[7—9] the present routes using *o*-dibromobenzenes may be useful as complements, since they utilize readily available starting materials.

Results and Discussion

Reaction of Benzyl Ketones. When benzyl phenyl ketone (**1a**) (1 mmol) was treated with *o*-dibromobenzene (**2a**) (1 mmol) in the presence of $Pd(OAc)_2$ (0.05 mmol, 5 mol%), PPh_3 (0.2 mmol), and Cs_2CO_3 (2 mmol) in refluxing *o*-xylene for 1.5 h, a cross-coupling product, 2,3-diphenylbenzo[*b*]furan (**3a**), was quantitatively formed (Scheme 1 and Entry 1 in Table 1). Such a high yield coupling was also achieved by using a reduced amount of the palladium species (0.01 mmol) or a less effective base, K_2CO_3, in place of Cs_2CO_3, or at a lower temperature of 120 °C, while a longer reaction time was required (Entries 2—4). The reaction was, however, sluggish in a polar solvent such as DMF (Entry 5).

Table 2 summarizes the results for the reactions of aryl benzyl ketones **1b**—**d** with **2a** and of **1a** with substituted *o*-dibromobenzenes **2b**,**c**. From all of the reactions, the expected furans **3b**—**f** were obtained in fair to excellent yields. In contrast to the reaction of aryl benzyl ketones **1**, dibenzyl ketone (**4**) reacted with **2a** under similar conditions, forming two C–C bonds to give 1,3-diphenyl-2-indanone (**5**) in 64%



Scheme 1.

Table 1. Reaction of Benzy Phenyl Ketone (**1a**) with *o*-Dibromobenzene (**2a**)[a)]

Entry	Base	Bath temp	Time	Yield[b)]
		°C	h	%
1	Cs_2CO_3	160	1.5	100(78)
2[c)]	Cs_2CO_3	160	5	100
3	K_2CO_3	160	24	100
4	Cs_2CO_3	120	22	100
5[d)]	Cs_2CO_3	120	24	8

a) Reaction coditions: **1a** (1 mmol), **2a** (1 mmol), $Pd(OAc)_2$ (0.05 mmol), PPh_3 (0.2 mmol), Base (2 mmol), in *o*-xylene (5 cm^3). b) GLC yield based on amount of **1a** used. Value in parentheses indicates isolated yield. c) $Pd(OAc)_2$ (0.01 mmol) and PPh_3 (0.04 mmol) were used. d) DMF was used in place of *o*-xylene.

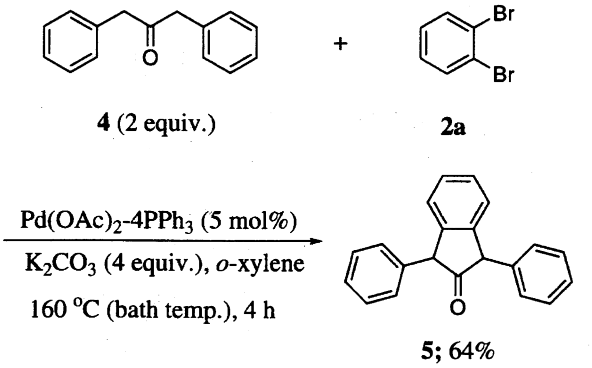
Table 2. Reaction of Benzyl Phenyl Ketones **1** with *o*-Dibromobenzenes **2**[a)]

1	**2**	Time/h	Product, Yield[b)]/%
1b	**2a**	4	**3b**, 100(74)
1c	**2a**	6	**3c**, 100(75)
1d	**2a**	2	**3d**, 56(49)
1a	**2b**	4	**3e**, 75(69)
1a	**2c**	2	**3f**, 57(40)

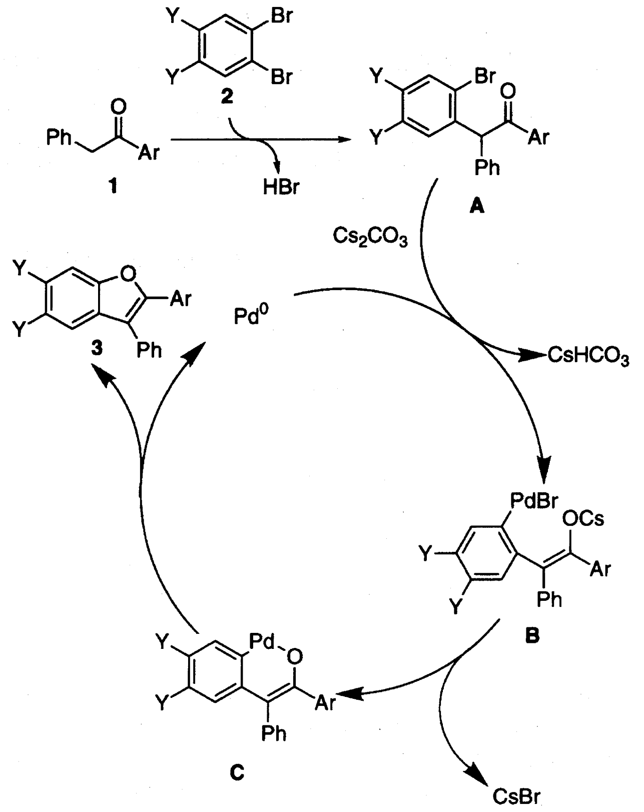
a) Reaction coditions: **1** (1 mmol), **2** (1 mmol), $Pd(OAc)_2$ (0.05 mmol), PPh_3(0.2 mmol), Cs_2CO_3 (2 mmol), in *o*-xylene (5 cm^3) at 160 °C (bath temp). b) GLC yield based on amount of **1** used. Value in parentheses indicates isolated yield.

yield (Scheme 2). No product having a C–O bond similar to **3** could be detected.

A plausible reaction sequence for the coupling of **1** with **2** is illustrated in Scheme 3, in which neutral ligands are omitted. As a control experiment, a mixture of **1a** (1 mmol), **2a** (1 mmol), and a reduced amount of Cs_2CO_3 (1 mmol) was heated in the presence of $Pd(OAc)_2$–$4PPh_3$ (5 mol%) in refluxing *o*-xylene for 2 h. It was confirmed that the expected monobromide (**A**; X = H, Ar = Ph) (44%) was formed together with **3a** (53%). This may indicate that the arylation first occurs at the benzylic position of **1**, forming a C–C bond by the mechanism proposed previously.[2b,3,4] Then, the next C–O bond formation may occur as follows: Oxidative addition of the remaining C–Br bond in **A** to palladium(0) species existing in the medium gives arylpalladium species **B**. This is transformed to arylpalladium enolate **C**, and the subsequent reductive elimination affords product **3**. It should be noted that such a reductive elimination, forming a C–O bond, in palladium-catalyzed arylation reactions is generally recognized to be less common,[1] while it has been recently demonstrated that, by using palladium complexes having sterically bulky mono- or bidentate ligands, aryl halides can be effectively coupled with alcohols and phenols to give aryl ethers.[7g,10] Nevertheless, as can be seen from the reactions using phenolic substrates described below, even using a normal ligand such as PPh_3, reductive elimination to produce cyclic ethers may be considered to be not a very difficult process. The result of the reaction using **4**, exclusively giving indanone **5**, however, suggests that, when both *C*- and *O*-arylations of an enol are geometrically of equal possibility in an intramolecular case, the former preferably takes place.[5]

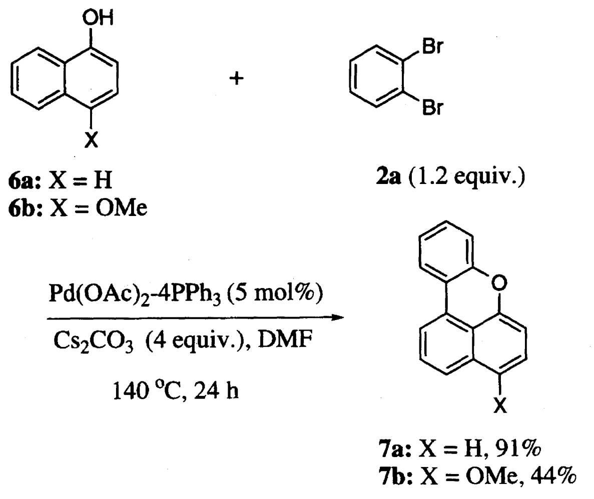


Scheme 2.

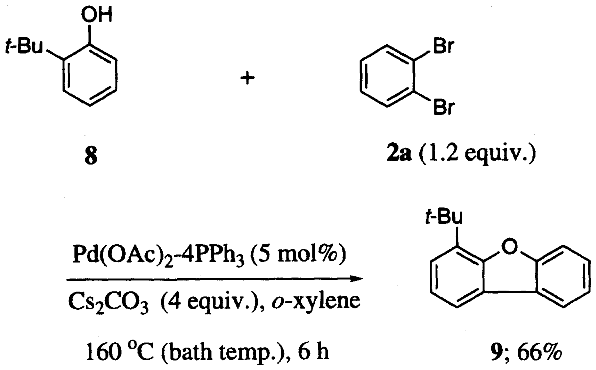


Scheme 3.

Reaction of Phenolic Compounds. The successive formation of C–C and C–O bonds was also observed in the reaction of certain phenolic substrates in place of **1**. Thus, when 1-naphthols **6a** and **6b** were treated with **2a** (1.2 equiv) in the presence of $Pd(OAc)_2$–$4PPh_3$ (5 mol%) and Cs_2CO_3 (4 equiv) in DMF at 140 °C for 24 h, the corresponding benzo[*b*]naphtho[1,8-*de*]pyrans **7a** and **7b** were produced in 91 and 44% yields, respectively (Scheme 4). The reaction of 2-*t*-butylphenol (**8**) with **2a** proceeded smoothly under similar conditions in refluxing *o*-xylene to afford 4-*t*-butyldibenzofuran (**9**) in a yield of 66% (Scheme 5). However, the reaction using 2-naphthol was unsuccessful in both DMF



Scheme 4.



Scheme 5.

and *o*-xylene.

The first step of the reactions of **6** and **8** seems to be the introduction of a 2-bromophenyl group at the 8 and 6 positions, respectively, which are spatially neighboring to their phenolic function, as in the simple arylations of these substrates with bromo- and iodobenzenes.[2a,2b,2e] The former may proceed via a diarylpalladium complex **D** formed by the coordination-assisted C–H activation by 2-bromophenylpalladium intermediate, while the latter may involve nucleophilic attack of the corresponding phenolate anion to the intermediate to give **E** (Chart 1). The final ring closure by C–O bond formation to give either **7** or **9** may occur in a similar way to that in Scheme 3.

Reaction of α,β-Unsaturated Carbonyl Compounds. The treatment of (*E*)-2-ethyl-2-hexenal (**10a**) (2 mmol) with **2a** (1 mmol) in the presence of $Pd(OAc)_2$ (0.05 mmol), PPh_3 (0.1 mmol), and Cs_2CO_3 (2 mmol) in DMF at 80 °C for 6 h afforded a small amount of 2-(2-ethylbenzocyclobutylidene)butanal (**11a**) (Scheme 6 and Entry 1 in Table 3). The use of a sterically bulky phosphine, $P(t\text{-}Bu)_3$,[10b,11] in place of PPh_3 was found to dramatically improve the product yield to 95% (Entry 3), while $P(o\text{-}tolyl)_3$ was ineffective (Entry 2). The ^{1}H NMR spectrum of the product after purification by column chromatography indicated that **11a** was produced as a mixture of its (*E*)- and (*Z*)-isomers in a ratio of 94 : 6. In contrast to the case of **1** described above, this reaction did not proceed at all in a less polar solvent such as toluene; no cross-coupling products could be detected by GLC-MS. In the presence of $Pd(OAc)_2$–$P(t\text{-}Bu)_3$, the reactions of (*E*)-2-methyl-2-pentenal (**10b**) with **2a** and of **10a** with **2b** afforded the corresponding benzocyclobutanes **11b** and **11c** as (*E*)/(*Z*) mixtures in 64 and 60% yields, respectively (Entries 4 and 5).

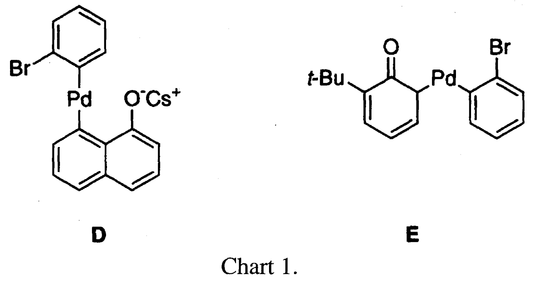
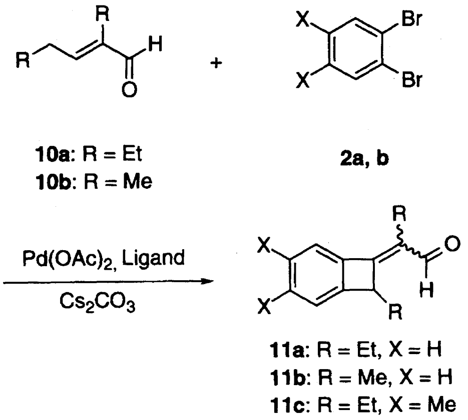


Chart 1.

While the use of $P(t\text{-}Bu)_3$ as ligand was essential for a high yield coupling in the case of **10**, the reaction of isophorone (**12**) with **2** could take place effectively in the presence of $Pd(OAc)_2$–PPh_3. In this case, not four-membered but five-membered cyclization occurred. Thus, the treatment of **12** (2 mmol) with **2a** and **2b** (1 mmol) using Cs_2CO_3 (4 mmol) at 80 °C gave the corresponding indene derivatives **13a** and **13b** in 94 and 80% yields, respectively (Scheme 7). Verbenone (**14**) also coupled with **2a** to afford compound **15** in 62% yield (Scheme 8).

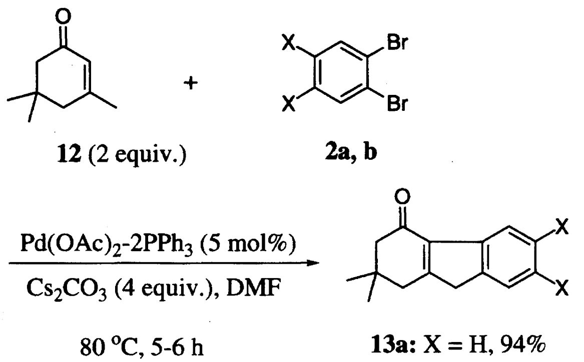


Scheme 6.

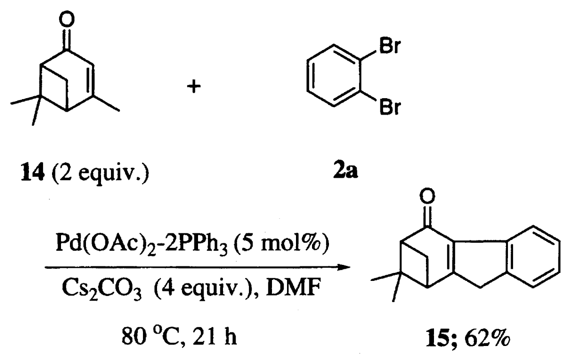
Table 3. Reaction of 2-Substituted 2-Alkenals **10** with *o*-Dibromobenzenes **2**[a)]

Entry	10	2	Ligand	Time/h	Product, Yield[b)]/%
1	**10a**	**2a**	PPh_3	6	**11a**, 12
2	**10a**	**2a**	$P(o\text{-}tolyl)_3$	6	n. d.
3	**10a**	**2a**	$P(t\text{-}Bu)_3$	2.5	**11a**,[c)] 95(77)
4[d)]	**10b**	**2a**	$P(t\text{-}Bu)_3$	2	**11b**,[e)] 64(45)
5	**10a**	**2b**	$P(t\text{-}Bu)_3$	4	**11c**,[f)] 60(50)

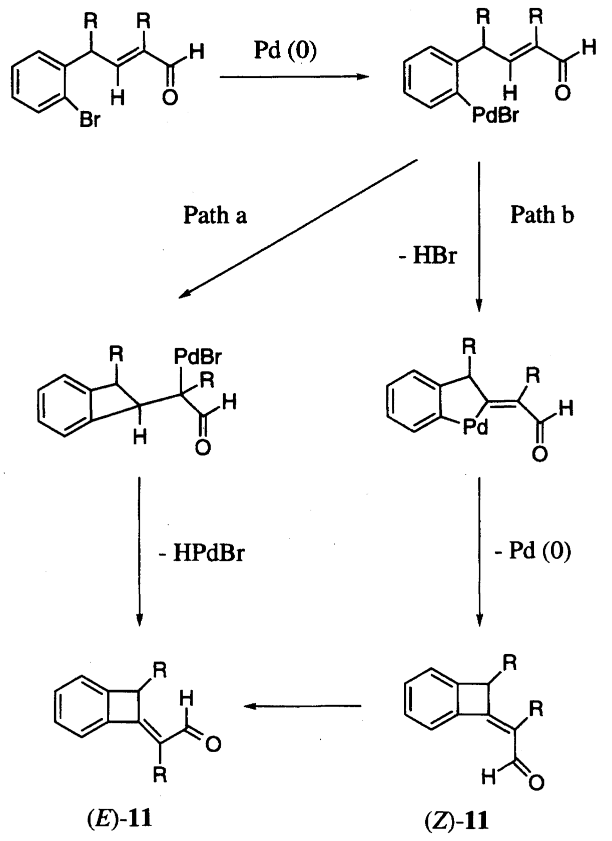
a) Reaction conditions: **10** (2 mmol), **2** (1 mmol), $Pd(OAc)_2$ (0.05 mmol), ligand (0.1 mmol), Cs_2CO_3 (2 mmol), in DMF (5 cm^3) at 80 °C. b) GLC yield based on amount of **2** used. Value in parentheses indicates isolated yield. c) $E:Z = 94:6$. d) $Pd(OAc)_2$ (0.1 mmol) and $P(t\text{-}Bu)_3$ (0.2 mmol) were used. e) $E:Z = 96:4$. f) $E:Z = 93:7$.



Scheme 7.



Scheme 8.



Scheme 9.

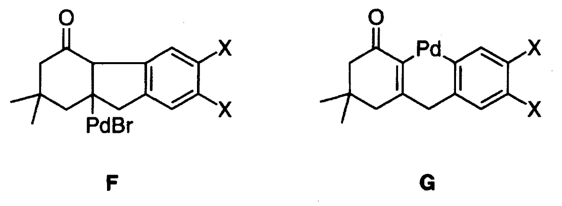


Chart 2.

In the reactions of α,β-unsaturated carbonyl compounds **10**, **12**, and **14** with **2**, the first stage may involve C–C coupling at their γ-position of carbonyl function, since the reactions of these carbonyl compounds with bromobenzene itself selectively occur at the position under similar conditions.[2d] Then, in the case using **10**, the second C–C bond formation at the β-position may occur via either Heck-type insertion of the olefinic moiety (Path a in Scheme 9) or C–H activation at the β-position (Path b).[12] Although the preferential formation of the (*E*)-isomer of **11** seems to be consistent with the former mechanism, the latter one can not be ruled out, since isomerization of the (*Z*)-compound to (*E*)-isomer may occur under the basic conditions employed.

In the cases using **12** and **14**, there seems to be no reasonable paths leading to cyclobutanes in the second C–C bond formation, since no hydrogen for β-hydrogen elimination or cyclopalladation exists at their β-position. This may be one of the major reasons that the annulation takes place not at the β-position, but at the α-position to give **13** and **15**. Thus, the cyclization reaction by C–C bond formation may proceed via either complex **F** or **G** (Chart 2). However, the precedence of **F** and **G** is not definitive at the present stage, as for the reaction of **10**.

Experimental

^{1}H and ^{13}C NMR spectra were recorded on a JEOL JNM-GSX spectrometer at 400 and 100 MHz or on a varian UNITY-INOVA 600 at 600 and 150 MHz, respectively, for $CDCl_3$ solutions. GLC-MS data were obtained with a Shimadzu QP-5050 spectrometer or with a JEOL JMC-DX-303 spectrometer. GLC analysis was carried out using a Shimadzu GC 8A gas chromatograph equipped with a Silicone OV-17 glass column (ϕ2.6 mm × 1.5 m). Aryl benzyl ketones **1b**—**d** were prepared by the Friedel–Crafts reaction of toluene, anisole, and chlorobenzene using phenylacetyl chloride and anhydrous aluminum chloride with or without 1,2-dichloroethane as solvent at room temperature. The other starting materials were commercially available. The solvents employed were purified by standard methods before use. The structures of all new products were unambiguously determined by ^{1}H and ^{13}C NMR with the aid of NOESY, COSY, and COLOC experiments.

General Procedure for the Reaction of Carbonyl or Phenolic Compounds with *o*-Dibromobenzenes. In a 100 cm^3 two-necked flask was placed a base (1—4 mmol), which was then dried at 150 °C in vacuo for 2 h. Then, $Pd(OAc)_2$ (0.01—0.1 mmol), a phosphine (0.04—0.2 mmol), a carbonyl or phenolic compound (1—2 mmol), **2** (1 mmol), and *o*-xylene or DMF (5 cm^3) were added. The resulting mixture was stirred under N_2 at 80—160 °C (bath temperature) for 1.5—24 h. After cooling, the reaction mixture was extracted with diethyl ether and dried over sodium sulfate. The product was isolated by column chromatography on silica gel using hexane-diethyl ether as eluent.

2,3-Diphenylbenzo[*b*]furan (3a):[13] Mp 123—123.5 °C; ^{1}H NMR δ = 7.23 (t, J = 7.3 Hz, 1H), 7.28—7.35 (m, 4H), 7.38—7.52 (m, 6H), 7.55 (d, J = 8.3, 1H), 7.65—7.67 (m, 2H); ^{13}C NMR δ = 111.10, 117.50, 120.02, 122.90, 124.67, 127.02, 127.61, 128.33, 128.41, 128.96, 129.77, 130.24, 130.67, 132.85, 150.53, 153.99; MS m/z 270 (M$^+$).

2-(4-Methylphenyl)-3-phenylbenzo[*b*]furan (3b):[14] Mp 97—97.5 °C; ^{1}H NMR δ = 2.35 (s, 3H), 7.12 (d, J = 8.3 Hz, 2H), 7.23 (t, J = 7.3 Hz, 1H), 7.31 (dt, J = 1.5, 7.4 Hz, 1H), 7.39—7.56 (m, 9H); ^{13}C NMR δ = 21.34, 111.02, 116.80, 119.87, 122.83, 124.44, 126.97, 127.50, 127.84, 128.91, 129.15, 129.77, 130.30, 133.01, 138.38, 150.83, 153.91; MS m/z 284 (M$^+$). Found: C, 88.36; H, 5.59%. Calcd for $C_{21}H_{16}O$: C, 88.70; H, 5.67%.

2-(4-Methoxyphenyl)-3-phenylbenzo[*b*]furan (3c): Mp 98.5—99 °C; ^{1}H NMR δ = 3.81 (s, 3H), 6.83—6.86 (m, 2H), 7.22 (t, J = 7.3 Hz, 1H), 7.30 (dt, J = 1.5, 7.4 Hz, 1H), 7.37—7.54 (m, 7H), 7.57—7.61 (m, 2H); ^{13}C NMR δ = 55.26, 110.93, 113.90, 115.98, 119.71, 122.80, 123.30, 124.22, 127.44, 128.49, 128.92, 129.78, 130.35, 133.07, 150.72, 153.84, 159.71; MS m/z 300 (M$^+$). Found: C, 83.97; H, 5.37%. Calcd for $C_{21}H_{16}O_2$: C, 83.98%; H, 5.37.

2-(4-Chlorophenyl)-3-phenylbenzo[*b*]furan (3d): Mp 99—100 °C; ^{1}H NMR δ = 7.22—7.30 (m, 3H), 7.34 (dt, J = 1.5, 7.4 Hz, 1H), 7.41—7.50 (m, 6H), 7.55 (d, J = 8.3 Hz, 1H), 7.57—7.59 (m, 2H); ^{13}C NMR δ = 111.12, 117.99, 120.11, 123.06, 124.95, 127.84, 128.16, 128.69, 129.08, 129.14, 129.67, 130.11, 132.51, 134.18, 149.36, 153.97; MS m/z 304, 306 (M$^+$). Found: C, 78.53; H, 4.28; Cl, 11.60%. Calcd for $C_{20}H_{13}ClO$: C, 78.82; H, 4.30; Cl, 11.63%.

5,6-Dimethyl-2,3-diphenylbenzo[*b*]furan (3e):[15] Mp 144—145 °C; ^{1}H NMR δ = 2.31 (s, 3H), 2.39 (s, 3H), 7.22—7.31 (m, 4H), 7.33 (s, 1H), 7.38—7.50 (m, 5H), 7.62 (d, J = 6.8 Hz, 2H); ^{13}C NMR δ = 20.11, 20.67, 111.47, 117.11, 119.90, 126.65, 127.31, 127.83, 127.99, 128.19, 128.75, 129.60, 130.82, 131.36, 133.09, 133.73, 149.52, 152.72; MS m/z 298 (M$^+$). Found: C, 88.44; H, 6.12%. Calcd for $C_{22}H_{18}O$: C, 88.56; H, 6.08%.

5,6-Difluoro-2,3-diphenylbenzo[*b*]furan (3f): Mp 123—123.5 °C; ^{1}H NMR δ = 7.23 (dd, J = 7.8, 10.3 Hz, 1H), 7.29—7.32 (m, 3H), 7.36 (dd, J = 6.3, 9.7 Hz, 1H), 7.40—7.49 (m, 5H), 7.59—7.62 (m, 2H); ^{13}C NMR δ = 100.33 (d, $J_{C\text{–}F}$ = 22.0 Hz), 106.77 (d, $J_{C\text{–}F}$ = 20.2 Hz), 117.31—117.36 (m), 125.79—125.87 (m), 126.82, 128.03, 128.50, 128.67, 129.17, 129.51, 130.05, 131.94, 148.24 (dd, $J_{C\text{–}F}$ = 14.7, 241.7 Hz), 148.76 (d, $J_{C\text{–}F}$ = 11.0 Hz), 148.95 (dd, $J_{C\text{–}F}$ = 15.6, 246.3 Hz), 152.26 (d, $J_{C\text{–}F}$ = 4.6 Hz); MS m/z 306 (M$^+$). Found: C, 78.15; H, 3.96%. Calcd for $C_{20}H_{12}F_2O$: C, 78.42; H, 3.95%.

1,3-Diphenyl-2-indanone (5):[16] Mp 149—150 °C; ^{1}H NMR δ = 4.82 (s, 2H), 7.14 (d, J = 7.1 Hz, 4H), 7.22—7.37 (m, 10H); ^{13}C NMR δ = 59.05, 125.67, 127.14, 128.14, 128.54, 128.72, 137.84, 140.64, 212.63; MS m/z 284 (M$^+$). Found: C, 88.43; H, 5.68%. Calcd for $C_{21}H_{16}O$: C, 88.70; H, 5.67%.

Benzo[*b*]naphtho[1,8-*de*]pyran (7a): Mp 103—104 °C; ^{1}H NMR δ = 6.91 (dd, J = 2.0, 6.6 Hz, 1H), 7.07—7.12 (m, 2H), 7.27 (t, J = 7.6 Hz, 1H), 7.31—7.37 (m, 2H), 7.40 (t, J = 7.8 Hz, 1H), 7.56 (d, J = 7.6 Hz, 1H), 7.58 (d, J = 7.8 Hz, 1H), 7.82 (dd, J = 1.2, 7.5 Hz, 1H); ^{13}C NMR δ = 107.81, 113.97, 117.08, 119.64, 120.49, 121.53, 122.64, 123.23, 125.51, 126.87, 127.11, 127.16, 129.64, 134.80, 150.83, 151.83; MS m/z 218 (M$^+$). Found: C, 87.97; H, 4.80%. Calcd for $C_{16}H_{10}O$: C, 88.05; H, 4.62%.

4-Methoxybenzo[*b*]naphtho[1,8-*de*]pyran (7b): Mp 150—151 °C; ^{1}H NMR δ = 3.96 (s, 3H), 6.74 (d, J = 8.3 Hz, 1H), 6.85 (d, J = 8.3 Hz, 1H), 7.04 (dd, J = 1.0, 8.3 Hz, 1H), 7.07 (t, J = 7.3 Hz, 1H), 7.26 (dt, J = 1.7, 6.8 Hz, 1H), 7.42 (dd, J = 7.3, 8.8 Hz, 1H), 7.63 (d, J = 6.8 Hz, 1H), 7.82 (dd, J = 1.5, 7.9 Hz, 1H), 7.91 (d, J = 8.3 Hz, 1H); ^{13}C NMR δ = 55.76, 105.16, 106.63, 114.99, 117.01, 120.09, 120.38, 122.24, 122.75, 122.99, 126.09, 126.72, 126.98, 129.79, 144.77, 149.03, 152.33; MS m/z 218 (M$^+$). Found: C, 82.24; H, 4.98%. Calcd for $C_{17}H_{12}O_2$: C, 82.24; H, 4.87%.

4-(*t*-Butyl)dibenzofuran (9): Oil; ^{1}H NMR δ = 1.25 (s, 9H), 7.26 (t, J = 7.3, 7.8 Hz, 1H), 7.33 (t, J = 7.3 Hz, 1H), 7.38 (dd, J = 1.2, 7.6 Hz, 1H), 7.45 (t, J = 1.2, 7.6 Hz, 1H), 7.60 (dt, J = 8.3 Hz, 1H), 7.82 (dd, J = 1.2, 7.6 Hz, 1H), 7.94 (d, J = 7.3 Hz, 1H); ^{13}C NMR δ = 29.81, 34.50, 111.58, 118.39, 120.44, 122.42, 122.58, 123.82, 124.24, 124.49, 126.78, 135.19, 154.47, 155.66. HRMS Found: m/z (M$^+$) 224.1206. Calcd for $C_{16}H_{16}O$: M, 224.1201.

2-(2-Ethylbenzocyclobutylidene)butanal (11a) ($E : Z$ = 94 : 6): Oil; ^{1}H NMR δ = 1.05 (t, J = 7.6 Hz, 3H), 1.12 (t, J = 7.6 Hz, 3H), 1.76—1.84 (m, 1H), 2.12—2.18 (m, 1H), 2.51 (q, J = 7.6 Hz, 2H), 4.12 (dd, J = 4.1, 4.6 Hz, 1H, Z), 4.36 (dd, J = 4.4, 4.6 Hz, 1H, E), 7.32—7.40 (m, 4H), 9.87 (s, 1H, E), 10.26 (s, 1H, Z). HRMS Found: m/z (M$^+$) 200.1198. Calcd for $C_{14}H_{16}O$: M, 200.1201.

2-(2-Methylbenzocyclobutylidene)propanal (11b) ($E : Z$ = 96 : 4): Oil; ^{1}H NMR δ = 1.62 (d, J = 6.8 Hz, 3H), 2.02 (s, 3H), 4.16 (dd, J = 6.9, 7.1 Hz, 1H, Z), 4.44 (dd, J = 7.0, 7.1 Hz, 1H, E), 7.26—7.40 (m, 4H), 9.91 (s, 1H, E), 10.27 (s, 1H, Z); MS m/z 160 (M$^+$). Found: C, 83.64; H, 7.12%. Calcd for $C_{12}H_{12}O$: C, 83.69; H, 7.02%.

2-(2-Ethyl-4,5-dimethylbenzocyclobutylidene)butanal (11c) ($E : Z$ = 93 : 7): Oil; ^{1}H NMR δ = 1.04 (t, J = 7.3, 7.8 Hz, 3H), 1.11 (t, J = 7.3, 7.8 Hz, 3H), 1.75—1.80 (m, 1H), 2.09—2.15 (m, 1H), 2.30 (s, 3H), 2.33 (s, 3H), 2.49 (q, J = 7.8 Hz, 2H), 4.06 (dd, J = 4.1, 4.8 Hz, 1H, Z), 4.30 (dd, J = 4.1, 4.7 Hz, 1H, E), 7.12 (s, 1H), 7.15 (s, 1H), 9.83 (s, 1H, E), 10.22 (s, 1H, Z); MS m/z 228 (M$^+$). Found: C, 84.18; H, 9.04%. Calcd for $C_{16}H_{20}O$: C, 84.16; H, 8.83%.

1,2,3,9-Tetrahydro-2,2-dimethylfluoren-4(1*H*)-one (13a): Oil; ^{1}H NMR δ = 1.13 (s, 6H), 2.43 (s, 2H), 2.64 (s, 2H), 3.52 (s, 2H), 7.21 (dt, J = 1.0, 7.6 Hz, 1H), 7.32 (t, J = 7.3, 7.8 Hz, 1H), 7.42 (d, J = 7.3 Hz, 1H), 8.09 (d, J = 7.8 Hz, 1H); ^{13}C NMR δ = 28.55, 35.53, 40.94, 41.92, 52.65, 122.28, 123.45, 125.20, 126.82, 135.50, 140.35, 141.05, 164.67, 196.26. HRMS Found: m/z (M$^+$) 212.1194. Calcd for $C_{15}H_{16}O$: M, 212.1201.

1,2,3,9-Tetrahydro-2,2,6,7-tetramethylfluoren-4(1*H*)-one (13b): Mp 141—142 °C; ^{1}H NMR δ = 1.11 (s, 6H), 2.29 (s, 3H), 2.31 (s, 3H), 2.40 (s, 2H), 2.59 (s, 2H), 3.45 (s, 2H), 7.19 (s, 1H), 7.87 (s, 1H); ^{13}C NMR δ = 19.86, 19.97, 28.51, 29.68, 35.54, 40.94, 41.55, 52.65, 123.22, 124.72, 133.45, 135.01, 135.43, 138.18, 138.71, 164.09, 196.34; MS m/z 240 (M$^+$). Found: C, 84.69; H, 8.28%. Calcd for $C_{17}H_{20}O$: C, 84.96; H, 8.39%.

1,2,3,9-Tetrahydro-1,3-methano-2,2-dimethylfluoren-4(1*H*)-one (15): Oil; ^{1}H NMR δ = 0.95 (s, 3H), 1.60 (s, 3H), 2.39 (d, J = 9.3 Hz, 1H), 2.81 (t, J = 5.4, 5.9 Hz, 1H), 2.94 (t, J = 5.4, 5.9 Hz, 1H), 3.03—3.08 (m, 1H), 3.53 (d, J = 24.4 Hz, 1H), 3.71 (d, J = 23.9 Hz, 1H), 7.19—7.23 (dt, J = 1.0, 7.8 Hz, 1H), 7.34 (d, J = 7.3, 7.8 Hz, 1H), 7.45 (d, J = 7.8 Hz, 1H), 7.95 (d, J = 7.3 Hz, 1H); ^{13}C NMR δ = 22.63, 26.97, 40.62, 42.98, 45.52, 58.20, 58.79, 121.72, 123.74, 124.90, 126.93, 133.85, 139.63, 141.65, 174.62, 199.36. HRMS Found: m/z (M$^+$) 224.1195. Calcd for $C_{16}H_{16}O$: M, 224.1201.

This work was partly supported by a Grant-in-aid for Scientific Research from the Ministry of Education, Science, Sports and Culture. We thank Ms. Y. Miyaji and Ms. T. Muneishi of Instrumental Analysis Center, Osaka University for helpful assistance in obtaining NMR spectra.

References

1 a) R. F. Heck, "Palladium Reagents in Organic Syntheses," Academic Press, New York (1985). b) A. de Meijere and F. E. Meyer, *Angew. Chem., Int. Ed. Engl.*, **33**, 2379 (1994). c) J. Tsuji, "Palladium Reagents and Catalysts," Wiley, Chichester (1995). d) "Metal-Catalyzed Cross Coupling Reactions," ed by P. J. Stang and F. Diederich, Wiley-VCH, Weinheim (1997).

2 a) T. Satoh, Y. Kawamura, M. Miura, and M. Nomura, *Angew. Chem., Int. Ed. Engl.*, **36**, 1740 (1997). b) T. Satoh, J.-I. Inoh, Y. Kawamura, Y. Kawamura, M. Miura, and M. Nomura, *Bull. Chem. Soc. Jpn.*, **71**, 2239 (1998). c) J.-I. Inoh, T. Satoh, S. Pivsa-Art, M. Miura, and M. Nomura, *Tetrahedron Lett.*, **39**, 4673 (1998). d) Y. Terao, T. Satoh, M. Miura, and M. Nomura, *Tetrahedron Lett.*, **39**, 6203 (1998). e) Y. Kawamura, T. Satoh, M. Miura, and M. Nomura, *Chem. Lett.*, **1998**, 931.

3 a) M. Palucki and S. L. Buchwald, *J. Am. Chem. Soc.*, **119**, 11108 (1997). b) J. Ahman, J. P. Wolfe, M. V. Troutman, M. Palucki, and S. L. Buchwald, *J. Am. Chem. Soc.*, **120**, 1918 (1998).

4 a) B. C. Hamann and J. F. Hartwig, *J. Am. Chem. Soc.*, **119**, 12382 (1997). b) M. Kawatsura and J. F. Hartwig, *J. Am. Chem. Soc.*, **121**, 1473 (1999). c) K. H. Shaughnessy, B. C. Hamann, and J. F. Hartwig, *J. Org. Chem.*, **63**, 6546 (1998).

5 a) H. Muratake, A. Hayakawa, and M. Natsume, *Tetrahedron Lett.*, **38**, 7577 (1997). b) H. Muratake and M. Natsume, *Tetrahedron Lett.*, **38**, 7581 (1997).

6 Palladium-catalyzed coupling reactions of *o*-dibromobenzene with alkenes[a)] and alkynes[b)] to produce cyclic compounds. a) A. de Meijere, Z. Z. Song, A. Lansky, S. Hyuda, K. Rauch, M. Noltemeyer, B. König, and B. Knieriem, *Eur. J. Org. Chem.*, **1998**, 2289. b) J. A. John and J. M. Tour, *Tetrahedron*, **53**, 15515 (1997).

7 For benzofurans and/or benzopyrans: a) D. E. Ames and A. Opalko, *Synthesis*, **1983**, 234. b) T. Hosokawa and S.-I. Murahashi, *Acc. Chem. Res.*, **23**, 49 (1990). c) G. Dyker, *Angew. Chem., Int. Ed. Engl.*, **31**, 1023 (1992). d) G. Dyker, *J. Org. Chem.*, **58**, 6426 (1993). e) R. C. Larock, E. K. Yum, M. J. Doty, and K. K. C. Sham, *J. Org. Chem.*, **60**, 3270 (1995). f) A. Arcadi, S. Cacchi, M. D. Rosario, G. Fabrizi, and F. Marinelli, *J. Org. Chem.*, **61**, 9280 (1996). g) M. Palucki, J. P. Wolfe, and S. L. Buchwald, *J. Am. Chem. Soc.*, **118**, 10333 (1996). h) D. D. Hennings, S. Iwasa, and V. H. Rawal, *J. Org. Chem.*, **62**, 2 (1997).

8 For benzocyclobutanes: a) J. C. Bradley and T. Durst, *J. Org. Chem.*, **56**, 5459 (1991). b) G. Dyker, *Angew. Chem., Int. Ed. Engl.*, **33**, 103 (1994). c) M. Catellani and L. Ferioli, *Synthesis*, **1996**, 769.

9 For indenes: a) B. M. Trost and R. Walchi, *J. Am. Chem. Soc.*, **109**, 3487 (1987). b) B. O'Connor, Y. Zhang, and E. Negishi, *Tetrahedron Lett.*, **29**, 3903 (1988). c) J. K. Mukhopadhyaya, S. Pal, and U. R. Ghatak, *Synth. Commun.*, **25**, 1641 (1995). d) G. Dyker and P. Grundt, *Tetrahedron Lett.*, **37**, 619 (1996). e) G. Dyker, F. Nerenz, P. Siemen, P. Bubenitschek, and P. G. Jones, *Chem. Ber.*, **129**, 1265 (1996). f) D. Bruyére, G. Gaignard, D. Bouyssi, and G. Balme, *Tetrahedron Lett.*, **38**, 827 (1997).

10 a) R. A. Widenhoefer and S. L. Buchwald, *J. Am. Chem. Soc.*, **120**, 6504 (1998). b) G. Mann, C. Incarvito, A. L. Rheingold, and J. F. Hartwig, *J. Am. Chem. Soc.*, **121**, 3224 (1999), and references therein.

11 a) M. Nishiyama, T. Yamamoto, and Y. Koie, *Tetrahedron Lett.*, **39**, 617 (1998). b) M. Miura, S. Pivsa-Art, G. Dyker, J. Heiermann, T. Satoh, and M. Nomura, *Chem. Commun.*, **1998**, 1889. c) A. F. Littke and G. C. Fu, *J. Org. Chem.*, **64**, 10 (1999).

12 G. Dyker, *Chem. Ber./Recueil*, **130**, 1567 (1997), and references therein.

13 A. Fürstner and D. N. Jumbam, *Tetrahedron*, **48**, 5991 (1992).

14 M. Bernard, L. Bernard, V. Joel, and C. Ernest, *Bull. Soc. Chim. Fr.*, **5**, 848 (1987).

15 J. B. M. Somers, A. Couture, A. Lablache-Combier, and W. H. Laarhoven, *J. Am. Chem. Soc.*, **107**, 1387 (1985).

16 H. Yoshida, H. Sano, T. Ogata, and K. Matsumoto, *Bull. Chem. Soc. Jpn.*, **61**, 4341 (1988).