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TETRAHEDRON

Multiple arylation of alkyl aryl ketones and α,β-unsaturated carbonyl compounds via palladium catalysis

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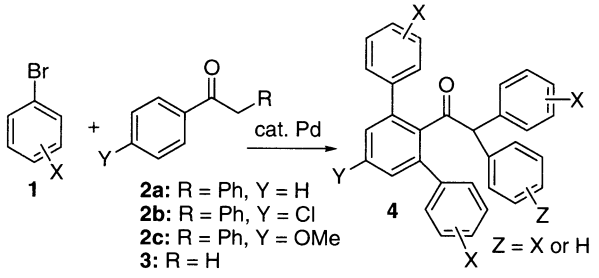
Abstract—Alkyl (ethyl to butyl) aryl ketones have been found to undergo multiple arylation on the alkyl chains accompanied by oxidative unsaturation upon treatment with excess aryl bromides in the presence of a palladium catalyst and a base. In the case of phenyl propyl ketones, for example, the arylation occurs up to five times on the α-and γ-positions as well as the *ortho*-position of the phenyl ring to give 1-(biphenyl-2-yl)-2,4,4,4-tetraphenyl-2-buten-1-ones along with other arylation products. A number of α,β-unsaturated carbonyl compounds are also arylated multiply on the α- and γ-positions.

1. Introduction

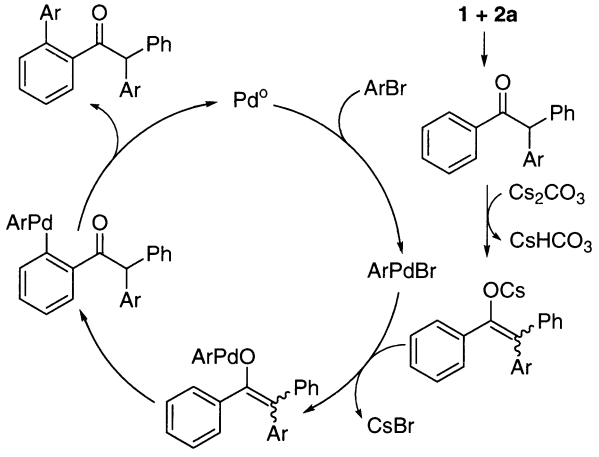
Palladium-catalyzed arylation reactions using aryl halides are now recognized to be highly useful for making aromatic fine compounds.[1,2] For example, the reaction of alkenes (the Mizoroki–Heck reaction) and that of organoboron compounds (the Suzuki–Miyaura reaction) are very often employed.

Meanwhile, it was recently reported by several groups including ours that ketones and α,β-unsaturated carbonyl compounds can effectively undergo arylation at their α-[3–6] and γ-positions,[3d,e,7,8] respectively, under the conditions similar to those for the Mizoroki–Heck reaction. The reaction is considered to involve the coupling of enolates or dienolates with arylpalladium species generated in situ. We also demonstrated that benzyl phenyl ketones (**2**) as well as acetophenone (**3**) undergo not only α-arylation, but also *ortho*-arylation to give diphenylmethyl 2,6-diphenylphenyl ketone and its derivatives **4** as the predominant products (Scheme 1).[3c] The latter arylation is considered to involve the coordination of enolate oxygen to arylpalladium species and the subsequent *ortho*-palladation as the key steps (Scheme 2).[9]

Since the sequential multiple arylation appears to be useful as a synthetic method of oligophenyl compounds,[10] we examined the reaction of other alkyl phenyl ketones with excess aryl bromides. It was found that ethyl, propyl and butyl phenyl ketones are multiply arylated on the alkyl groups accompanied by oxidative unsaturation and among the ketones, the propyl derivatives also undergo *ortho*-arylation. Consequently, the reaction of a number of α,β-unsaturated carbonyl compounds with excess aryl bromides has also been undertaken. The results are reported herein.



Scheme 1.



Scheme 2.

Keywords: aryl halides; arylation; carbonyl compounds; palladium and compounds.

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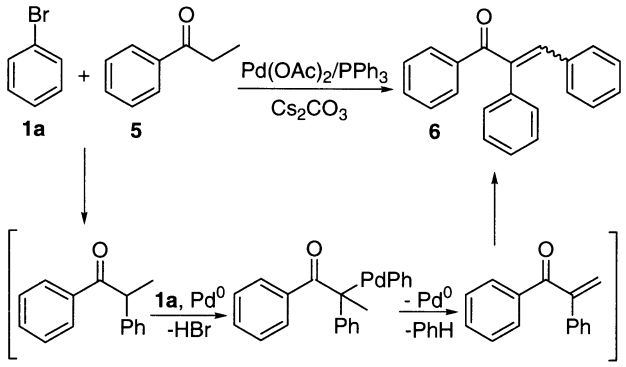


Scheme 3.

The reaction of butyrophenone (**7a**) with **1a** was found to produce a number of products. Thus, treatment of **7a** with 6 equiv. of **1a** in the presence of $Pd(OAc)_2$, PPh_3 and Cs_2CO_3 for 2 h gave a mixture of mono- **8**, tri- **9a** and **10**, tetra- **11** and pentaphenylated compounds **12a** in comparable yields (Scheme 4 and entry 6).

The (*E*)-stereochemistry of **11** and **12a** was determined by NOE experiments in the measurement of their ^1H NMR spectra. It is also noted that the double bond in **9a** does not conjugate with the carbonyl group, which may be due to the fact that it is thermodynamically more favorable than its double bond isomer. The reaction with 7.5 equiv. of **1a** for 23 h gave **11** and **12a** as the major products together with

Table 1. Arylation of aromatic ketones or aldehydes with aryl bromides

Entry	Bromide (mmol)	Ketone or aldehyde	$Pd(OAc)_2$ (mmol)	PR_3	Time (h)	Product(s); % yield[a]
1[b]	**1a** (4)	**2a**	–[c]	–	20	**4** (X=Y=Z=H); 61 (40)
2[b]	**1a** (4)	**2b**	–[c]	–	6	**4** (X=Z=H, Y=Cl); 65 (59)
3	**1a** (4)	**2c**	–[c]	–	71	**4** (X=Z=H, Y=OMe); 18
4	**1a** (5)	**3**	–[d]	–	49	**4** (X=Y=Z=H); 26
5	**1a** (4)	**5**	0.05	PPh_3	20	**6**; 59 [(*E*)/(*Z*)=2:1]
6	**1a** (6)	**7a**	0.1	PPh_3	2	**8**; 20, **9a**; 23, **10**; 12 (12), **11**; 30 (26), **12a**; (15)
7	**1a** (7.5)	**7a**	0.1	PPh_3	23	**10**; 11 (8), **11**; 37 (29), **12a**; (21)
8	**1a** (6)	**7a**	0.1	P(*o*-tolyl)$_3$	2	**8**;14, **9a**; 78
9	**1a** (6)	**7a**	0.1	P(*t*-Bu)$_3$	2	**8**; 78 (58), **9a**; 19
10	**1a** (4)	**7a**	0.075	P(*o*-tolyl)$_3$	4.5	**8**;12, **9a**; 81 (48)
11	**1b** (4)	**7a**	0.075	P(*o*-tolyl)$_3$	2	**9b**; 64 (41)[e]
12	**1c** (4)	**7a**	0.075	P(*o*-tolyl)$_3$	2	**9c**; 50 (34)[e]
13	**1a** (7.5)	**7b**	0.1	PPh_3	2	**12b**; (52)[e]
14	**1b** (7.5)	**7a**	0.1	P(4-F–C_6H_4)$_3$	23	**12c**; (26) [e]
15	**1b** (7.5)	**7b**	0.1	P(4-F–C_6H_4)$_3$	23	**12d**; (49)[e]
16	**1a** (7.5)	**13**	0.075	PPh_3	23	**14**; (28), **15**; (21)
17	**1a** (4)	**16**	0.025	PPh_3	5	**17**; (47)
18	**1a** (1)	**18**[f]	0.05	PPh_3	1.5	**19**; 45
19[g]	**1a** (1)	**18**[f]	0.05	PPh_3	0.5	**19**; 61 (44)

The reaction was carried out using 1 mmol of ketone in the presence of Cs_2CO_3 as base in refluxing *o*-xylene at a bath temperature of 160°C under nitrogen. [Bromide]=[Cs_2CO_3], [PR_3]/[$Pd(OAc)_2$]=4.

[a] Determined by GLC analysis. Value in parentheses indicates isolated yield.

[b] Taken from the data in Ref. 8.

[c] $Pd(PPh_3)_4$ (0.005 mmol) was used.

[d] $Pd(PPh_3)_4$ (0.01 mmol) was used.

[e] Other products were not characterized.

[f] 1.5 mmol of **18** was used.

[g] Reaction in DMF at 140°C.

2. Results and discussion

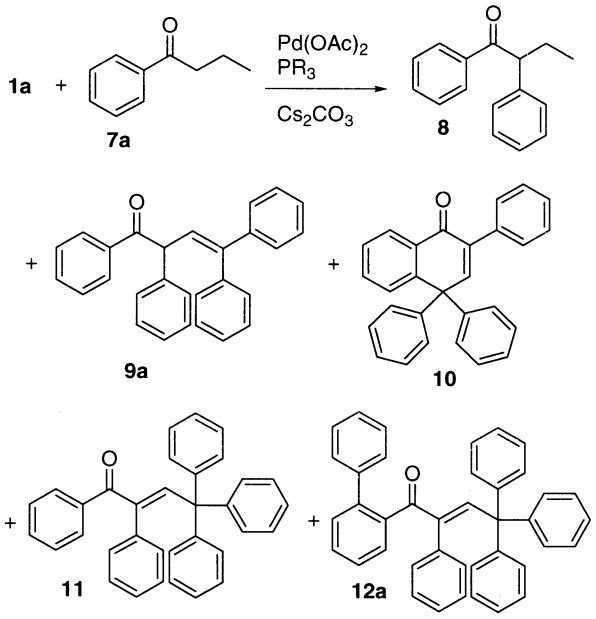
When propiophenone (**5**) (1 mmol) was treated with bromobenzene (**1a**) (4 mmol) in the presence of $Pd(OAc)_2$ (0.05 mmol) and PPh_3 (0.2 mmol) using Cs_2CO_3 (4 mmol) as base in refluxing *o*-xylene for 20 h, 1,2,3-triphenyl-2-propen-1-one (**6**) was produced in 59% yield with a (*E*)/(*Z*) ratio of 2:1 (Scheme 3 and entry 5 in Table 1).

The formation of **6** may be reasonably explained by the mechanism involving oxidative unsaturation.[11] After α-phenylation of **5**, the enolate from the primary product reacts with phenylpalladium bromide to form an alkylphenylpalladium intermediate. Then, elimination of PhPdH occurs to give 1,2-diphenyl-2-propen-1-one with the liberation of Pd(0) species and benzene. The α,β-unsaturated ketone undergoes second phenylation as in the usual reaction via carbopalladation.

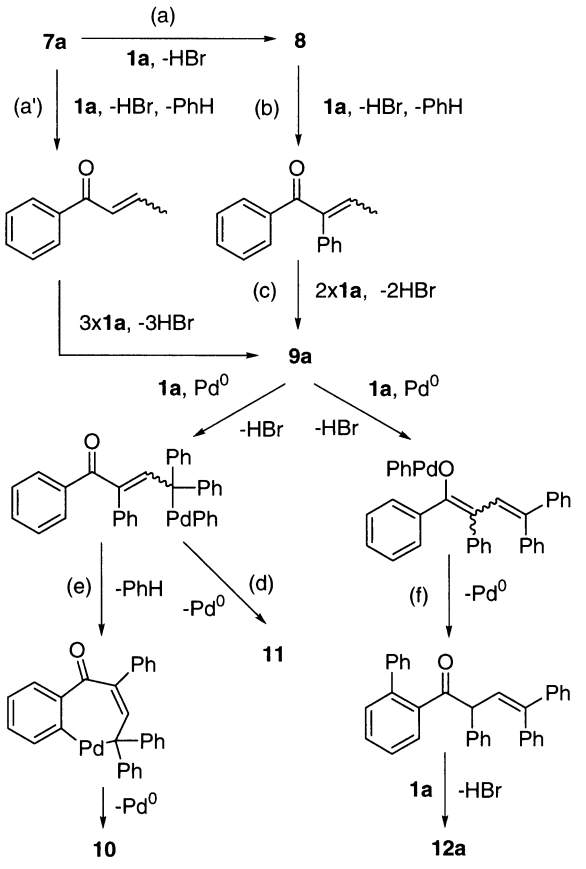
a minor amount of **10**, **8** and **9a** being almost completely disappeared (entry 7). It was of considerable interest that treatment of **7a** with 6 equiv. of **1a** using P(*o*-Tolyl)$_3$ and P(*t*-Bu)$_3$ in place of PPh_3 for 2 h afforded **9a** and **8**, respectively, as the predominant products (entries 8 and 9).

The above results indicate that the reaction of **7a** involves (a) α-phenylation leading to **8**, (b) oxidative unsaturation of **8**, (c) γ-diphenylation to **9a**, (d) further γ-phenylation of **9a** to **11**, (e) oxidative cyclization of **9a** to **10** and (f) *ortho*-phenylation of **9a** followed by γ-phenylation to **12a** (Scheme 5).

The lack of α,γ-diphenylated product implies that the γ-diphenylation [step (c)] is significantly fast. Compounds **10**–**12a** seem to be the end products, since they have no more active hydrogens that lead to enolates. The steps (b) and (d)–(f) can be suppressed selectively by selecting



Scheme 4.



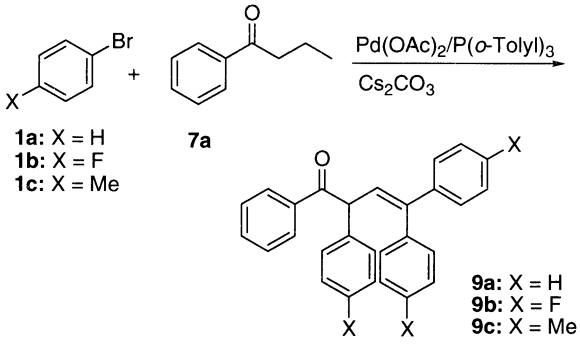
Scheme 5.

ligands appropriately. The steric bulkiness of ligands appears to be the major factor affecting the rate of the steps.[12]

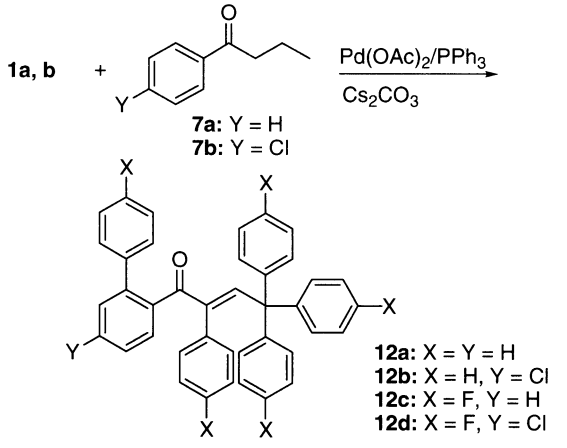
In expectation, from the reactions of **7a** with 4 equiv. of 4-fluoro- and 4-methylbromobenzenes, (**1b**) and (**1c**), as well as that with **1a**, using P(*o*-Tolyl)$_3$ as ligand were produced the corresponding triarylated products **9a–c** in substantial yields (Scheme 6 and entries 10–12).

To obtain some insight into factors affecting the penta-arylation leading to **12**, the reactions of 4-chlorophenyl propyl ketone (**7b**) with **1a** using PPh_3 and of **7a** and **b** with **1b** using P(4-FC_6H_4)$_3$[13] were carried out (Scheme 7 and entries 13–15).

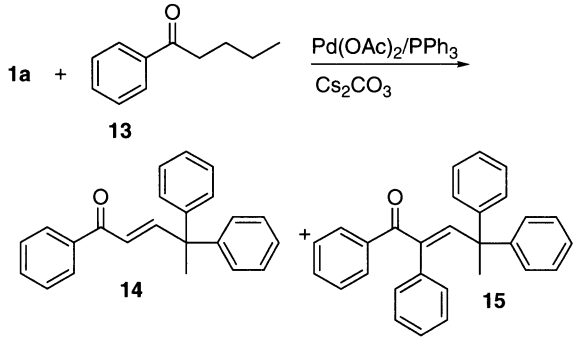
It was observed that **7b** affords considerably enhanced yields of **12** (entries 13 and 15 vs 7 and 14). This implies that the 4-chloro substituent enhances step (f) in Scheme 5 (*ortho*-arylation). It should be noted that in the reactions of benzyl phenyl ketones (**2**) with **1a**, the 4-chloro derivative **2b** (Y=Cl) also reacted considerably faster than **2a** (Y=H),



Scheme 6.



Scheme 7.



Scheme 8.

whereas **2c** (Y=OMe) was consumed very slowly (Scheme 1 and entries 1–3). These results suggest that an electron-withdrawing substituent on alkyl phenyl ketones enhances *ortho*-arylation, possibly by promoting enolate formation.

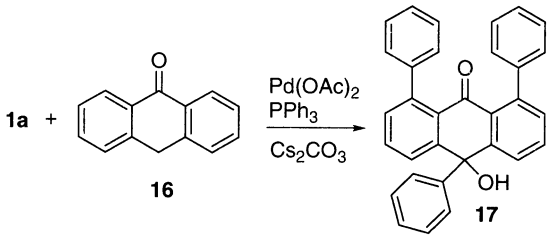
The reaction of valerophenone (**13**) with **1a** using PPh_3 as ligand gave a mixture of γ,γ-diphenylated product **14** and α,γ,γ-triphenylated one **15** (Scheme 8 and entry 16).

It is reasonable to consider that the initial unsaturation of **13** followed by γ,γ-diphenylation leads to **14**. The triphenylated compound **15** could be formed by either α-phenylation followed by unsaturation and γ,γ-diphenylation as in steps (a)–(c) in Scheme 5 or initial unsaturation followed by α,γ,γ-triphenylation. Therefore, in the reaction of **7**, an alternative route involving initial unsaturation [step (a′) in Scheme 5] should also be considered to participate. Indeed, this was supported by the reaction of (*E*)-1-phenyl-2-buten-1-one (**20**) as the intermediate (vide infra, Scheme 11).

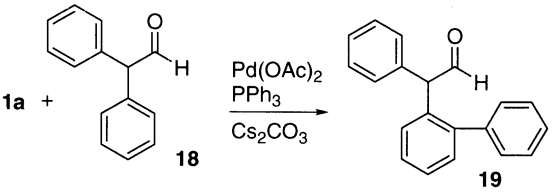
Two substrates, anthrone (**16**) and diphenylacetaldehyde (**18**), which are structural relatives of benzyl phenyl ketones (**2**), were also reacted with **1a**.

The ketone **16** underwent triphenylation at the 1-, 8- and 10-positions, which parallels the reaction of **2** (Scheme 9 and entry 17). It was, however, observed that the 10-position was unexpectedly hydroxylated. The hydroxyl group would come from the base or adventitious water, but the mode of its addition is not definitive at the present stage. The reaction of **18** with 4 equiv. of **1a** gave a complex mixture involving mono- to triphenylated products along with other unidentified compounds, which was confirmed by GC–MS. However, *ortho*-monophenylated compound **19** could be obtained by using 1.5 equiv. of **18** (Scheme 10 and entry 18). The reaction in DMF gave a better yield (entry 19). The formation of **19** suggests that *ortho*-arylation of benzyl carbonyl compounds is possible, while it favorably occurs in benzoyl compounds as indicated by the results using **2**.

The results of the reactions of **7** and **13** may suggest that various α,β-unsaturated carbonyl compounds can undergo



Scheme 9.



Scheme 10.

multiple arylation. Consequently, a number of the compounds are treated with excess **1a** (Table 2).

The reaction of (*E*)-1-phenyl-2-buten-1-one (**20**) with **1a** gave a mixture of **10**–**12a** as in the reaction using **7a** (Scheme 11 and entry 1). This indicates that as described above, the arylation of **7** may, in part, proceed after unsaturation of the propyl group.

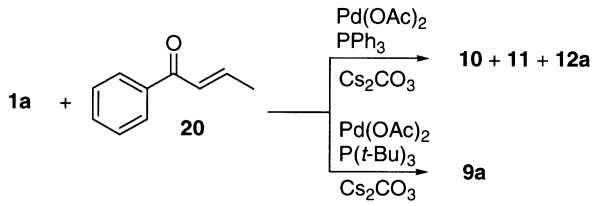
It was of interest that the reaction using P(*t*-Bu)$_3$ gave **9a** as the single major product along with trace amounts of **10** and **11** (entry 2). The conditions employed were similar to those for the reaction of **7a** in entry 9 of Table 1 in which the monophenylated product **8** was produced as the major one. These results suggest that the bulky ligand can effectively enhance α,γ,γ-triphenylation of the α,β-unsarurated ketone to **9a**, while its further transformations to **10**–**12a** as well as the unsaturation of **8** are suppressed.[12]

Treatment of (*E*)-2-octenal (**21**) with 4 equiv. of **1a** using $Pd(OAc)_2$–PPh_3 gave a mixture of γ,γ-diphenylated product

Table 2. Arylation of α,β-unsaturated carbonyl compounds with bromobenzene

Entry	Substrate	**1a** (mmol)	$Pd(OAc)_2$ (mmol)	PR_3	Solvent	Temperature[a] (°C)	Time (h)	Product(s); % yield[b]
1	**20**	7.5	0.125	PPh_3[c]	*o*-Xylene	160	2	**10**; 10 (8), **11**; 18 (12), **12a**; (34)
2	**20**	7.5	0.075	P(*t*-Bu)$_3$[c]	*o*-Xylene	160	2	**9a**; 85
3	**21**	4	0.025	PPh_3	*o*-Xylene	160	3	**22**; 34 (29), **23**; **44** (34)
4	**24a**	3	0.1	PPh_3	*o*-Xylene	160	24	**25a**; 15
5	**24a**	3	0.1	P(*t*-Bu)$_3$	DMF	80	24	**25a**; 53 (53)
6	**24a**	3	0.1	PPh_3	DMF	80	24	**26**;[d] 54
7	**24b**	3	0.05	P(*t*-Bu)$_3$	DMF	60	7	**25b**; (59)
8	**24c**	3	0.05	P(*t*-Bu)$_3$	DMF	60	3	**25c**; (36)
9[e]	**27**	2	0.05	PPh_3	DMF	80	5	**28**; 79 (56)
10[f]	**27**	4	0.05	P(*t*-Bu)$_3$	DMF	80	45	**29**; 64 (48)
11	**30**	4	0.05	P(*t*-Bu)$_3$	*o*-Xylene	160	4	**31**; 60 (55)
12	**32**	4	0.075	PPh_3[c]	*o*-Xylene	160	40	**33**; (21), **34**; (27)

The reaction was carried out using 1 mmol of substrate in the presence of Cs_2CO_3 as base. [PhBr]=[Cs_2CO_3], [PR_3]/[$Pd(OAc)_2$]=2.
[a] Bath temperature.
[b] Determined by GLC analysis. Value in parentheses indicates isolated yield.
[c] [PR_3]/[$Pd(OAc)_2$]=4.
[d] (*E*)-2-ethyl-4-phenyl-2-hexenal.
[e] Taken from the data in Ref. 7.
[f] 6 mmol of Cs_2CO_3 was used.

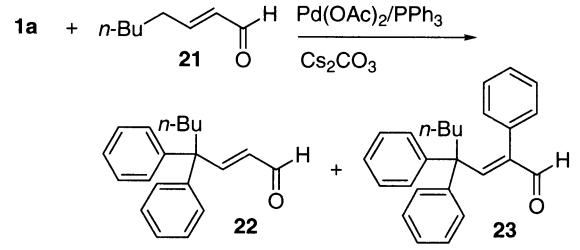


Scheme 11.

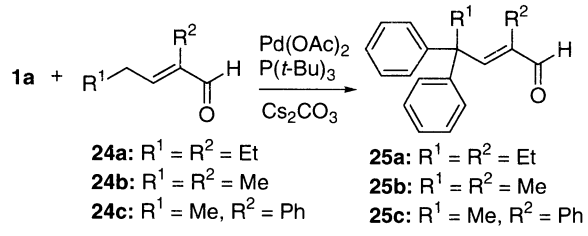
22 and α,γ,γ-triphenylated one **23** in comparable yields (Scheme 12 and entry 3). This parallels the reaction of **13** (Scheme 8).

The reaction of (*E*)-2-ethyl-2-hexenal (**24a**) under similar conditions gave the expected γ,γ-diphenylated product **25a**, but the yield was poor (Scheme 13 and entry 4). Using $P(t\text{-Bu})_3$ as ligand in DMF at a lower temperature of 80°C was found to considerably improve the yield (entry 5).

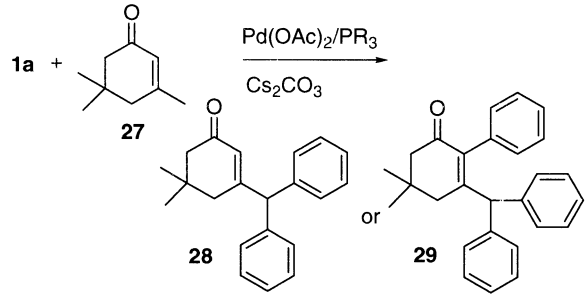
It is noted that as reported previously,[7] the reaction of **24a** using PPh_3 in DMF selectively gave γ-monophenylated product, (*E*)-2-ethyl-4-phenyl-2-hexenal (**26**), even in the presence of 3 equiv. of **1a** (entry 6). The reactions of (*E*)-2-methyl-2-pentenal (**24b**) and (*E*)-2-phenyl-2-pentenal



Scheme 12.



Scheme 13.



Scheme 14.

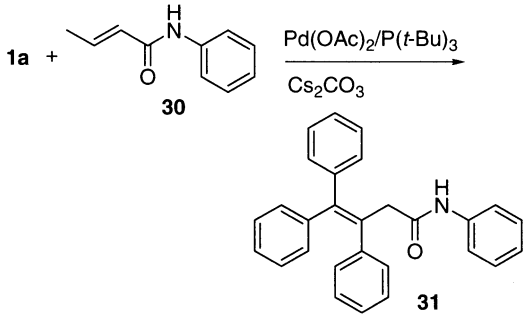
(**24c**) using $P(t\text{-Bu})_3$ in DMF gave the corresponding γ,γ-diphenylated products, **25b** and **c**, as expected (entries 7 and 8). In the reaction of isophorone (**27**), the use of PPh_3 and $P(t\text{-Bu})_3$ resulted in the selective formation of γ,γ-diphenylated product **28** and α,γ,γ-triphenylated one **29**, respectively (Scheme 14 and entries 9 and 10).

The reaction of (*E*)-*N*-phenyl-2-butenamide (**30**) using $P(t\text{-Bu})_3$ in *o*-xylene unexpectedly gave β,γ,γ-triphenylated product **31** (Scheme 15 and entry 11), while using PPh_3 was formed a complex mixture. In this special case, β-phenylation via carbopalladation could initially occur.

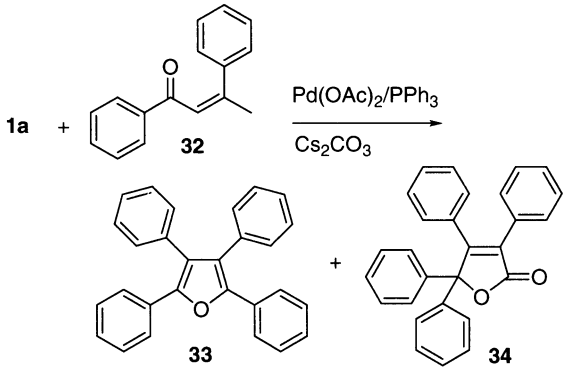
It was also interesting that two kinds of diphenylated and cyclized products **33** and **34** were obtained from the reaction of (*Z*)-1,3-diphenyl-2-buten-1-one (**32**) (Scheme 16 and entry 12).

The furan **33** may be formed by α,γ-diphenylation followed by oxidative cyclization with the aid of phenylpalladium species. However, the modes of phenylation and addition of an external oxygen (as in the case of **16**) leading to **34** are unclear.

In summary, we have demonstrated that alkyl aryl ketones as well as α,β-unsaturated carbonyl compounds can be multiply arylated upon treatment with excess aryl bromides using palladium catalysts. This appears to provide a straightfoward method for preparing a number of oligoaryl compounds.



Scheme 15.



Scheme 16.

3. Experimental

3.1. General

^{1}H and ^{13}C NMR spectra were recorded at 400 and 100 MHz, respectively, for $CDCl_3$ solutions. MS analysis was made by EI. GLC analysis was carried out using a Silicone OV-17 glass column (i.d. 2.6 mm×1.5 m). Benzyl phenyl ketones **2b** and **c** were prepared by the Friedel–Crafts reaction of the corresponding substituted benzenes with phenylacetyl chloride in the presence of $AlCl_3$. Amide **30** was prepared by the reaction of *trans*-crotonyl chloride with aniline. Other starting materials were commercially available. The solvents employed were purified by standard methods before use. The following experimental procedure may be regarded as typical in methodology and scale.

3.1.1. Reaction of butyrophenone (7a) with bromobenzene (1a). In a 100 cm^3 two-necked flask was placed Cs_2CO_3 (7.5 mmol, 2.45 g), which was then dried at 150°C in vacuo for 2 h. Then, $Pd(OAc)_2$ (0.1 mmol, 22.4 mg), PPh_3 (0.4 mmol, 105 mg), **1a** (7.5 mmol, 1.18 g), **7a** (1 mmol, 148 mg), 1-methylnaphthalene (ca. 100 mg) as internal standard and *o*-xylene (5 cm^3) were added. The resulting mixture was stirred under N_2 at 160°C (bath temperature) for 23 h. After cooling, the reaction mixture was extracted with diethyl ether and dried over sodium sulfate. The product mixture was fractionated by column chromatography on silica gel using hexane–toluene as eluent. Compounds **10** (30 mg, 8%), **11** (131 mg, 29%) and **12a** (111 mg, 21%) were isolated in this order. Their characterization data as well as other products are given below.

3.2. Products

Compounds **4** (X=Y=Z=H),[8] **4** (X=Z=H, Y=Cl),[8] (*E*)-**6**,[14] (*Z*)-**6**,[14] **8**,[15] **9a**,[16] **17**,[17] **26**,[7] **28**,[7] **33**[18] and **34**[19] are known. The characterization data of new compounds are given below.

3.2.1. 2-Phenyl-1-(4-methoxy-1,1′:3,1′-terphenyl-2-yl)-2-ethanone (4; X=Z=H, Y=OMe). Oil; ^{1}H NMR δ 3.84 (s, 3H), 4.70 (s, 1H), 6.70 (d, *J*=7.3 Hz, 4H), 6.79 (s, 2H), 6.98 (t, *J*=6.8, 7.3 Hz, 4H), 7.04 (t, *J*=6.8 Hz, 2H), 7.15 (d, *J*=7.3 Hz, 4H), 7.22 (t, *J*=7.3, 7.6 Hz, 4H), 7.25 (t, *J*=7.6 Hz, 2H); ^{13}C NMR δ 55.40, 65.45, 114.95, 126.40, 127.12, 127.50, 127.94, 128.08, 128.80, 129.60, 138.26, 140.41, 142.60, 159.07, 20288; MS *m*/*z* 454 (M^+). Anal. calcd for $C_{33}H_{26}O_2$: C, 87.20; H, 5.77. Found: C, 86.92; H, 6.05.

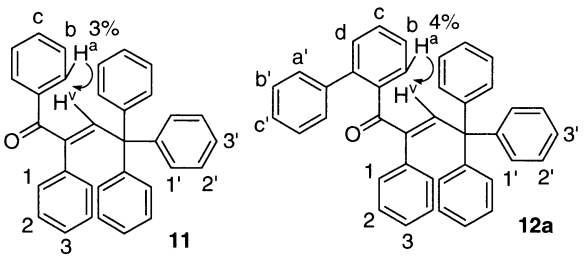
3.2.2. 1-Phenyl-2,4,4-tri(4-fluorophenyl)-3-buten-1-one (9b). Oil; ^{1}H NMR δ 5.34 (d, *J*=10.3 Hz, 1H), 6.59 (d, *J*=10.3 Hz, 1H), 6.92–7.01 (m, 4H), 7.07–7.11 (m, 4H), 7.15–7.22 (m, 4H), 7.36 (t, *J*=7.3, 8.1 Hz, 2H), 7.50 (t, *J*=7.3 Hz, 1H), 7.73 (dd, *J*=1.5, 8.1 Hz, 2H); ^{13}C NMR δ 52.82, 115.09 (d, *J*=21.1 Hz), 115.67 (d, *J*=21.1 Hz), 115.97 (d, *J*=21.1 Hz), 127.23, 128.63, 128.63, 129.03 (d, *J*=7.4 Hz), 129.66 (d, *J*=7.3 Hz), 131.34 (d, *J*=8.3 Hz), 133.33, 134.89 (d, *J*=3.7 Hz), 135.06 (d, *J*=3.7 Hz), 135.91, 137.44 (d, *J*=2.8 Hz), 141.33, 161.91 (d, *J*=248.2 Hz), 162.33 (d, *J*=248.2 Hz), 162.47 (d, *J*=248.2 Hz), 198.57; MS *m*/*z* 428 (M^+). Anal. calcd for $C_{28}H_{19}F_3O$: C, 78.49; H, 4.47. Found: C, 78.10; H, 4.68.

3.2.3. 1-Phenyl-2,4,4-tri(4-methylphenyl)-3-buten-1-one (9c). Mp 115–117°C; ^{1}H NMR δ 2.29 (s, 3H), 2.30 (s, 3H), 2.41 (s, 3H), 5.39 (d, *J*=10.3 Hz, 1H), 6.59 (d, *J*=10.3 Hz, 1H), 7.01–7.19 (m, 12H), 7.32 (t, *J*=7.7 Hz, 2H), 7.45 (t, *J*=7.7 Hz, 1H), 7.75 (d, *J*=7.7 Hz, 2H); ^{13}C NMR δ 21.03, 21.05, 21.30, 53.41, 126.29, 127.41, 128.11, 128.40, 128.73, 128.73, 129.05, 129.60, 129.72, 132.85, 136.39, 136.60, 136.66, 137.08, 137.13, 139.20, 142.79, 199.29; MS *m*/*z* 416 (M^+). Anal. calcd for $C_{31}H_{28}O$: C, 89.38; H, 6.77. Found: C, 89.15; H, 6.77.

3.2.4. 2,4,4-Triphenyl-1(*4H*)-naphthalenone (10). Mp 223–224°C; ^{1}H NMR δ 7.23–7.40 (m, 14H), 7.41 (dt, *J*=1.5, 7.3 Hz, 1H), 7.42 (s, 1H), 7.44 (dd, *J*=1.5, 7.7 Hz, 1H), 7.49 (dd, *J*=1.5, 8.2 Hz, 2H), 8.34 (dd, *J*=1.8, 7.3 Hz, 1H); ^{13}C NMR δ 55.39, 127.28, 127.28, 127.58, 128.00, 128.08, 128.63, 128.89, 128.97, 130.78, 131.87, 132.30, 135.66, 135.91, 144.14, 146.00, 152.37, 183.61; MS *m*/*z* 372 (M^+). Anal. calcd for $C_{28}H_{20}O$: C, 90.29; H, 5.41. Found: C, 90.30; H, 5.60.

3.2.5. (*E*)-1,2,4,4,4-Pentaphenyl-2-buten-1-one (11). Mp 148–151°C; ^{1}H NMR δ 6.74 (d, *J*=7.3 Hz, 2H; H^1), 6.81 (t, *J*=7.3 Hz, 2H; H^2), 6.89 (t, *J*=7.3 Hz, 1H; H^3), 7.07–7.15 (m, 15H; $H^{1'}$–$H^{3'}$), 7.40 (t, *J*=7.3 Hz, 2H; H^b), 7.42 (s, 1H; H^v), 7.51 (t, *J*=7.3 Hz, 1H; H^c), 7.90 (d, *J*=7.3 Hz, 2H; H^a); ^{13}C NMR δ 61.35, 126.37, 126.50, 127.14, 127.69, 128.30, 128.89, 130.08, 130.19, 132.45, 135.05, 137.69, 142.88, 145.25, 146.29, 198.08; MS *m*/*z* 450 (M^+). Anal. calcd for $C_{34}H_{26}O$: C, 90.63; H, 5.82. Found: C, 90.46; H, 5.89.

3.2.6. (*E*)-1-(1,1′-Biphenyl-2-yl)-2,4,4,4-tetraphenyl-2-buten-1-one (12a). Mp 136–138°C; ^{1}H NMR δ 6.41 (d, *J*=7.6 Hz, 2H; H^1), 6.62 (dd, *J*=1.8, 6.9 Hz, 6H; $H^{1'}$), 6.73 (t, *J*=7.6 Hz, 2H; H^2), 6.83 (t, *J*=7.3, 7.6 Hz, 1H; H^3), 6.97–7.06 (m, 11H; $H^{a'}$, $H^{2'}$, $H^{3'}$), 7.30 (t, *J*=7.6 Hz, 2H; $H^{b'}$), 7.34 (dd, *J*=1.5, 7.6 Hz, 1H; H^d), 7.40 (t, *J*=7.3, 7.6 Hz, 1H; $H^{c'}$), 7.47 (t, *J*=7.3, 7.6 Hz, 1H; H^c), 7.48 (s, 1H; H^v), 7.52 (t, *J*=7.3, 7.6 Hz, 1H; H^b), 7.58 (dd, *J*=1.8, 7.3 Hz, 1H; H^a); ^{13}C NMR δ 61.28, 126.14, 126.29, 126.57, 127.26, 127.49, 127.59, 128.68, 128.73, 129.24, 129.43, 129.60, 129.89, 130.03, 133.89, 139.88, 140.05, 140.62, 144.11, 144.92, 155.48, 201.77; MS *m*/*z* 526 (M^+). Anal. calcd for $C_{40}H_{30}O$: C, 91.22; H, 5.74. Found: C, 91.08; H, 5.74. The NOE peak enhancements in **11** and **12a** were as follows:



3.2.7. (*E*)-1-(5-Chloro-1,1′-biphenyl-2-yl)-2,4,4,4-tetraphenyl-2-buten-1-one (12b). Mp 179–181°C; ^{1}H NMR δ

6.39 (dd, *J*=1.1, 8.4 Hz, 2H), 6.62 (dd, *J*=1.8, 8.4 Hz, 6H), 6.72 (t, *J*=7.7 Hz, 2H), 6.83 (t, *J*=7.3 Hz, 1H), 6.99 (t, *J*=1.5, 8.4 Hz, 6H), 7.02–7.07 (m, 5H), 7.31 (t, *J*=7.7, 8.4 Hz, 2H), 7.32 (s,1H), 7.41 (d, *J*=7.3 Hz, 1H), 7.45 (dd, *J*=1.8, 8.1 Hz, 1H), 7.47 (s, 1H), 7.52 (d, *J*=8.1 Hz, 1H); ^{13}C NMR δ 61.38, 126.25, 126.42, 126.62, 127.56, 127.70, 127.82, 128.87, 129.08, 129.40, 129.51, 130.02, 130.21, 133.64, 135.70, 138.29, 139.29, 141.83, 143.86, 144.77, 155.49, 200.62; MS *m/z* 560, 562 (M^+). Anal. calcd for $C_{40}H_{29}ClO$: C, 85.62; H, 5.21; Cl, 6.32. Found: C, 85.77; H, 5.28; Cl, 6.49.

3.2.8. (*E*)-1-(4′-Fluoro-1,1′-biphenyl-2-yl)-2,4,4,4-tetra(4-fluorophenyl)-2-buten-1-one (12c). Mp 187–189°C; ^{1}H NMR δ 6.30–6.34 (m, 2H), 6.51 (t, *J*=8.8 Hz, 2H), 6.55–6.59 (m, 6H), 6.72–6.77 (m, 6H), 6.98–7.06 (m, 4H), 7.31 (d, *J*=7.3 Hz, 1H), 7.40 (s, 1H), 7.47–7.56 (m, 3H); ^{13}C NMR δ 59.59, 113.80 (d, *J*=22.1 Hz), 114.65 (d, *J*=21.1 Hz), 115.67 (d, *J*=21.1 Hz), 127.93, 128.71, 129.43 (d, *J*=3.7 Hz), 129.57, 130.30, 130.85 (d, *J*=8.3 Hz), 130.99 (d, *J*=8.3 Hz), 131.27 (d, *J*=8.3 Hz), 136.63 (d, *J*=3.7 Hz), 138.58, 139.40, 140.27 (d, *J*=3.7 Hz), 143.23, 154.50, 161.26 (d, *J*=248.2 Hz), 161.58 (d, *J*=248.2 Hz), 162.54 (d, *J*=248.2 Hz), 201.06; MS *m/z* 616 (M^+). Anal. calcd for $C_{40}H_{25}F_5O$: C, 77.91; H, 4.09. Found: C, 77.74; H, 4.21.

3.2.9. (*E*)-1-(5-Chloro-4′-fluoro-1,1′-biphenyl-2-yl)-2,4,4,4-tetra(4-fluorophenyl)-2-buten-1-one (12d). Mp 190–193°C; ^{1}H NMR δ 6.30 (dd, *J*=5.4, 8.6 Hz, 2H), 6.51 (t, *J*=8.6 Hz, 2H), 6.58 (dd, *J*=5.3, 8.4 Hz, 6H), 6.76 (t, *J*=8.4 Hz, 6H), 6.96–6.99 (m, 2H), 7.05 (t, *J*=8.4 Hz, 2H), 7.30 (d, *J*=1.8 Hz, 1H), 7.40 (s, 1H), 7.45–7.50 (m, 2H); ^{13}C NMR δ 59.67, 113.87 (d, *J*=22.1 Hz), 114.72 (d, *J*=21.1 Hz), 115.88 (d, *J*=21.1 Hz), 128.08, 128.32, 129.20 (d, *J*=3.7 Hz), 129.50, 130.25, 130.80 (d, *J*=7.4 Hz), 130.97 (d, *J*=8.3 Hz), 131.26 (d, *J*=8.3 Hz), 135.30 (d, *J*=3.7 Hz), 136.22, 137.76, 140.13 (d, *J*=3.7 Hz), 142.96, 154.44, 161.30 (d, *J*=248.2 Hz), 161.62 (d, *J*=248.2 Hz), 162.80 (d, *J*=278.2 Hz), 199.91; MS *m/z* 650, 652 (M^+). Anal. calcd for $C_{40}H_{21}ClF_5O$: C, 73.79; H, 3.72. Found: C, 74.15; H, 4.06.

3.2.10. (*E*)-1,4,4-Triphenyl-2-penten-1-one (14). Oil; ^{1}H NMR δ 1.93 (s, 3H), 6.70 (d, *J*=15.8 Hz, 1H), 7.20–7.26 (m, 6H), 7.31 (t, *J*=7.0, 7.7 Hz, 4H), 7.44 (t, *J*=7.3, 7.7 Hz, 2H), 7.53 (t, *J*=7.3 Hz, 1H), 7.61 (d, *J*=15.8 Hz, 1H), 7.86 (dd, *J*=1.5, 7.7 Hz, 2H); ^{13}C NMR δ 27.21, 50.24, 124.05, 126.58, 127.79, 128.33, 128.53, 128.53, 132.74, 137.94, 146.54, 155.99, 190.83; HRMS *m/z* (M^+) calcd for $C_{23}H_{20}O$ 312.1514, found 312.1515.

3.2.11. (*E*)-1,2,4,4-Tetraphenyl-2-penten-1-one (15). Oil; ^{1}H NMR δ 1.49 (s, 3H), 6.99–7.01 (m, 2H), 7.07 (s, 1H), 7.11–7.14 (m, 4H), 7.18–7.21 (m, 5H), 7.23–7.28 (m, 4H), 7.39 (t, *J*=7.7, 7.3 Hz, 2H), 7.49 (t, *J*=7.3 Hz, 1H), 7.79 (dd, *J*=1.5, 7.7 Hz, 2H); ^{13}C NMR δ 28.63, 50.55, 126.29, 127.32, 127.59, 127.64, 128.21, 128.23, 129.44, 129.87, 132.25, 135.75, 137.90, 140.76, 148.75, 149.50, 197.64; HRMS *m/z* (M^+) calcd for $C_{29}H_{24}O$ 388.1827, found 388.1826.

3.2.12. 2-(Biphenyl-2-yl)phenylacetaldehyde (19). Oil; ^{1}H NMR δ 5.04 (d, *J*=1.4 Hz, 1H), 7.05 (d, *J*=6.8 Hz, 2H), 7.19–7.41(m, 12H), 9.86 (d, *J*=1.4 Hz, 1H); ^{13}C NMR δ 60.65, 127.31, 127.43, 127.77, 128.26, 128.76, 128.98, 129.03, 129.29, 129.54, 130.76, 133.66, 137.05, 140.71, 143.32, 198.96; MS *m/z* 272 (M^+). Anal. calcd for $C_{20}H_{16}O$: C, 88.20; H,5.92. Found: C, 87.80; H, 6.02.

3.2.13. (*E*)-4,4-Diphenyl-2-octenal (22). Oil; ^{1}H NMR δ 0.85 (t, 3H, *J*=7.3 Hz, 3H), 1.08–1.14 (m, 2H), 1.29–1.35 (m, 2H), 2.29–2.34 (m, 2H), 5.94 (dd, *J*=7.7, 16.1 Hz, 1H), 7.13–7.33 (m, 10H), 7.38 (d, *J*=16.1 Hz, 1H), 9.63 (d, *J*=7.7 Hz, 1H); ^{13}C NMR δ 13.91, 23.27, 26.91, 38.30, 54.12, 126.71, 128.30, 128.34, 131.46, 144.85, 163.78, 194.11; HRMS *m/z* (M^+) calcd for $C_{20}H_{22}O$ 278.1671, found 278.1673.

3.2.14. (*E*)-2,4,4-Triphenyl-2-octenal (23). Oil; ^{1}H NMR δ 0.67 (t, *J*=6.9 Hz, 3H), 0.86–0.92 (m, 4H), 1.90–1.96 (m, 2H), 6.71 (dd, *J*=1.3, 7.9 Hz, 2H), 7.12–7.28 (m, 13H), 7.52 (s, 1H), 9.71 (s, 1H); ^{13}C NMR δ 13.83, 22.81, 27.08, 38.25, 53.86, 126.41, 127.63, 127.67, 128.13, 128.23, 129.03, 133.10, 143.26, 146.97, 161.07, 194.92; HRMS *m/z* (M^+) calcd for $C_{26}H_{26}O$ 354.1984, found 354.1980.

3.2.15. (*E*)-2-Ethyl-4,4-diphenyl-2-hexenal (25a). Mp 62–63°C; ^{1}H NMR δ 0.48 (t, *J*=7.3 Hz, 3H), 0.80 (t, *J*=7.3 Hz, 3H), 1.83 (q, *J*=7.3 Hz, 2H), 2.43 (q, *J*=7.3 Hz, 2H), 7.16 (s, 1H), 7.20–7.32 (m, 10H), 9.05 (s, 1H); ^{13}C NMR δ 9.61, 11.23, 18.67, 34.18, 53.78, 126.42, 128.24, 128.24, 145.73, 146.41, 159.73, 196.37; MS *m/z* 278 (M^+). Anal. calcd for $C_{20}H_{22}O$: C, 86.29; H, 7.97. Found: C, 86.23; H, 7.94.

3.2.16. (*E*)-2-Methyl-4,4-diphenyl-2-pentenal (25b). Oil; ^{1}H NMR δ 1.35 (d, *J*=1.5 Hz, 3H), 1.97 (s, 3H), 7.10 (q, *J*=1.5 Hz, 1H), 7.21–7.34 (m, 10H), 9.49 (s, 1H); ^{13}C NMR δ 10.39, 28.79, 50.08, 126.60, 127.53, 128.45, 140.07, 146.90, 162.36, 196.31; MS *m/z* 250 (M^+). Anal. calcd for $C_{18}H_{18}O$: C, 86.36; H, 7.25. Found: C, 86.07; H, 7.22.

3.2.17. (*E*)-2,4,4-Triphenyl-2-pentenal (25c). Oil; ^{1}H NMR δ 1.51 (s, 3H), 6.82 (dd, *J*=1.5, 7.8 Hz, 2H), 7.14–7.31 (m, 13H), 7.37 (s, 1H), 9.69 (s, 1H); ^{13}C NMR δ 28.42, 50.81, 126.60, 127.56, 127.68, 127.76, 128.41, 129.28, 133.14, 143.23, 147.89, 162.07, 194.92; HRMS *m/z* (M^+) calcd for $C_{23}H_{20}O$: 312.1514, found 312.1516.

3.2.18. 5,5-Dimethyl-2-phenyl-3-(diphenylmethyl)-2-cyclohexen-1-one (29). Mp 105–106°C; ^{1}H NMR δ 1.05 (s, 6H), 2.31 (s, 2H), 2.40 (s, 2H), 5.21 (s, 1H), 7.01–7.36 (m, 15H); ^{13}C NMR δ 28.18, 33.10, 41.06, 51.85, 54.68, 126.80, 127.47, 128.24, 128.41, 129.13, 129.56, 135.79, 138.95, 140.98, 157.05, 198.77; MS *m/z* 366 (M^+). Anal. calcd for $C_{27}H_{26}O$: C, 88.48; H, 7.15. Found: C, 88.09; H, 7.11.

3.2.19. *N*-Phenyl-3,4,4-triphenyl-3-butenamide (31). Mp 207–208°C; ^{1}H NMR δ 3.62 (s, 2H), 6.93–6.96 (m, 2H), 7.04–7.40 (m, 19H); ^{13}C NMR δ 44.95, 119.66, 124.22, 126.57, 127.13, 127.51, 127.65, 128.54, 128.55, 128.91, 129.54, 129.60, 130.67, 132.50, 137.71, 141.58, 142.07, 142.21, 144.32, 168.64; MS *m/z* 329 (M^+). Anal. calcd for $C_{28}H_{23}ON$: C, 86.34; H, 5.95; N, 3.59. Found: C, 85.99; H, 5.67; N, 3.70.

References

1. Tsuji, J. *Palladium Reagents and Catalysts*; Wiley: Chichester, 1995.
2. *Metal-Catalyzed Cross-Coupling Reactions*; Diederich, F., Stang, P. J., Eds.; Wiley–VCH: Weinheim, 1997.
3. (a) Satoh, T.; Kawamura, Y.; Miura, M.; Nomura, M. *Angew. Chem., Int. Ed. Engl.* **1997**, *36*, 1740. (b) Satoh, T.; Inoh, J.-I.; Kawamura, Y.; Kawamura, Y.; Miura, M.; Nomura, M. *Bull. Chem. Soc. Jpn* **1998**, *71*, 2239. (c) Satoh, T.; Kametani, Y.; Terao, Y.; Miura, M.; Nomura, M. *Tetrahedron Lett.* **1999**, *40*, 5345. (d) Terao, Y.; Satoh, T.; Miura, M.; Nomura, M. *Bull. Chem. Soc. Jpn* **1999**, *72*, 2345. (e) Terao, Y.; Satoh, T.; Miura, M.; Nomura, M. *Tetrahedron* **2000**, *56*, 1315.
4. (a) Palucki, M.; Buchwald, S. L. *J. Am. Chem. Soc.* **1997**, *119*, 11108. (b) Ahman, J.; Wolfe, J. P.; Troutman, M. V.; Palucki, M.; Buchwald, S. L. *J. Am. Chem. Soc.* **1998**, *120*, 1918. (c) Old, D. W.; Wolfe, J. P.; Buchwald, S. L. *J. Am. Chem. Soc.* **1998**, *120*, 9722. (d) Fox, J. M.; Huang, X.; Chieffi, A.; Buchwald, S. L. *J. Am. Chem. Soc.* **2000**, *122*, 1360.
5. (a) Hamann, B. C.; Hartwig, J. F. *J. Am. Chem. Soc.* **1997**, *119*, 12382. (b) Kawatsura, M.; Hartwig, J. F. *J. Am. Chem. Soc.* **1999**, *121*, 1473. (c) Shaughnessy, K. H.; Hamann, B. C.; Hartwig, J. F. *J. Org. Chem.* **1998**, *63*, 6456.
6. (a) Muratake, H.; Hayakawa, A.; Natsume, M. *Tetrahedron Lett.* **1997**, *38*, 7577. (b) Muratake, H.; Natsume, M. *Tetrahedron Lett.* **1997**, *38*, 7581. (c) Muratake, H.; Nakai, H. *Tetrahedron Lett.* **1999**, *40*, 2355.
7. Terao, Y.; Satoh, T.; Miura, M.; Nomura, M. *Tetrahedron Lett.* **1998**, *39*, 6203.
8. Related reaction with cyclopentadienes: Dyker, G.; Heiermann, J.; Miura, M.; Inoh, J.-I.; Pivsa-Art, S.; Satoh, T.; Nomura, M. *Chem. Eur. J.* **2000**, *6*, 3426.
9. Related reactions: (a) With benzanilides Kametani, Y.; Satoh, T.; Miura, M.; Nomura, M. *Tetrahedron Lett.* **2000**, *41*, 2655. With phenols: (b) Kawamura, Y.; Satoh, T.; Miura, M.; Nomura, M. *Chem. Lett.* **1999**, 961 and Ref. 3a,b.
10. Müller, M.; Kübel, C.; Müllen, K. *Chem. Eur. J.* **1998**, *4*, 2099 and reference therein.
11. Oxidative unsaturation accompanied by β-hydrogen elimination: see Ref. 1, chap. 1.
12. Bulky monodentate phosphines including P(*t*-Bu)$_3$ have been found to be effective for α-monoarylation of ketones: see Refs. 4d,5b.
13. Use of the corresponding triarylphosphine can avoid the contamination of phenyl group from PPh_3: see Ref. 8.
14. Duke, P. J.; Boykin, Jr., D. W. *J. Org. Chem.* **1972**, *37*, 1436.
15. Reddy, G. D.; Ramamurthy, V. *J. Org. Chem.* **1987**, *52*, 5521.
16. Futami, Y.; Nishino, H.; Kurosawa, K. *Bull. Chem. Soc. Jpn* **1989**, *62*, 3182.
17. House, H. O.; Koepsell, D.; Jaeger, W. *J. Org. Chem.* **1973**, *38*, 1167.
18. Kar, S. K.; Kar, A. *J. Org. Chem.* **1977**, *42*, 390.
19. Guy, R.; Hardy, J. C. *Bull. Soc. Chim. Fr.* **1970**, 3572.