Tetrahedron Vol. 37, pp. 31 to 36.
© Pergamon Press Ltd. 1981 Printed in Great Britain

0040-4020/81/0101-0037$02.00/0

REACTION OF DIAZONIUM SALTS WITH TRANSITION METALS—III[1]

PALLADIUM(0)-CATALYZED ARYLATION OF UNSATURATED COMPOUNDS WITH ARENEDIAZOIUM SALTS

K. Kikukawa, K. Nagira, F. Wada and T. Matsuda*
Department of Organic Synthesis, Faculty of Engineering, Kyushu University, Hakozaki, Higashiku, Fukuoka 812, Japan

(*Received in Japan* 11 *January* 1980)

Abstract—Palladium (0) catalyzed reactions of arenediazonium salts for arylation of aliphatic and cyclic olefins and allylic alcohols, styrene and ethyl acrylate were studied. Effects of the olefinic compounds and other reaction variables on the arylation were presented. Arylpalladium species was proposed as the most plausible intermediated in this reaction.

Arenediazonium salts have been utilized to achieve transformation of the aryl-nitrogen bond to aryl-alkenyl bond in Meerwein arylation (copper salts catalyzed arylation of olefinic compounds).[2] The arylation is a useful synthetic procedure, because of the availability of a variety of aryl amines and good product yields. However, it generally requires the olefins to be activated by an electron-withdrawing group, such as cyano, aryl, vinyl, ethynyl or chloro group. Recently Doyle *et al.* reported a modified Meerwein arylation with significant improvement by the use of free aryl amines and alkyl nitrite in place of arenediazonium salts.[3] However, the limitation in olefinic compounds still remains.

Arylpalladium reagents obtained from several sources, such as aryl halides or arylmercurials, have been utilized extensively for olefin arylation (Heck arylation[4]), and the arylation is known to be free from the requirement for activation in the olefinic substances. In a previous communication,[5] we reported a novel arylation of olefins by arenediazonium salts in the presence of a catalytic amount of palladium (0). Various styrene derivatives have been synthesized in good yields by the reaction of arenediazonium tetrafluoroborates with ethylene, which is a poor substrate in the Meerwein arylation,[2] under the catalysis of bis(dibenzylideneacetone) palladium (0) $\{Pd(dba)_2\}$.[1,6]

Now we wish to present the results obtained by surveying the effects of olefinic substrates and type of the diazonium salts as well as reaction variables to clarify the scope of the utility of the novel arylation.

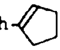
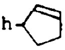
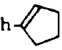
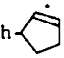
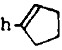
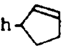
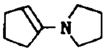
RESULTS AND DISCUSSION

Effect of olefinic substances and arenediazonium salts. The results in Table 1 show that the present arylation with arenediazonium salts and palladium catalyst affords good or fair yields of products for various olefins, including those which give poor results in the Meerwein arylation. Neither electron-withdrawing and releasing groups on the double bond cause serious effects on the arylation except for acrylonitrile and an enamine. Addition of acrylonitrile to the reaction mixture led to precipitation metallic palladium and prevented progress of the arylation, and 1-pyrrolidinyl-cyclopentene reacted with diazonium salt to give tarry material. Lower yield observed for internal olefins suggests that the arylation is susceptible to steric factor,[7] though cycloolefins except for cyclohexene gave good yields. Simple olefinic hydrocarbons afforded mixtures of double bond isomers. The formation of these isomers can be explained in terms of isomerization of the products and also of starting olefins by the catalysis of a hydridopalladium intermediate[8] under the reaction conditions. A time course of phenylation of cyclopentene in Fig. 1 clearly indicates that 3-phenylcyclopentene is the initial product, which then undergoes isomerization to 1-phenyl and/or other isomers as shown in Scheme 1. Figure 1 also reveals a good correlation between gas evolution and the outcome of the phenylated products. Most of the arylations summarized in Tables 1 and 2 are considered to complete with 0.5–1.0 h at room temperature.

A variety of arenediazonium salts can be used for this arylation as shown in Table 2. The product yields, however, seems to be affected by the stability of the diazonium salts, as themselves or under reaction conditions, through the formation of variable amount of tarry products. Deactivation of the catalyst by the formation of tarry materials, one of the important factors in the reaction, can be overcome considerably by increasing the amount of the catalyst. Reactions of naphthalene-1- and -2-diazonium tetrafluoroborates with ethylene (7.5 kg/cm^2) under the similar conditions gave the corresponding vinyl naphthalenes. Fair yields obtained with bromo- and chloro substituted diazonium salts indicate that the aryl-nitrogen bond is more reactive to zero-valent palladium than aryl-halogen bond. Nitrobenenediazonium salts (para and ortho), which are good substrates in the Meerwein arylation, gave nitrobenzene in this system.

Effect of medium. Acetonitrile, methylenechloride and acetone were found appropriate as reaction medium. But use of alcoholic solvent caused reduction of diazonium salts. Effect of the solvents not only varied depending on the starting olefins, but also

Table 1. Arylation of olefins by arenediazonium salts$^{a)}$

Run	Olefin	$ArN_2X^{b)}$	Solvent$^{c)}$	Catalyst$^{d)}$ (%)	Products (% isomeric composition$^{e)}$)	Yield$^{f)}$ (%)
1	$CH_2{=}CHCH_2OH$	PhN_2Cl	aq-AN	A(2)	$PhCH_2CH_2CHO$ (90) PhCH(Me)CHO (10) PhCH=CHCHO (trace)	41
2	$CH_2{=}C(Me)CHO$	"	"	"	$PhCH_2CH(Me)CHO$ (95) $PhC(Me)_2CHO$ (5)	67
3	$CH_2{=}CHCOOEt$	MeN_2Cl	"	"	(E)MeCH=CHCOOEt	10
4	"	MeN_2BF_4	AN	B(4)	"	94
5	"	PhN_2BF_4	"	B(2)	(E)PhCH=CHCOOEt	91
6	"	N_2BF_4	"	B(4)	(E) CH=CHCOOEt	83
7	$CH_2{=}CHPh$	PhN_2Cl	aq-AN	A(2)	(E)PhCH=CHPh	8
8	"	PhN_2BF_4	AN	B(2)	"	94
9	"	"	MC	"	"	51
10	MeCH=CHPh	"	"	"	(E)PhCH=C(Me)Ph	6
11	$CH_2{=}C(Me)Ph$	"	"	B(7)	"	40
12	$CH_2{=}CHCH_2Ph$	"	"	B(4)	(E)PhCH=C(Me)Ph (60) (E)$PhCH{=}CHCH_2Ph$ (40)	60
41	$CH_2{=}CH_2$	1-Naphthyl-N_2BF_4	MC-AC	B(2)	1-Vinylnaphthalene	68
42	"	2-Naphthyl-N_2BF_4	"	"	2-Vinylnaphthalene	72
13	1-pentene	PhN_2BF_4	MC	"	Phenylpentenes	49
14	2-hexene	PhN_2BF_4	MC	B(2)	Phenylhexenes	18
15	cyclopentene	"	"	"	Ph (10), Ph (90)$^{g)}$	70
16	"	PhN_2Cl	aq-AN	A(2)	Ph (41), Ph (59)$^{g)}$	70
17	"	"	"	B(2)	Ph (58), Ph (42)$^{g)}$	60
18	cyclohexene	PhN_2BF_4	MC	B(4)	Phenylcyclohexenes	18
19	cycloheptene	"	"	"	Phenylcycloheptenes	78
20	cyclooctene	"	"	"	Phenylcyclooctenes	72
21	$CH_2{=}CHCN$	"	"	B(2)	Tarry products	-
22		"	"	"	"	-

(a) All procedures cited here were carried out at room temperature for 1.5-2 h with sodium acetate as base.

(b) PhN_2Cl: *in-situ* prepared in water (actual species might be PhN_2OAc). PhN_2BF_4: isolated salt.

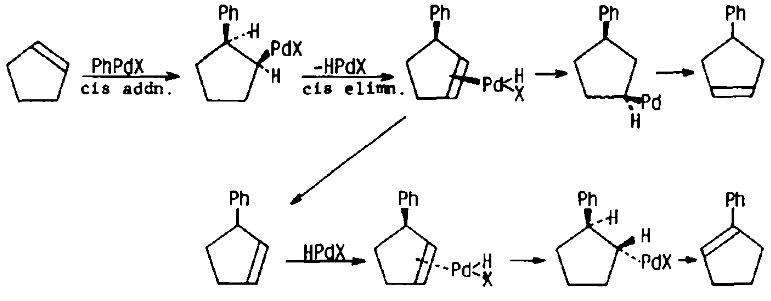
(c) aq-AN: aqueous acetonitrile (15%). AN: acetonitrile, MC: methylene chloride, MC-AC: methylene chloride/acetone (1/1).

(d) A: Zero valent Pd prepared *in-situ* from $PdCl_2$ and sodium formate. B: $Pd(dba)_2$

(e) Determined by GLC.

(f) Isolated yields based on ArN_2BF_4 or anilines (for ArN_2Cl).

(g) Small amounts of 4-phenylcylopentene might be included.

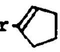
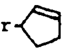


Scheme 1.

appeared in the isomer distribution of the arylated olefins. Reactive olefins, such as cyclopentene, was affected little by the medium, and could be allowed to react with *in situ* prepared diazonium chloride in aqueous acetonitrile. Better results, however, were obtained under non-aqueous conditions for most of olefins. Acetonitrile generally gave good results for the olefins attached by electron-withdrawing group, such as styrene or ethyl acrylate. Methylenechloride, a poor solvent for diazonium tetrafluoroborates and sodium acetate but good for $Pd(dba)_2$, tends to increase the isomerization as shown in Table 2. Thus, in the reaction of cyclopentene with *p*-chlorobenzenediazonium salt replacement of the medium from acetonitrile to methylenechloride brought about exclusive formation of the isomerized product, 1-(*p*-chlorophenyl) cyclopentene.

Examination of catalyst system. The initial experiments had been started with the zero-valent palladium catalyst prepared by reduction of palladium chloride with sodium formate, but use of the catalyst in aqueous acetonitrile was restricted to the olefins being either

Table 2. Arylation of cyclopentene

Run	X in XN_2BF_4	Solvent[a]	$Pd(dba)_2$ %	Reaction time(min)	Yield[b] %	% isomeric composition[c] Ar	 Ar [d]
15	H	MC	2	75	70	10	90
23	"	AN	2	140	67	20	80
24	p-CH_3	MC	2	90	46	10	90
25	"	AN	2	145	71	50	50
26	m-CH_3	MC	8.4	150	27	94	6
27	"	AN	2	145	25	0	100
28	o-CH_3	AN	2	120	24	0	100
29	p-CH_3O	AN	4	25	30	46	54
30	"	MC-AC	4	45	31[e]	2	98
31	p-Cl	MC	4	75	35	100	0
32	"	AN	4	60	49	0	100
33	m-Cl	MC	2	180	75	90	10
34	"	AN	2	150	60	10	90
35	o-Cl	MC	8	50	71	30	70
36	"	AN	2	145	25	0	100
37	p-Br	MC	8.3	25	41	99	1
38	p-F	AN	2	145	44	15	85
39	o-NO_2	AN	2	175	5[f]	0	100
40	p-NO_2[g]	aq-AN	2	-	11	0	100

(a) See Table 1. (b) Isolated yield based on ArN_2BF_4.

(c) Determined by GLC. (d) GLC analysis with capirally column indicated the presence of small amounts of 4-arylcyclopentene.

(e) Anisole (8%) was formed. (f) Nitrobenzene (30%) was formed.

(g) *In-situ* prepared diazonium chloride was used.

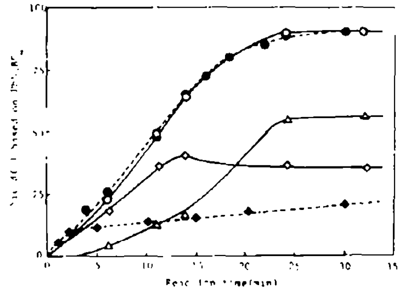


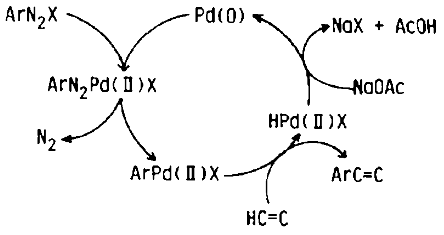
Fig. 1. Time course of phenylation of cyclopentene. ●, Gas evolution: ○, Total yield of phenylcylopentenes: ◇, 3-phenylcyclopentene, △, 1-phenylcyclopentene: ◆, Gas evolution in the absence of catalyst or base (Run 52 or 55).

reactive or water soluble. Table 3 shows the effects of various metal complexes and bases in the reaction of cyclopentene with benzenediazonium tetrafluoroborate at 24.5°. The best catalyst was proved to be $Pd(dba)_2$. Combinations of $Pd(dba)_2$ with a representative bidentate ligands (one molar equivalent) inhibited or markedly suppressed the arylation, and the rate of gas evolution decreased to the extent corresponding to spontaneous decomposition of diazonium salt in the absence of one of the reactants (see closed square in Fig. 1.) Tetrakis (triphenylphosphine) palladium(0) showed some catalytic activity, but was much less effective than $Pd(dba)_2$. The inhibitory effect seems to be related with the behavior of these ligand that they are better ligand to palladium in an oxidized state rather than in zero-valent state. Stabilization of arylpalladium species by their coordination is reasonably considered to depress its catalytic activity under the present reaction conditions. Other low valent metal complexes, $Ni(COD)_2$ and $[RhCl(COD)]_2$ showed no catalytic activity. Sodium acetate is most effective as base, and triethylamine, a good base in the Heck arylation,[4] reacted with diazonium salts to give tarry materials.

When a equimolar amount of benzenediazonium tetrafluoroborate was added to $Pd(dba)_2$ in acetonitrile, nitrogen was evolved immediately even at Dry Ice-methanol temperature, and its amount corresponded to that of the diazonium salt utilized. Addition of cyclopentene to the reaction mixture, and raising the temperature to 20 produced phenylcyclopentenes in a moderate yield (17%, based on $Pd(dba)_2$ used). While, in the presence of $(PPh_3)_4Pd(0)$ the diazonium salt afforded a mixture of aryl- and arylazopalladium complexes.[9]

$$ArN_2BF_4 + (PPh_3)_4Pd \rightarrow [ArPd(PPh_3)_3]^+BF_4^- + [ArN_2Pd(PPh_3)_3]^-BF_4^-.$$

The observations obtained in this study can be explained reasonably by the following catalytic cycle involving arylpalladium species (Scheme 2.) Counter anion (X) of diazonium salt might be replaced by acetate anion prior to the reaction of diazonium salt with Pd(0) when aqueous acetonitrile was used as solvent.



Scheme 2.

EXPERIMENTAL

Materials. All of the unsaturated compounds, solvents, ligands and crystalline arylamines were used as received except for 1-pyrrolidinyl-cyclopentene, which was prepared as described in the literature.[10] Liquid arylamines were distilled and stored under nitrogen. Dicyclo-octadiene nickel(0) (E. Merck, Darmstadt) was used as received. Tetrakis (triphenylphosphine) palladium(0),[11] bis (dibenzylideneacetone) palladium(0)[12] and cyclooctadiene rhodium(I) chloride[13] were prepared by the published methods. Arenediazonium tetrafluoroborates were prepared by the conventional method.[14]

General procedure. Reactions were carried out in a two-necked flask under nitrogen. An arenediazonium salt was added to a solution of unsaturated compound, sodium acetate and catalyst. After the completion of gas evolution, the arylated products were isolated by the method depending on the structure of the products Typical examples follow.

3-Phenylpropanal (Arylation in aqueous acetonitrile with in situ prepared diazonium salts). Aniline (0.1 mol) was diazotized by a conventional procedure in aqueous hydrochloric acid with aqueous sodium nitrite (7.0 g) at 0-5°. To the diazotized solution (total 150 ml) was added 25 g of sodium acetate and the solution was filtered. The cold filtration was added dropwise to a mixture of 0.2 mol of allyl alcohol, 0.002 mol of Li_2PdCl_4 and 2 g of sodium formate in 50 ml of 60% aqueous acetonitrile over a 30 min period at room temperature. The palladium solution had been warmed to 30 for 10-20 min to give a partial deposition of metallic palladium and cooled to room temperature before the addition of diazonium salt. A rapid gas evolution started immediately after the addition and ceased within 5 min after completion of the addition. Volatile products were separated by steam distillation. From the distillate, organic products were extracted by benzene (30 ml × 3). The organic extract was treated with saturated aqueous sodium bisulfite to form crystalline adduct. A distillation of an ether extract after a decomposition of the adduct by aqueous sodium carbonate gave 4.9 g of a mixture of phenylpropanols. B.p. 100-105°/15 mmHg. A GLC analysis revealed that the product was consisted with 90 of 3-phenylpropanol, 10% of 2-phenylpropanol and trace of cinnamaldehyde. Each product was separated by preparative GLC. NMR spectra of the products agreed with published spectra.[15]

3-Phenyl-2-methyl propanol. 2-Methallyl alcohol was used instead of allyl alcohol in the procedure described above. A distillation of the steam distillate gave 10 g of products (95% of $PhCH_2CH(CH_3)CHO$, 5% of $PhC(CH_3)_2CHO$ and trace of unknown compounds). A purification through the formation of sodium bisulfite adduct gave 7.0 g of 3-phenyl-2-methyl propanol with 99% purity. B.p. 83°/4 mmHg. The NMR spectrum was identical with the published one.[15]

Phenylcyclopentenes (Arylation in non-aqueous solvent with isolated diazonium tetrafluoroborate). To a mixture of 0.5 mmol of $Pd(dba)_2$, 76 mmol of sodium acetate and 50 mmol of cyclopentene in 80 ml of methylene chloride was added 25 mmol of benzenediazonium tetrafluoroborate all at once with stirring at room temperature. A rapid gas evolution and exothermic reaction were observed. Saturated aqueous

Table 3. Effect of catalyst and base on phenylation of cyclopentene.[a]

Run	Catalyst	Base	Solvent[b]	Rate of gas evolution[c]	Reaction time(min)	Yield[d] %
43	$Pd(dba)_2$	NaOAc	MC	fast	90	90
44	"	"	AC	fast	90	90
45	$Pd(dba)_2$-Diphos[e]	"	MC	slow	90	10
46	$Pd(dba)_2$-Dipy[e]	"	"	slow	90	0
47	$Pd(dba)_2$-Phen[e]	"	"	slow	90	0
48	$Pd(dba)_2$-TMEDA[e]	"	"	slow	90	0
49	$Pd(PPh_3)_4$	"	AN	slow	260	31[f]
50	$Ni(COD)_2$	"	"	slow	90	0
51	$[RhCl(COD)]_2$	"	"	slow	90	0
52	None	"	"	slow	90	0
53	$Pd(dba)_2$	Et_3N	"	fast	90	0
54	"	Na_2CO_3	"	slow	90	0
55	"	None	"	slow	90	0

(a) The following molar ratio was employed in thermostatted cell (24.5). Catalyst: PhN_2BF_4: Base: Cyclopentene = 1: 50 : 150: 150.

(b) See Table 1.

(c) fast: Gas evolution finished within 25 min. (See closed circle in Fig. 1.) slow: Gas evolution did not finish within the reaction time. (See closed square in Fig. 1.)

(d) GLC yield based on PhN_2BF_4.

(e) Equimolar amount of the ligand was used. Diphos: 1,2-bis(diphenylphosphino)ethane, Dipy: 2,2'-Dipyridine, Phen: *o*, *o*'-phenanthroline, TMEDA: N, N, N', N'-tetramethylethylenediamine.

(f) Diphenyl was also formed.

sodium carbonate (50 ml) was added to the reaction mixture after stirring for 1h. When acetonitrile was used as solvent, 100 ml of ether was added at this time. The organic layer was washed by 50 ml of aqueous sodium chloride and dried over anhydrous magnesium sulfate. After removal of excess olefin and solvent, the residue was purified by passing it through a short silica gel column with hexane. A distillation of the first fraction gave 2.53 g of phenylcyclopentenes. B.p. 102–107°/26 mmHg. Isomer distribution was determined by GLC analysis. Each isomer was separated by preparative GLC. 1-Phenylcyclopentene; m.p. 28–29°, NMR spectrum (ppm from TMS) 7.0–7.4 (m, Ph, 5H), 6.05 (t, J = 2, C2, 1H), 2.25–2.80 (m, C3 and C5, 4H), 1.95 (quintet with fine structure, J = 7, C4, 2H). 3-Phenylcyclopentene; 7.10 (s, Ph, 5H), 5.55–6.00 (m, C1 and C2, 2H), 3.81 (m, C3, 1H), 2.15–2.68 (m, C5 and trans proton to phenyl at C4, 3H), 1.40–2.15 (m, cis proton to phenyl at C4, 1H).

Arylcyclopentenes. All of the arylcyclopentenes were obtained by the almost same procedure described for phenylcyclopentenes. NMR spectra of 1- or 3-arylcyclopentenes closely resembled those of 1- or 3-phenylcyclopentene, respectively. *p*-Tolylcyclopentenes; b.p. 135–139°/50 mmHg. 1-*p*-Tolylcyclopentene; m.p. 54–57°. *m*-Tolylcyclopentenes; b.p. 121–123°/20 mmHg. 3-*o*-Tolylcyclopentene, b.p. 115–120°/25 mmHg. *p*-Methoxyphenylcyclopentenes; b.p. 140–141°/23 mmHg. 1-*p*-Methoxyphenylcyclopentene; m.p. 84–89°. 1-*p*-Chlorophenylcyclopentene; m.p 74–74.5°. 3-*p*-Chlorophenylcyclopentene; b.p. 128–130°/22 mmHg. *m*-Chlorophenylcyclopentenes; b.p. 133–141°/22 mmHg. *o*-Chlorophenylcyclopentenes; b.p. 120–124°/18 mmHg. 1-*p*-Bromophenylcyclopentene; m.p. 89–96.6°. *p*-Fluorophenylcyclopentenes; b.p. 97–98°/14 mmHg.

Two or three peaks on GLC of arylcyclopentenes were reduced to single peak corresponding to arylcyclopentane by hydrogenation (Pd/C, atmospheric pressure) except for halogenated phenylcyclopentenes, which gave a small amount of phenylcyclopentane with expected halogenophenylcyclopentane. The formation of phenylcyclopentane might be recognized by reductive dehalogenation.

Phenylcycloolefins. Phenylcyclohexenes; b.p. 124–125°/27 mmHg. Phenylcycloheptenes; b.p. 156–157°/43 mmHg. Phenylcyclooctenes; b.p. 115–118°/5 mmHg. All of these phenylcocloolefins were converted to corresponding phenylcycloalkanes by hydrogenation.

Phenylpentenes and -hexenes. GLC analysis of the distilled products revealed the presence of many isomers. The ratio of number of aliphatic protons to that of aromatic one on NMR spectrum was 9:5 for phenylpentenes and 11:5 for phenylhexenes. Phenylpentenes; b.p. 106–108°/43 mmHg. Phenylhexenes; b.p. 60–64°/5 mmHg.

Stilbene and ethyl cinnamate derivatives. Stilbene; m.p. 124.2–125.0°. 1-Methyl-1,2-diphenylethylene; m.p. 83.5–84.0°. 1,3-Diphenylpropene; b.p. 138°/6 mmHg. Ethylcinnamate; b.p. 114–115°/8 mmHg. Ethyl *p*-methylcinnamate; b.p. 131°/8 mmHg. Ethyl *m*-methylcinnamate; b.p. 120°/7 mmHg. NMR and IR spectra of these compounds were reasonably assigned to the expected structures. Stilbene and ethyl cinnamate were also confirmed by the comparison of IR, NMR and the retention time on GLC of authentic sample (commercial origin).

Vinylnaphthalenes. The same procedure described in the previous paper[1] was employed. 1-Vinylnaphthalene; b.p. 134–136°/21 mmHg. 2-Vinylnaphthalene; m.p. 64–66°.

Time course of the phenylation of cyclopentene. In a 20 ml of two necked thermostatted cell (24.5°), 0.05 mmol of $Pd(dba)_2$, 7.6 mmol of sodium acetate, 0.4 ml of cyclopentene, 8 ml of methylene chloride and undecane as internal standard for GLC were charged under N_2. Benzenediazonium tetrafluoroborate (2.5 mmol) was added all at once with stirring. Gas evolution was measured by gas buret continuously. Samples were withdrawn at appropriate time intervals by a microsyringe and directly analyzed on GLC (Silicone SE-30).

All of the reactions cited in Table 3 were carried out in the same procedure.

REFERENCES

[1] Part II: K. Kikukawa, N. Terao, K. Nagira, F. Wada and T. Matsuda, *Bull. Chem. Soc. Japan* **52**, 2609 (1979).

[2] C. S. Rondestvest, *Organic Reactions* **11**, 189 (1960); **24**, 225 (1977).

[3] M. P. Doyle, B. Siegfreid, R. C. Elliott and J. F. Dellaria, *J. Org. Chem.* **42**, 243 (1977).

[4] R. F. Heck, *Pure Appl. Chem.* **50**, 691 (1978); *Acc. Chem. Res.* **12**, 146 (1979).

[5] K. Kikukawa and T. Matsuda, *Chem. Lett.* 159 (1977).

[6] K. Kikukawa, K. Nagira and T. Matsuda, *Bull. Chem. Soc. Jpn* **50**, 2207 (1977).

[7] R. F. Heck, *J. Am. Chem. Soc.* **90**, 5518, 5526 (1968).

[8] R. F. Heck, *Ibid.* **93**, 6896 (1971).

[9] K. Kikukawa, R. Yamashita, M. Takagi, and T. Matsuda, *VIIIth Int. Conf. Organometallic Chemistry*, Kyoto (1977), Abstract p. 253.

[10] S. R. Sandler and W. Karo, *Organic Functional Group Preparations*, Vol. 1 p. 93. Academic Press, New York (1971).

[11] D. R. Coulson, *Inorganic Synth.* **13**, 121 (1972).

[12] T. Ukai, H. Kawazura, Y. Ishii, J. J. Bonnet and J. A. Ibers, *J. Organometal. Chem.* **65**, 253 (1974).

[13] J. A. McCleverty and G. Wilkinson, *Inorganic Synth.* **8**, 211 (1966).

[14] A. Roe, *Organic Reactions* **5**, 105 (1949).

[15] A. J. Chalk and S. A. Magennis, *J. Org. Chem.* **41**, 273 (1976).