

Ni(0)-Trialkylphosphine Complexes. Efficient Homo-coupling Catalyst for Aryl, Alkenyl, and Heteroaromatic Halides

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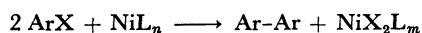
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Bis(trialkylphosphine)nickel(0) generated *in situ* from bis(trialkylphosphine)nickel(II) chloride was found to be an effective catalyst for a homo-coupling of aryl, alkenyl, or heteroaromatic halides with zinc powder. The catalytic reaction proceeded very well in NMP or HMPA solvent under mild conditions to afford dehalogenative-coupling products in good yields.

It has been shown recently that several zerovalent nickel complexes exhibit specific ability in a reductive coupling of aryl or alkenyl halides.¹⁾ These nickel(0) complexes may be divided into two groups according to the kinds of coordinated ligands: One group is characterized by the presence of phosphorus ligands, especially triphenylphosphine, while another is characterized by the absence of them.

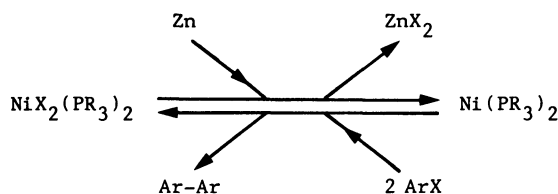


L = PPh₃,²⁻⁵⁾ 1,5-COD,^{2,6)} none (or solvent)⁷⁻⁹⁾ n, m = 2—4

Although the reactivities of nickel(0) complexes containing trialkylphosphine ligands in the coupling reaction have been little reported,³⁾ the complexes are much more reactive than triarylphosphine analogs in certain organometallic reactions, such as oxidative additions of aryl or alkenyl halides.¹⁰⁾ It is also known that trialkylphosphine ligands impart better thermal stability to some organometallics than triarylphosphine ligands do.¹¹⁾ Thus, nickel(0) complexes containing trialkylphosphine ligands are expected to show interesting reactivities in the title reaction. In this paper, we will describe a facile homo-coupling of aryl, alkenyl, and heteroaromatic halides with zinc powder in the presence of catalytic amounts of bis(trialkylphosphine)nickels(0) which are generated *in situ* by a reduction of bis(trialkylphosphine)nickel(II) chlorides, with zinc powder.

Results and Discussion

General Survey of Reaction Conditions and Homo-coupling of Aryl Halides. All zerovalent nickel used in this study were prepared *in situ* by the reduction of divalent nickel complexes with zinc powder.¹²⁾ 2—10 mol% of the nickel(II) precursor was used together with an excess of zinc powder intending to render the reaction catalytic in nickel as shown in Scheme 1 (*vide infra*).



Scheme 1.

Following this convenient method, bis(triphenylphosphine)-, bis(triethylphosphine)-, or metallic nickel(0) was generated *in situ*, and their catalytic activities in the homo-coupling of bromobenzene with zinc powder were compared with one other. Hexamethylphosphoric triamide (HMPA) was used as a solvent since *in situ* generated metallic nickel is known to work in the solvent.⁷⁾ Runs 1—3 in Table 1 clearly show that bis(triethylphosphine)nickel(0) is the most favorable judging from the turnover number of the catalyst. Encouraged by this result, the catalytic activities of nickel(0)-trialkylphosphine complexes toward various organic halides containing an otherwise inert sp²-carbon-halogen bond were investigated in detail.

Among the bis(trialkylphosphine)nickel(II)-chloride precursors examined, both triethylphosphine (PEt₃) and tributylphosphine (PBu₃) complexes gave biphenyl in better yields than either 1,2-bis(diethylphosphino)ethane (Et₂PCH₂CH₂PEt₂) or tricyclohexylphosphine (PCy₃) complex (Runs 7, 12, 14—16). The addition of two molar equivalents of tributylphosphine retarded the reaction with bis(tributylphosphine)nickel(II) chloride considerably (Runs 12 and 13).¹³⁾ As solvent for this reaction, *N*-methyl-2-pyrrolidone (NMP) as well as HMPA were effective, whereas other solvents like 1,1,2,2-tetramethylurea (TMU), *N,N*-dimethylformamide (DMF), acetonitrile (AN), or tetrahydrofuran (THF) were less effective (Runs 3, 7—11). Throughout the entire research, we preferred to use NMP unless otherwise noted since no special care need in the handling of this solvent in contrast with HMPA.¹⁴⁾ The addition of potassium iodide was effective for a smooth catalytic reaction (Runs 5 and 6).

The reaction of iodobenzene proceeded more readily than that of bromobenzene (Runs 5 and 7), whereas that of chlorobenzene did not react to completion even at elevated temperatures like 80 °C (Runs 17 and 18). Several functional groups such as ester, ketone, or alkyl were compatible with this reaction and a bulky substituent did not much alter the total reactivity (Runs 19—21). Thus, 2,2'-dibenzoylbiphenyl was readily obtained from 2-iodobenzophenone at 30 °C in a good yield.

Homo-coupling of Alkenyl Halides. The reaction of alkenyl bromides also proceeded very well under mild conditions to afford conjugated alkadienes in good yields as shown in Table 2. Interesting stereochemistry was observed in the reaction of (*E*)- or (*Z*)- β -bromostyrene: Only one of the two double bonds in the produced alkadiene retained the configuration of the

alkenyl halide (Runs 26 and 27). Thus, for example, (*E*)- β -bromostyrene afforded (*E,E*)-1,4-diphenyl-1,3-butadiene mainly with a small amount of (*E,Z*)-isomer, but no (*Z,Z*)-isomer. The fact that third isomers ((*E,E*)-isomer from (*Z*)-alkenyl halide and (*Z,Z*)-isomer from

(*E*)-alkenyl halide) were obtained from neither (*E*)- nor (*Z*)- β -bromostyrene seems to indicate that *cis*,*trans*-isomerization of the alkenyl group does not occur on nickel. Therefore, it may be speculated that the isomerization happened on the transferred-alkenyl ligand at

TABLE 1. NICKEL(0)-CATALYZED HOMO-COUPLING OF ARYL HALIDES^{a)}

Run	Aryl halide	Nickel(II) complex	Solvent	Temp °C	Time h	Biaryl ^{b)} %
1	C ₆ H ₅ Br	NiBr ₂ (PPh ₃) ₂	HMPA	30	2	25
2	C ₆ H ₅ Br	NiBr ₂	HMPA	30	2	34 ^{c)}
3	C ₆ H ₅ Br	NiCl ₂ (PEt ₃) ₂	HMPA	30	2	95
4	C ₆ H ₅ I	NiCl ₂ (PEt ₃) ₂	HMPA	25	3	93
5	C ₆ H ₅ I	NiCl ₂ (PEt ₃) ₂	NMP	25	1	88
6 ^{d)}	C ₆ H ₅ I	NiCl ₂ (PEt ₃) ₂	NMP	25	12	19
7	C ₆ H ₅ Br	NiCl ₂ (PEt ₃) ₂	NMP	30	2	74
8	C ₆ H ₅ Br	NiCl ₂ (PEt ₃) ₂	TMU	30	2	61
9	C ₆ H ₅ Br	NiCl ₂ (PEt ₃) ₂	DMF	50	12	15
10	C ₆ H ₅ Br	NiCl ₂ (PEt ₃) ₂	AN	50	12	0
11	C ₆ H ₅ Br	NiCl ₂ (PEt ₃) ₂	THF	50	12	0
12	C ₆ H ₅ Br	NiCl ₂ (PBu ₃) ₂	NMP	30	2	81
13 ^{e)}	C ₆ H ₅ Br	NiCl ₂ (PBu ₃) ₂	NMP	30	4	35 ^{f)}
14	C ₆ H ₅ Br	NiCl ₂ (Et ₂ PCH ₂ CH ₂ PEt ₂)	NMP	30	4	7 ^{g)}
15	C ₆ H ₅ Br	NiCl ₂ (PCy ₃) ₂	NMP	30	4	0
16	C ₆ H ₅ Br	NiCl ₂ (PCy ₃) ₂	NMP	80	4	75
17	C ₆ H ₅ Cl	NiCl ₂ (PBu ₃) ₂	HMPA	80	10	18
18	C ₆ H ₅ Cl	NiCl ₂ (PEt ₃) ₂	HMPA	80	10	25
19	<i>p</i> -CH ₃ C ₆ H ₄ I	NiCl ₂ (PEt ₃) ₂	NMP	30	2	(87)
20	<i>m</i> -CH ₃ O ₂ CC ₆ H ₄ Br	NiCl ₂ (PEt ₃) ₂	NMP	30	3	(91)
21	<i>o</i> -C ₆ H ₅ COC ₆ H ₄ I	NiCl ₂ (PEt ₃) ₂	NMP	30	6	(67)

a) In the presence of 0.25 mmol (Runs 1–18) or 2 mmol (Runs 19–21) of aryl halide in 0.3 ml (Runs 1–18) or 4 ml (Runs 19–21) of solvent under nitrogen. The molar ratio of the component was as follows: ArX/Ni(II)/Zn/KI=1.0/0.04/1.0/2.0 (Runs 1–16, 20, and 21), 1.0/0.08/1.0/2.0 (Run 17), 1.0/0.25/1.0/2.0 (Run 18), or 1.0/0.02/0.5/1.0 (Run 19). b) Yields were determined by GLC using internal standards. Yields in parentheses were isolated ones. c) 50% of iodobenzene was obtained. d) Run without potassium iodide. e) Run with 0.02 mmol of tributylphosphine. f) 38% of iodobenzene was obtained. g) 34% of iodobenzene was obtained.

TABLE 2. NICKEL(0)-CATALYZED HOMO-COUPLING OF ALKENYL AND HETEROAROMATIC HALIDES^{a)}

Run	RX	Solvent	Temp °C	Time h	R-R ^{b)} %
22	2-Bromo-1,1-diphenylethene	NMP	50	1	97
23	2-Bromo-1,1-diphenylethene	NMP	30	1.5	(96)
24	2-Bromo-1,1-diphenylethene	HMPA	50	1	97
25	1-Bromo-2-methylpropene	HMPA	50	1	83
26	(<i>Z</i>)- β -Bromostyrene ^{c)}	NMP	50	1	76 (3/20/77) ^{d)}
27	(<i>E</i>)- β -Bromostyrene ^{c)}	NMP	50	1	85 (95/5/0) ^{d)}
28	3-Bromofuran	HMPA	40	3	80
29	Methyl 2-bromo-5-furancarboxylate	HMPA	40	24	(90)
30	3-Iodothiophene	HMPA	40	1	(83)
31	2-Iodothiophene	HMPA	40	2	(87)
32	2-Bromothiophene	HMPA	40	4	7
33	3-Iodopyridine	HMPA	40	4	0
34	2-Iodopyridine	HMPA	40	4	0

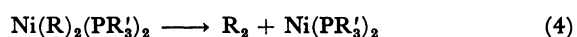
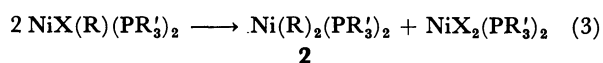
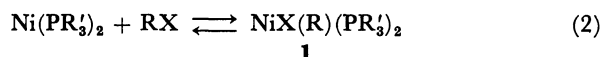
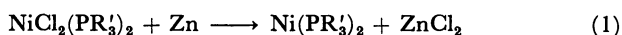
a) In the presence of 0.25 mmol (Runs 22, 24–28, 32–34) or 2 mmol (Runs 23, 29–31) of organic halide in 0.3 ml (Runs 22, 24–28, 32–34) or 4 ml (Runs 23, 29–31) of solvent under nitrogen. The molar ratio of the component was as follows: RX/NiCl₂(PEt₃)₂/Zn/KI=1.0/0.04/1.0/2.0 (Runs 22–27) or 1.0/0.1/1.5/2.0 (Runs 28–34). b) Yields were determined by GLC using internal standards. Yields in parentheses were isolated ones.

c) *Z/E*=98/2. d) (*E,E*) : (*E,Z*) : (*Z,Z*). e) *Z/E*<1/99.

the stage of disproportionation between two oxidative-addition adducts to produce a diorganonickel species (*vide infra*).

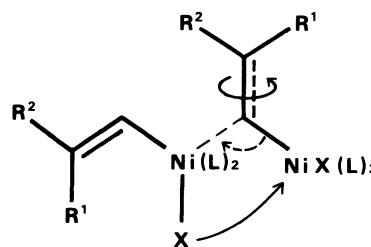
Homo-coupling of Heteroaromatic Halides. The homo-coupling of 2- or 3-bromofuran proceeded well in HMPA solvent to afford the corresponding dimer in good yield (Runs 28 and 29). On the other hand, neither reactions of 2- nor 3-bromothiophene proceeded to completion under conditions similar to those adopted above; however both iodothiophenes afforded dimers in good yields (Runs 30–32). In the case of 2- or 3-halopyridine, neither bromo nor iodo compounds afforded any of the corresponding dimers (Runs 33 and 34). Thus, the order of decreasing reactivities of heteroaromatic halides in the nickel(0)-catalyzed homo-coupling with zinc powder is 3-furyl \geq 2-furyl $>$ 2-thienyl, 3-thienyl $>$ 2-pyridyl, 3-pyridyl. Since, in a series of substituted halobenzenes, electron-withdrawing substituents usually enhance the reactivities in the nickel(0)-promoted homo-coupling,^{2,4,7,9} the least reactivities of halopyridines were unexpected judging from the fact that halopyridines have the most electron deficient heterocycles among the examined compounds.¹⁵ The observed difference in reactivities might suggest that not only a term of electron density but also other terms such as coordinating abilities of hetero atoms to nickel(0) and/or -(II) species must be considered as well when the reactivities of a series of heteroaromatic halides are compared.

Reaction Path. The results presented above lead to the following equations as the most plausible sequences of the reaction. The bis(trialkylphosphine)-nickel(0) which comes from the reduction of bis(trialkylphosphine)nickel(II) chloride with zinc powder



(Eq. 1) readily reacts with aryl, alkenyl, or some heteroaromatic halides to give an oxidative-addition adduct (1) (Eq. 2). Following this, the disproportionation between the two adducts occurs to give a nickel(II)-halide complex and a diorganonickel(II) species (2) (Eq. 3) which subsequently yields a dimer (Eq. 4). This type of decomposition is well-established and is not catalytic by nature.¹⁶ To ensure the catalytic cycle, the original nickel(0) must be regenerated from the nickel(II) thus formed, and zinc powder in at least a stoichiometric quantity is required.

It is well-known that oxidative addition of alkenyl halides towards various low valent transition metal complexes proceeds with retention of configuration¹⁷ and it is also believed that reductive elimination from various organometallic compounds proceeds again with retention of configuration of the alkenyl ligands.¹⁸ Thus, observed partial cis,trans-isomerization in the reaction of alkenyl halides probably happened at the stage of disproportionation on the trans-



ferred alkenyl ligand (*vide ante*).¹⁹

Experimental

All reagents including zinc powder (purchased from Kanto Chemicals) were used directly as obtained commercially, unless otherwise noted. The solvents were distilled and were dried over a Molecular Sieve (3A). The bis(trialkylphosphine)-nickel(II) chlorides were prepared by previously reported method.²⁰ 2-Iodobenzophenone,²¹ (*E*)-,²² or (*Z*)- β -bromostyrene,²³ 2-bromo-1,1-diphenylethene,²⁴ 2-,²⁵ or 3-iodopyridine,²⁶ and 3-iodothiophene²⁷ were prepared according to procedures in the literatures. A Hitachi 160 gas chromatograph was used for the GLC analysis. ¹H NMR spectra were obtained on a JOEL PMX 60 spectrometer.

General Procedure for Homo-coupling. **Preparation of Dimethyl 3,3'-Biphenyldicarboxylate:** A mixture of methyl *m*-bromobenzoate (430 mg, 2 mmol), bis(triethylphosphine)-nickel(II) chloride (29.3 mg, 0.08 mmol), zinc powder (134 mg, 2 mmol), potassium iodide (664 mg, 4 mmol), and NMP (4 ml) was evacuated, flushed with nitrogen, and kept at 30 °C for 3 h with stirring. To the resulting mixture, dilute hydrochloric acid (0.1 mol dm⁻³, 30 ml) was added. The organic materials were extracted with two 20 ml portions of ether, washed with three 30 ml portions of aqueous sodium chloride, and dried over anhydrous sodium sulfate. Evaporation of the solvent gave 247 mg of dimethyl 3,3'-biphenyldicarboxylate (91%) which was proved to be essentially pure and not contaminated by triethylphosphine by NMR and GLC analysis. Mp 99.5–101 °C (lit.²⁸ 104 °C). Recrystallization from ethanol gave 217 mg (80%) of the biaryl. Mp 102–103 °C. Found: C, 71.03; H, 5.26%. Calcd for C₁₆H₁₄O₄: C, 71.10; H, 5.22%.

4,4'-Dimethylbiphenyl: Mp 121–121.5 °C (lit.²⁹ 121 °C). Found: C, 92.36; H, 7.82%. Calcd for C₁₄H₁₄: C, 92.26; H, 7.74%.

2,2'-Dibenzoylbiphenyl: Mp 169.5–170.5 °C (lit.³⁰ 171 °C). Found: C, 86.15; H, 5.18%. Calcd for C₂₆H₁₈O₂: C, 86.15; H, 5.02%.

1,1,4,4-Tetraphenyl-1,3-butadiene: Mp 198.5–199.5 °C (lit.³¹ 207–210 °C). Found: C, 93.96; H, 6.31%. Calcd for C₂₈H₂₂: C, 93.81; H, 6.19%.

Dimethyl 2,2'-Bifuryl-5,5'-dicarboxylate: Mp 228–229 °C (lit.³² 233–234 °C). Found: C, 57.42; H, 3.98%. Calcd for C₁₂H₁₀O₆: C, 57.61; H, 4.03%.

3,3'-Bithienyl: Mp 133–134 °C (lit.³³ 130–132 °C). Found: C, 58.17; H, 3.69%. Calcd for C₈H₆S₂: C, 57.80; H, 3.64%.

2,2'-Bithienyl: Mp 28–29 °C (lit.³⁴ 33 °C). Found: C, 57.68; H, 3.67%. Calcd for C₈H₆S₂: C, 57.80; H, 3.64%.

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