Synthetic Methods

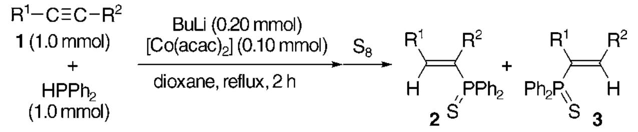
Cobalt-Catalyzed *syn* Hydrophosphination of Alkynes**

*Hirohisa Ohmiya, Hideki Yorimitsu, and Koichiro Oshima**

Organophosphorus compounds play vital roles in various fields of chemistry, for example, as synthetic reagents, ligands for transition-metal complexes, biologically active substances, advanced materials, and building blocks of supramolecular assemblies. Hydrophosphination, the addition of trivalent phosphine compounds to carbon–carbon multiple bonds, is a straightforward method for the synthesis of organophosphorus compounds.[1] In contrast to the ready availability of hydrophosphonylation reactions wherein pentavalent phosphorus compounds are involved,[2] hydrophosphination by metal catalysis often encounters difficulties. Lanthanide complexes catalyze hydrophosphinations with superb efficiency.[3] However, the catalytic system requires synthetic organic chemists to prepare intricate and highly air- and moisture-sensitive metal complexes. Although palladium- and nickel-catalyzed reactions have been reported, the scope of the alkynes available for use is limited.[4–6] Moreover, the stereoselectivity of reactions catalyzed by lanthanide and Group 10 reagents are highly substrate-dependent. The development of a facile, efficient, and general hydrophosphination reaction has been awaited. Herein, we report such a hydrophosphination reaction in the presence of a cobalt salt.[7] The reaction proceeded in a completely *syn* fashion, which is therefore complementary to *anti* selective radical hydrophosphination reactions.[8]

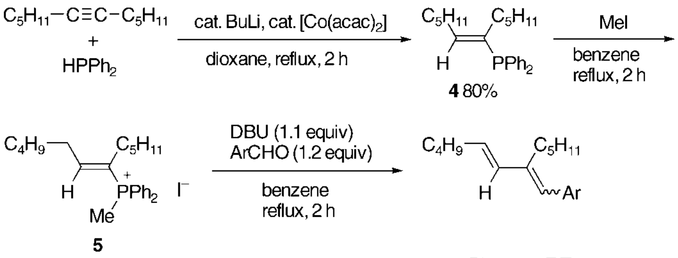
Treatment of diphenylphosphane (1.0 mmol) in THF (1.0 mL) with butyllithium (0.20 mmol) yielded an orange mixture of lithium diphenylphosphide and diphenylphosphane. [Co(acac)$_2$] (acac = acetylacetonate; 0.10 mmol), dioxane (3 mL), and 6-dodecyne (**1a**; 1.0 mmol) were added to the mixture. The resulting black mixture was heated at reflux for two hours to provide the corresponding *syn* adduct **2a** quantitatively after sulfidation[9] (Table 1, entry 1). The free alkenyldiphenylphosphane is relatively insensitive to oxygen so we could isolate 1-pentyl-1-heptenyldiphenylphosphane (**4**) in 80% yield on a 10-mmol scale without special care being required in its isolation and subsequent handling (Scheme 1).

Table 1: Cobalt-catalyzed *syn* hydrophosphination of alkynes.



Entry	R^1	R^2	**1a–m**	Yield [%][a]	**2a–m/3a–m**[a]
1	C_5H_{11}	C_5H_{11}	**1a**	100 (89)	–
2	C_5H_{11}	Me	**1b**	100 (82)	66:34
3	Ph	Me	**1c**	85 (74)	82:18
4	*p*-$MeOC_6H_4$	Me	**1d**	82 (79)	82:18
5	*p*-FC_6H_4	Me	**1e**	85 (82)	80:20
6[b]	*o*-$MeOC_6H_4$	Me	**1f**	49 (41)	80:20
7	$C_{10}H_{21}$	H	**1g**	93 (83)	71:29
8	*t*C_4H_9	H	**1h**	87 (81)	100:0
9[b]	$(PhCH_2)_2NCH_2$	H	**1i**	54 (42)	100:0
10[c]	Ph	H	**1j**	72 (70)	89:11
11[c]	*p*-$MeOC_6H_4$	H	**1k**	76 (72)	90:10
12	*p*-$H_2NC_6H_4$	H	**1l**	53 (49)	95:5
13[c]	Et_3Si	H	**1m**	69 (62)	94:6

[a] Yields were determined by ^{1}H NMR spectroscopic analysis with dibenzyl ether as an internal standard. Yields of isolated product are given in parentheses. [b] Reaction was carried out over 12 h. [c] Diphenylphosphane (1.5 mmol) was used.



6a: Ar = Ph; 61%, *E/Z* = 90:10

6b: Ar = *p*-BrC_6H_4; 61%, *E/Z* = 91:9

Scheme 1. The hydrophosphination reaction and further treatment of reaction product **4** to obtain a precusor of phosphorus ylides.

The reaction resulted in no or little conversion in the absence of either [Co(acac)$_2$] or butyllithium. Furthermore, butylmagnesium bromide, diethylzinc, and potassium *tert*-butoxide could not be used in place of butyllithium. The use of $CoCl_2$, [Co(acac)$_3$], or CoF_2 slightly lowered the yields by approximately 20% under reaction conditions that were otherwise the same. We examined [Rh(acac)$_2$], [Ru(acac)$_3$], [Pd(acac)$_2$], [Ni(acac)$_2$], [Mn(acac)$_2$], [Fe(acac)$_3$], CuI, $ReCl_3$, [Cp_2TiCl_2], and [Cp_2ZrCl_2] (Cp = cyclopentadienyl) as catalysts and none of them showed any catalytic activity. The reaction did not take place at ambient temperature, and dioxane proved to be the best solvent; others, such as heptane (63%), diethylene glycol dimethyl ether (diglyme; 53%), xylene (64%), and THF (29%) were shown to be less effective. Dicyclohexylphosphane, diphenylphosphane oxide, and dialkyl phosphite did not add to alkynes under similar conditions. The reaction was rendered slower as the amount of butyllithium or the cobalt catalyst was lowered; however, a longer reaction time resulted in high product yields, for example, a quantitative yield of **2a** was obtained after the

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[*] H. Ohmiya, Dr. H. Yorimitsu, Prof. Dr. K. Oshima
Department of Material Chemistry
Graduate School of Engineering, Kyoto University
Kyoto-daigaku Katsura, Nishikyo-ku, Kyoto 615-8510 (Japan)
Fax: (+81) 75-383-2438
E-mail: oshima@orgrxn.mbox.media.kyoto-u.ac.jp

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mixture was heated for 12 hours in the presence of 0.05 mmol of [Co(acac)$_2$] and 0.20 mmol of butyllithium.

A variety of alkynes were subjected to hydrophosphination (Table 1), and all reactions afforded the corresponding *syn* adducts exclusively irrespective of the substrates. The regioselectivity was governed by the steric interactions of the two alkyne substituents and was generally high in the reactions of **1**. The two resulting regioisomers could be readily separated from each other by chromatographic purification on silica gel or fractional crystallization from acetonitrile. The use of 1-aryl-1-propynes as the substrates provided 1-aryl-2-diphenylthiophosphinyl-1-propenes predominantly (entries 3–6). The methoxy substituent at the *ortho* position hindered the reaction, although no change in regioselectivity was observed (entry 6). Hydrophosphination of terminal alkynes was facile (entries 7–13), and addition across *tert*-butylacetylene led to the exclusive formation of **2h** (entry 8). Propargylamine **1i** underwent hydrophosphination with perfect *anti*-Markovnikov selectivity although the reaction rate was slow (entry 9). The reaction of aryl acetylenes afforded modest yields of the alkenylphosphine derivatives (entries 10–12). Interestingly, an amino moiety did not interfere with the reaction as much as would be expected (entry 12). Triethylsilylacetylene participated in the hydrophosphination to yield primarily a 1-silyl-2-thiophosphanylethene derivative (entry 13). The use of 1,6-heptadiyne as a substrate resulted in a complex mixture, and addition to conjugated diyne and diene compounds, such as 4,6-decadiyne and 1,3-undecadiene, led to slow conversion rates, thus giving the corresponding adducts in no more than 20 % yield. The exact mechanism of this reaction, including the role of the acac ligand, is not clear at this stage. Further investigation is necessary to clarify the reaction pathway.

We investigated the utility of the products of the hydrophosphination reaction (Scheme 1). The isolated free phosphane **4** was treated with iodomethane to produce phosphonium salt **5** and then benzaldehyde and 1,8-diazabicyclo-[5.4.0]undec-7-ene (DBU) were added to the salt. The reaction mixture was heated for two hours to provide the conjugated diene **6a** in good yield with concomitant production of styrene (30 %).[10] The preparation of ylides from 1-alkenylphosphines and their application to the Wittig reaction are rather difficult processes and have not been established so far.[11] The present strategy offers a simple synthesis of conjugated dienes and related π-electron systems.

In summary, we have developed a universally stereoselective hydrophosphination reaction of alkynes with diphenylphosphane that is mediated by a cobalt catalyst and butyllithium. The procedure is simple and scaleable; thus, it is applicable to the practical synthesis of new ligands and advanced materials.

Experimental Section

A typical procedure for the cobalt-catalyzed hydrophosphination of alkynes **1a**: A solution of diphenylphosphane (186 mg, 1.0 mmol) in anhydrous THF (1 mL) was placed in a 30-mL flask and butyllithium (1.6 M hexane solution, 0.13 mL, 0.20 mmol) was then added under argon. The mixture turned orange and was stirred for 30 min at 0 °C. Anhydrous [Co(acac)$_2$] (26 mg, 0.10 mmol), dioxane (3 mL), and 6-dodecyne (**1a**, 166 mg, 1.0 mmol) were added successively. The resulting black mixture was heated at reflux for 2 h. The reaction was quenched with distilled water (1 mL) after the mixture was cooled to room temperature and S_8 (32 mg, 0.10 mmol) was then added. The reaction mixture was stirred for 15 min at ambient temperature and then poured into water. The product was extracted with ethyl acetate (2 × 20 mL), the combined organic layers were dried over sodium sulfate, and the solvent was removed. ^{1}H NMR spectroscopic analysis with dibenzyl ether as an internal standard revealed quantitative formation of the corresponding product **2a**. Only one signal was detected by ^{31}P NMR spectroscopic analysis. Purification of the crude oil by column chromatography on silica gel (hexane/ethyl acetate, 20:1) provided **2a** (341 mg, 0.89 mmol) in 89 % yield.

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[9] An 80 % yield of 1-pentyl-1-heptenyldiphenylphosphane (**4**) was isolated without oxidation by the addition of sulfur. The yield for this compound is lower than that obtained after sulfidation (89 %), which results from slow oxidation of **4** by molecular oxygen. We isolated adducts as phosphane sulfides to clarify the efficiency of the hydrophosphination reaction (Table 1).

[10] The reaction with alphatic aldehydes suffered from low yields.

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