

A highly regioselective hydrophosphination of terminal alkynes with tetraphenyldiphosphine in the presence of palladium catalyst

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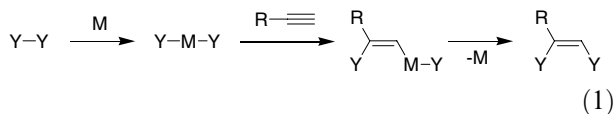
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Abstract—A novel palladium-catalyzed hydrophosphination of alkynes with tetraphenyldiphosphine takes place regioselectively to provide vinylic phosphines, which undergo air-oxidation during workups, affording the corresponding vinylphosphine oxides in good yields.

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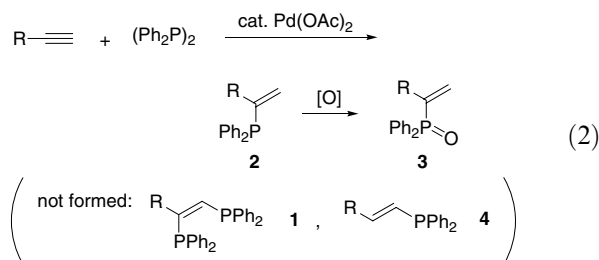
A number of transition-metal-catalyzed addition reactions with alkyne based on the cleavage of inter-element linkages,¹ such as B–B,² Si–Si,³ Ge–Ge,⁴ Sn–Sn,⁵ S–S,⁶ and Se–Se⁶ bonds, provide a useful tool to a variety of vicinally bifunctionalized alkenes, Eq. 1.



In 1991, we have revealed that organic disulfides and diselenides add to terminal alkynes stereoselectively in the presence of a palladium catalyst to afford the corresponding vicinal bithiolated and biselenated alkenes, respectively, in excellent yields.⁶ Since organic sulfur and selenium compounds were widely believed to be representative catalyst poisons, this finding has opened up a new field of transition-metal-catalyzed addition reactions of group 16 heteroatom compounds with alkynes.⁷

In sharp contrast, group 15 inter-element compounds such as diphosphines (R₂P–PR₂) have not been featured, despite organic phosphorus compounds being synthetically useful intermediates.⁸ Thus, we examined the reaction of tetraphenyldiphosphine (Ph₂P–PPh₂) with alkynes in the presence of several catalysts. Among the catalysts examined, divalent and zero-valent palladium

complexes, such as Pd(OAc)₂ and Pd(PPh₃)₄, exhibit catalytic activity toward the addition reactions to alkynes. Surprisingly, however, the desired bisphosphination⁹ of alkynes did not occur, and instead, novel hydrophosphination^{10–12} took place selectively. In this Letter, we wish to report a novel palladium-catalyzed hydrophosphination of alkynes with tetraphenyldiphosphine, Eq. 2.



When the reaction of alkyne (0.3 mmol) with tetraphenyldiphosphine (0.1 mmol) in the presence of palladium diacetate (5 mol %) in degassed C₆D₆ (0.6 mL) was conducted at 80 °C for 18 h, vinylphosphine (2) was formed regioselectively, which led to the corresponding vinylphosphine oxide (3) after usual workups under the atmosphere. In this reaction, neither bisphosphination product (1) nor regioisomeric hydrophosphination product (4) was obtained.

The vinylic area of the ¹H NMR spectra of the product formed by the palladium-catalyzed reaction of 1-octyne

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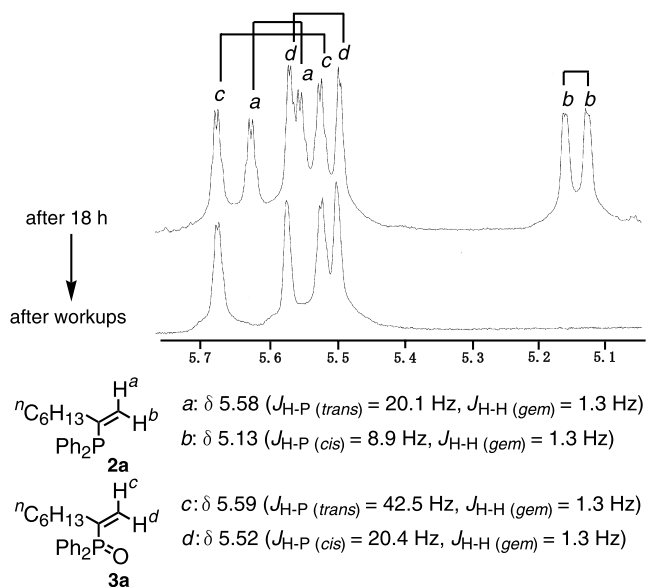


Figure 1. ^1H NMR Spectra (vinyl area) of vinylphosphine and its oxide.

with tetraphenyldiphosphine is shown in **Figure 1** (the upper spectrum: the resulting mixture after 18 h; the lower spectrum: the product obtained after workups under the atmosphere). These spectra show that the initial products are a mixture of vinylic phosphine (**2a**) and its oxide (**3a**), and the following air-oxidation of **2a** leads to the formation of vinylic phosphine oxide (**3a**) predominantly.

Table 1¹³ represents the results of the $\text{Pd}(\text{OAc})_2$ -catalyzed hydrophosphination of terminal alkynes with $(\text{Ph}_2\text{P})_2$. 1-Octyne and 5-methyl-1-hexyne underwent the palladium(0)-catalyzed hydrophosphination, providing the corresponding vinylic phosphine oxide (**3a** and **3b**), respectively, with excellent regioselectivity (entries 1 and 2). In the case of aromatic alkynes such as phenylacetylene and *p*-methylphenylacetylene, the hydrophosphination took place successfully (entries 3¹⁴ and 4). Functionalities such as cyano and chloro groups, are tolerant of the reaction, affording the corresponding hydrophosphination products (**3e** and **3f**) in good yields (entries 5¹⁵ and 6). On the other hand, internal alkynes did not undergo the desired hydrophosphination (the starting alkynes were recovered) (entry 7).

Although the reaction pathway for the present hydrophosphination of alkynes requires further detailed mechanistic investigations,¹⁶ a possible catalytic cycle is shown in **Scheme 1**: (1) the oxidative addition of tetraphenyldiphosphine to the low-valent palladium(0) complex generated in situ;^{17,18} (2) the coordination of alkyne to the palladium species followed by phosphino-palladation to afford a vinylpalladium intermediate (**A**); (3) the coordination of alkyne and the following reductive elimination to afford a vinylphosphine (**B**);¹⁹ (4) regeneration of the palladium catalyst by the elimination of alkynylphosphine²⁰ (**D**) from the alkynylpalladium intermediate (**C**).

Table 1. $\text{Pd}(\text{OAc})_2$ -catalyzed hydrophosphination of alkynes with $(\text{Ph}_2\text{P})_2$

$$\text{R-C}\equiv\text{C} + (\text{Ph}_2\text{P})_2 \xrightarrow[\text{C}_6\text{D}_6, 80^\circ\text{C}, 18\text{ h}]{\text{Pd}(\text{OAc})_2, 5\text{ mol}\%} \text{R-C}=\text{C}(\text{Ph}_2\text{P}) \xrightarrow{(\text{O})} \text{R-C}=\text{C}(\text{Ph}_2\text{P}=\text{O})$$

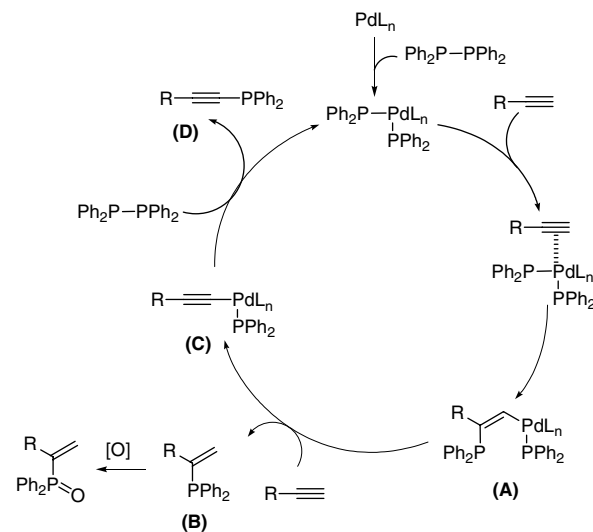
3a-f

Entry	Alkyne	Product	Yield ^a (%)
1	$n\text{-C}_6\text{H}_{13}\text{-C}\equiv\text{C}$	$n\text{-C}_6\text{H}_{13}\text{-C}=\text{C}(\text{Ph}_2\text{P}=\text{O})$ 3a	(58)
2	$\text{CH}_3\text{CH}_2\text{CH}_2\text{C}\equiv\text{CCH}_3$	$\text{CH}_3\text{CH}_2\text{CH}_2\text{-C}=\text{C}(\text{Ph}_2\text{P}=\text{O})$ 3b	57
3 ^b	$\text{Ph-C}\equiv\text{C}$	$\text{Ph-C}=\text{C}(\text{Ph}_2\text{P}=\text{O})$ 3c	68(66)
4	$\text{p-CH}_3\text{C}_6\text{H}_4\text{-C}\equiv\text{C}$	$\text{p-CH}_3\text{C}_6\text{H}_4\text{-C}=\text{C}(\text{Ph}_2\text{P}=\text{O})$ 3d	55
5 ^c	$\text{NC-CH}_2\text{CH}_2\text{C}\equiv\text{C}$	$\text{NC-CH}_2\text{CH}_2\text{-C}=\text{C}(\text{Ph}_2\text{P}=\text{O})$ 3e	79(50)
6	$\text{Cl-CH}_2\text{CH}_2\text{C}\equiv\text{C}$	$\text{Cl-CH}_2\text{CH}_2\text{-C}=\text{C}(\text{Ph}_2\text{P}=\text{O})$ 3f	78(75)
7	$\text{CH}_3\text{C}\equiv\text{CCH}_2\text{CH}_3$		No reaction

^a ^1H NMR (isolated) yield.

^b Alkyne (5 equiv).

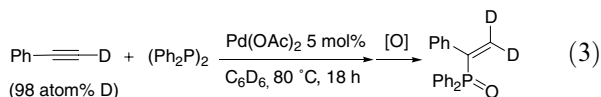
^c For 8 h.



Scheme 1. A possible reaction pathway for hydrophosphination of alkyne.

To clarify the hydrogen source of the present hydrophosphination of alkynes, we examined the palladium-catalyzed hydrophosphination using deuterated

phenylacetylene (98 at.% D), which provided the vinylphosphine oxide bearing two deuteriums on the terminal vinylic carbon (Eq. 3). Deuterium in C₆D₆ was not incorporated into the product. This result strongly suggests that the hydrogen source of the hydrophosphination comes from alkyne hydrogen.²¹ This is also supported by the fact that the hydrophosphination of internal alkynes did not proceed at all.



In summary, we have developed the highly regioselective hydrophosphination of terminal alkynes with tetraphenyldiphosphine catalyzed by palladium diacetate, which affords the corresponding 2-(diphenylphosphino)-1-alkenes in good yields. A detailed mechanistic study is now under investigation.

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13. When 1 mol of vinylphosphine oxide (**3**) was obtained from 1 mol of $(\text{Ph}_2\text{P})_2$, the yield was determined to be 100%.
14. For the spectral and analytical data of **3c**, see: 2-(Diphenylphosphinyl)-1-styrene: yellow oil; IR (neat) 3060, 1436, 1180, 1116, 727, 694, 532 cm^{-1} ; ^1H NMR (CDCl_3) δ 5.75 (d, $J = 20.0$ Hz, 1H), 6.24 (d, $J = 40.0$ Hz, 1H), 7.25 (d, $J = 40.0$ Hz, 3H), 7.42–7.60 (m, 8H), 7.72 (t, $J = 9.8$ Hz 4H); ^{13}C NMR (CDCl_3) δ 128.14 (d, $J = 8.2$ Hz), 128.47 (d, $J = 13.2$ Hz), 131.97 (d, $J = 13.2$ Hz); ^{31}P NMR (CDCl_3) δ 30.8; HRMS calcd for $\text{C}_{20}\text{H}_{17}\text{OP}$: 304.1017. Found: 304.1021.
15. For the spectral and analytical data of **3e**, see: 5-Cyano-2-(diphenylphosphinyl)-1-pentene: brown oil; IR (neat) 2358, 2341, 1437, 1182, 1119, 723, 696, 540 cm^{-1} ; ^1H NMR (CDCl_3) δ 1.83–1.99 (m, 2H), 2.25–2.37 (m, 2H), 2.46–2.53 (m, 2H), 5.58 (d, $J = 19.8$ Hz, 1H), 5.98 (d, $J = 42.3$ Hz, 1H), 7.50–7.62 (m, 6H), 7.62–7.83 (m, 4H); ^{13}C NMR (CDCl_3) δ 16.55, 24.46, 31.38, 119.20, 124.69, 130.69, 131.98 (d, $J = 42.2$ Hz); ^{31}P NMR (C_6D_6) δ 28.7; HRMS calcd for $\text{C}_{18}\text{H}_{18}\text{NOP}$: 295.1126. Found: 295.1129; Anal. Calcd for $\text{C}_{18}\text{H}_{18}\text{NOP}$: C, 73.21; H, 6.14; N, 4.74. Found: C, 72.92; H, 6.05; N, 4.58.
16. Since $(\text{Ph}_2\text{P})_2$ is subjected to air-oxidation, the influence of oxygen on this hydrophosphination is now under investigation.
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18. The formation of palladium(0) complex requires the presence of small amounts of water. The existence of H_2O was partly supported by the fact that the presence of small amounts of $\text{Ph}_2\text{P}(\text{O})\text{H}$ was confirmed by the measurement of ^{31}P NMR ($\delta = 18.1$ ppm, C_6D_6).
19. Although the precise pathway should wait for further detailed mechanistic experiments, a possible pathway from (**A**) to (**B**) may involve σ bond metathesis between vinylic C–Pd bond and acetylenic H–C bond of alkyne.
20. The presence of the alkynylphosphine (**D**) was confirmed by the measurement of ^{31}P NMR ($\delta = -32.5$ ppm, C_6D_6). The isolation of alkynylphosphine (**D**) was difficult due to its similar polarity as those of other by-products.
21. The fact that the hydrophosphination of alkynes in C_6D_6 did not afford any deuterized vinylphosphine, strongly suggests that the vinylic hydrogen of vinylphosphine was not derived from the solvent.