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Regio- and Stereoselective Synthesis of Alkenylphosphines: A Rhodium-Catalyzed Hydrophosphination of Alkynes Using a Silylphosphine

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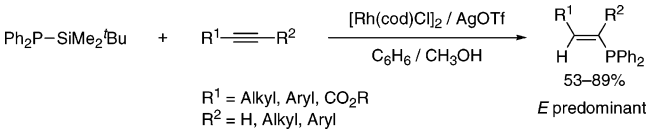

A novel rhodium-catalyzed hydrophosphination of alkynes using a silylphosphine as a phosphino group source is described. A variety of alkynes, both terminal and internal ones with aryl, alkyl, and carboxyl groups, gave the corresponding alkenylphosphines in a highly regioselective and syn-selective manner. Alkenes with an electron-withdrawing group also gave the corresponding adducts in good yields.

Organophosphorus compounds have received much attention because of their essential role in various fields of chemistry, especially when used as ligands in transition-metal catalysis. Although a variety of sophisticated phosphine ligands have been prepared for several kinds of catalytic reactions with high reactivity and/or selectivity, the preparation of these well-designed phosphorus compounds depends heavily on the classical phosphination methods using highly reactive organometals under extreme conditions or on the indirect oxidation−reduction processes through P(V) derivatives.[1] Although alkenylphosphines are a promising class of organophosphorus compounds both as synthetic reagents[2] and as ligands, their use is quite limited mainly because of the difficulties in their synthesis when using the methods mentioned above.[3,4] Some recent reports have described straightforward preparations of alkenylphosphines through the addition of secondary phosphines to alkynes but with certain limitations, for example, limitations of the substrate structure, selectivities, and availability of the catalyst.[5−7] We report here a novel hydrophosphination of carbon−carbon unsaturated bonds with a silylphosphine in the presence of a cationic rhodium catalyst, yielding a wide variety of alkenylphosphines with high regio- and stereoselectivities.

Silylphosphines offer considerable potential as synthetic equivalents of phosphines, masked phosphines, or phosphides, for the synthesis of several organophosphorus compounds.[8−10] However, catalytic reactions of silylphosphines, especially transition-metal-catalyzed reactions with cleavage of silicon−phosphorus bonds, are still limited.[10] Thus, we first surveyed suitable catalysts for the addition of a silylphosphine to a carbon−carbon triple bond via activation of the silicon−phosphorus bond. The reactivity of each catalyst was evaluated by using the reaction of (*tert*-butyldimethylsilyl)diphenylphosphine **1a** and ethynylbenzene **2a** in benzene under reflux (Table 1). Several catalysts such as Ru(0), Ru(II), Rh(I), Pd(0), Pd(II), and Ir(I) complexes, with or without additives or external ligands, were used in an attempt to realize the coupling reaction.[11] Among the tested catalysts, only cationic rhodium catalysts, generated by adding AgOTf to chlororhodium complexes, worked as expected to give the corresponding adduct.

Surprisingly, the silyl group did not incorporate into the adduct at all; instead, protodesilylated product **3a** was solely

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(3) Synthesis of alkenylphosphines by the uncatalyzed addition of lithium diphenylphosphide to phenylacetylene, see: Aguiar, A. M.; Archibald, T. G. *Tetrahedron Lett.* **1966**, 5471−5475.

(4) Catalytic addition of P(V)−H to alkynes, see: (a) Han, L.-B.; Tanaka, M. *Chem. Commun.* **1999**, 395−402. (b) Tanaka, M. *Top. Curr. Chem.* **2004**, *232*, 25−54.

(5) (a) Wicht, D. K.; Glueck, D. S. In *Catalytic Heterofunctionalization*; Togni, A., Grützmacher, H., Eds.; Wiley−VCH: Weinheim, 2001; Chapter 5. (b) Delacroix, O.; Gaumont, A. C. *Curr. Org. Chem.* **2005**, *9*, 1851−1882. (c) Alonso, F.; Beletskaya, I. P.; Yus, M. *Chem. Rev.* **2004**, *104*, 3079−3159.

(6) Ni- and Pd-catalyzed hydrophosphination: (a) Kazankova, M. A.; Efimova, I. V.; Kochetkov, A. N.; Afanas'ev, V. V.; Beletskaya, I. P. *Russ. J. Org. Chem.* **2002**, *38*, 1465−1474. (b) Kazankova, M. A.; Efimova, I. V.; Kochetkov, A. N.; Afanas'ev, V. V.; Beletskaya, I. P.; Dixneul, P. H. *Synlett* **2001**, 497−500. Co-catalyzed hydrophosphination, see: ref 4. Ru-catalyzed hydrophosphination: (c) Jérôme, F.; Monnier, F.; Lawicka, H.; Dérien, S.; Dixneuf, P. H. *Chem. Commun.* **2003**, *9*, 696−697. Yb-catalyzed hydrophosphination: (d) Komeyama, K.; Kobayashi, D.; Yamamoto, Y.; Takehira, K.; Takaki, K. *Tetrahedron* **2006**, *62*, 2511−2519. (e) Takaki, K.; Komeyama, K.; Kobayashi, D.; Kawabata, T.; Takehira, K. *J. Alloys Compd.* **2006**, *408*−*412*, 432−436. (f) Komeyama, K.; Kawabata, T.; Takehira, K.; Takaki, K. *J. Org. Chem.* **2005**, *70*, 7260−7266. (g) Takaki, K.; Koshoji, G.; Komeyama, K.; Takeda, M.; Shishido, T.; Kitani, A.; Takehira, K. *J. Org. Chem.* **2003**, *68*, 6554−6565. (h) Takaki, K.; Takeda, M.; Koshoji, G.; Shishido, T.; Takehira, K. *Tetrahedron Lett.* **2001**, *42*, 6357−6360.

(7) Addition of phosphine−borane to alkynes: Mimeau, D.; Gaumont, A.-C. *J. Org. Chem.* **2003**, *68*, 7016−7022.

(8) For a review, see: Fritz, G.; Scheer, P. *Chem. Rev.* **2000**, *100*, 3341−3401.

(9) (a) Hayashi, M.; Matsuura, Y.; Watanabe, Y. *Tetrahedron Lett.* **2005**, *46*, 5135−5138. (b) Hayashi, M.; Matsuura, Y.; Watanabe, Y. *Tetrahedron Lett.* **2004**, *45*, 9167−9169. (c) Hirano, K.; Yorimitsu, H.; Oshima, K. *Org. Lett.* **2004**, *6*, 4873−4875. (d) Kolodiazhnyi, O. I.; Guliaiko, I. V.; Kolodiazhna, A. O. *Tetrahedron Lett.* **2004**, *45*, 6955−6957.

(10) Transition-metal-catalyzed reaction of silylphosphines (a) Pd-catalyzed cross-coupling with aryl halides: Tunney, S. E.; Stille, J. K. *J. Org. Chem.* **1987**, 52, 748−753. (b) Ni-catalyzed cross-coupling with alkenyl halides: Kazankova, M. A.; Chirkov, E. A.; Kochetkov, A. N.; Efimova, I. V.; Beletskaya, I. P. *Tetrahedron Lett.* **1999**, *40*, 573−576. (c) Yb-catalyzed silylphosphination of alkynes: see ref 6e.

(11) The metal complexes with higher oxidation numbers were expected to be reduced since the Pd(II) complexes were reported to be reduced to Pd(0) by the reaction with a silylphosphine.[10a]

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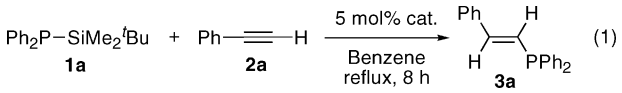
TABLE 1. Survey of the Rhodium Catalysts Suitable for the Reaction of 1a and 2a[a]

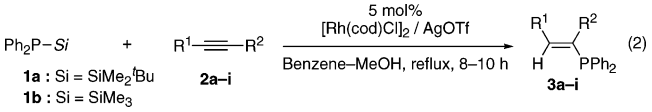
entry	catalyst	additives[a]	yield (%)[b]	*E*/*Z*[c]
1	$RhCl(PPh_3)_3$			
2	$RhCl(PPh_3)_3$	AgOTf	48	25:75
3	$[Rh(cod)Cl]_2$[d]			
4	$[Rh(cod)Cl]_2$[d]	AgOTf	72	95:5
5	$[Rh(cod)Cl]_2$[d]	AgOTf + MeOH	89	96:4
6	$[Rh(cod)Cl]_2$[d]	MeOH		
7	$[Rh(cod)Cl]_2$[d]	AgOTf + Ph_3P	50	30:70
8	[Rh(cod)Cl][d]	AgOTf + dppe[d]	62	50:50
9	$[Rh(cod)Cl]_2$[d]	$AgBF_4$		
10		AgOTf		

[a] The conditions indicated in eq 1 were applied in all cases. Amount of additives: AgOTf (5 mol %), Ph_3P (12 mol %), dppe (6 mol %), and MeOH (ca. 1.5 equiv). [b] Isolated yields. [c] Determined by ^1H NMR. [d] Abbreviations: cod, 1,5-cyclooctadiene; dppe, 1,2-bis(diphenylphosphino)ethane.



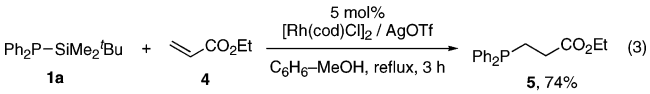
formed even though no proton source was added.[12] When the catalyst prepared in situ from $[Rh(cod)Cl]_2$ and AgOTf was used, syn-hydrophosphination proceeded to give the E isomer of **3a** with high regio- and stereoselectivities (entry 4). Addition of a small amount of methanol was effective for completing the cationic rhodium-catalyzed hydrophosphination (entry 5), whereas the neutral rhodium catalyst was not affected by methanol (entry 6). The reaction required the presence of both the rhodium catalyst and the silver salt; neither the neutral rhodium complex nor the silver triflate catalyzed the reaction individually. Entry 9 showed that the reactivity is strongly affected by the counteranion of the catalyst. Entries 2, 7, and 8 demonstrated that the presence of tertiary phosphine ligands decreased the selectivity and/or reactivity.[13] Aromatic hydrocarbons such as benzene or toluene are suitable solvents for this reaction, and heating is necessary for initial formation of active catalytic species where the color of the reaction mixture turned from yellow to dark red.[14]

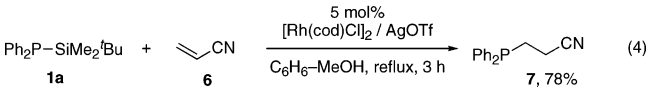
Selected results of the hydrophosphination of alkynes using $[Rh(cod)Cl]_2$/AgOTf as a catalyst are summarized in Table 2.



As shown in eq 2 and Table 2, several alkynes and silylphosphines undergo cationic rhodium-catalyzed hydrophosphination yielding the corresponding alkenylphosphines with high selectivities. In general, silylphosphine **1a** is the superior substrate as a result of its stability and degree of reactivity, but a similar reactivity of commercially available silylphosphine **1b** demonstrates the applicability of the reaction (entries 1 and 2). Notably, this reaction is very tolerant of the substituents in alkynes. syn-Hydrophosphination predominates in all cases with high selectivity. Terminal alkynes, irrespective of the presence of an alkyl or an aryl substituent, undergo hydrophosphination smoothly to give the corresponding alkenylphosphines **3a**−**d** in good yields (entries 1−5). In these cases, excellent regioselectivities are also observed; only traces of regioisomers could be detected by ^1H and ^{31}P NMR analyses of the reaction mixture. It should be noted that aliphatic alkynes also produced adducts with high selectivities, which are difficult to access by the other reported catalytic methods.[2,6e] Internal alkynes, regardless of their substituents, also gave hydrophosphination products in good yields and selectivities. Entries 6 and 7 demonstrated that the phosphine group shows a high tendency to attach to the β position of the alkene of the aromatic substituent. β-Phosphinoacrylates **3h**,**i** could be regioselectively obtained by the present hydrophosphination of substituted propiolates **2h**,**i**.[15] These results indicate that the transformation tolerates an alkoxycarbonyl group, which is a stronger directing group for β selectivity of phosphine addition than an aryl or alkyl substituent (entries 9 and 10).

In addition to alkynes, the present catalytic reaction could be extended to hydrophosphination of activated alkenes. The reaction of ethyl acrylate **4** and acrylonitrile **6** with **1a** under similar conditions gave the corresponding β-phosphinopropionic acid derivatives in good yields (eqs 3 and 4). Unfortunately, unactivated alkene such as styrene and 1-hexene gave no adduct.





A plausible mechanism is represented as follows: (1) coordination of the silylphosphine to the cationic Rh(I), (2) oxidative addition of the Si−P bond to the Rh(I) to give a Rh(III) intermediate, (3) coordination of an alkyne followed by insertion to the Rh−P bond to form an alkenylrhodium intermediate, and (4) cleavage of the Rh−Si bond of the intermediate via Si−H exchange by the action of a protic additive followed by reductive elimination to give the product and the original Rh(I) catalyst. Although several attempts of direct observation of the intermediates failed, a deuterium labeling experiment gave important evidence of the mechanism; when the reaction of 6-dodecyne was conducted in the presence of MeOD with a reduced amount of catalyst (1 mol %), almost one D atom (93% D) was incorporated into two positions (eq 5); one was the β position (alkenyl-D, 14%), and the other was the γ position (allylic-D, 79%). Formation of the latter one

(12) The authors could not confirm the certain source of the incorporated proton in these cases. However, a considerable amount of the silanol was formed as a side product in these reactions. Thus, the authors suggest that the proton may come from the contaminated water in hygroscopic AgOTf, though the triflate was thoroughly dried (over P_2O_5, 140 °C/0.1 mmHg, 2 h) and was handled with ordinary care.

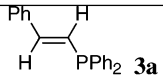
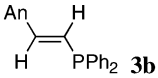
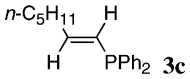
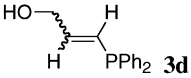
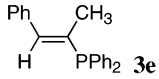
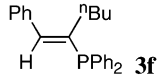
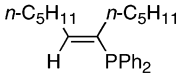
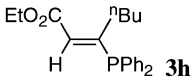
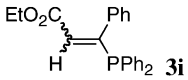
(13) The products of hydrophosphination, alkenylphosphines, did not interfere with the active species of the catalyst, though the products have a P(III) atom to coordinate. The reaction proceeded smoothly with the same reactivity and selectivity even in the presence of the alkenylphosphine product added externally to the catalyst.

(14) The color of the reaction mixture turned yellow again when all of the substrate was consumed.

(15) Electron deficient alkynes such as acetylenedicarboxylates and alkynylketones are known to undergo spontaneous insertion into the silicon−phosphorus bond of a silylphosphine to give the β-silylalkenylphosphines.[16] We found that substituted propiolates **2h**,**i** did not react directly with silylphosphines, even though those alkynes are classified as electron deficient alkynes. Therefore, **2h**,**i** could be applied as substrates of the present hydrophosphination.

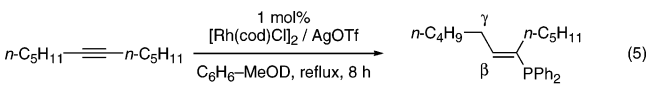
(16) See for examples: (a) Couret, C.; Escudie, J.; Satge, J.; Anh, N. T.; Soussan, G. *J. Organomet. Chem.* **1975**, *91*, 11−30. (b) Reisser, M.; Maier, A.; Maas, G. *Synlett* **2002**, 1459−1462.

TABLE 2. Rhodium-Catalyzed Hydrophosphination of Alkynes Using Silylphosphines 1a or 1b

Entry	Silylphosphine	Alkyne	Product	Yield (%) [a]	*E* : *Z* [b]
1	**1a**	Ph—≡—H **2a**	 **3a**	89	96 : 4
2	**1b**	**2a**	**3a**	77	96 : 4
3	**1a**	An—≡—H **2b**	 **3b**	53 [c]	92 : 8
4	**1a**	*n*-C_5H_{11}—≡—H **2c**	 **3c**	78	95 : 5
5	**1a**	$HOCH_2$—≡—H **2d**	 **3d**	66	80 : 20
6	**1a**	Ph—≡—CH_3 **2e**	 **3e**	68	92 : 8
7	**1a**	Ph—≡—^{n}Bu **2f**	 **3f**	72 [d]	95 : 5
8	**1a**	*n*-C_5H_{11}—≡—*n*-C_5H_{11} **2g**	 **3g**	67	>99 : 1
9	**1a**	EtO_2C—≡—^{n}Bu **2h**	 **3h**	81 [d]	>99 : 1
10	**1a**	EtO_2C—≡—Ph **2i**	 **3i**	76	80 : 20

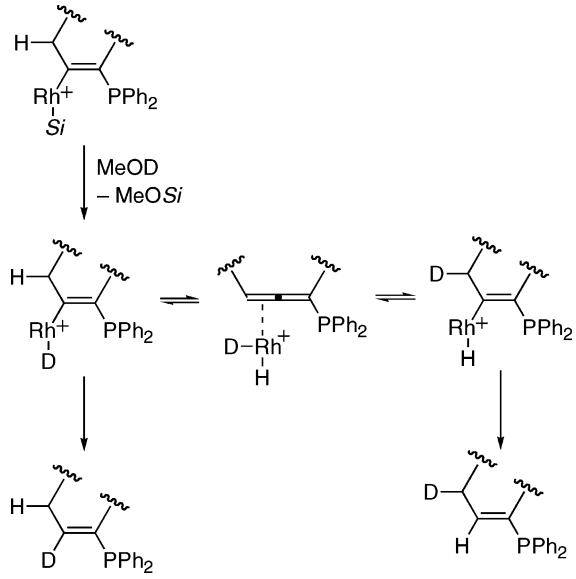
[a] Isolated yields. [b] Determined by ^1H and ^{31}P NMR. [c] An = *p*-$CH_3OC_6H_4$—. [d] Products were isolated as phosphine oxides after aerobic oxidation.

suggested the existence of alkenyl—Rh—D intermediate, which led to H—D exchange at the allylic position via the *β*-H elimination and to re-insertion of Rh—D to the resulted allenylphosphine (Scheme 1). Thus, the alcohol should cleave not the Rh—C bond but the Rh—Si bond at step (4) to give the Rh—D intermediate. Formation of the silyl ether also supported this route.



Several types of hydrophosphination of alkynes with P(III)—C bond formation[4−7] have been reported. Although some of those reactions include a coupling reaction of alkynes with silylphosphines, little superiority of the silyl group is observed in these reactions; the silylphosphine is reported to be less reactive than a secondary phosphine, or it gives a mixture of hydrophosphination and silylphosphination products.[6e,h,10b] On the contrary, the present reaction proceeded only with silylphosphines; no

SCHEME 1



adduct formed when a secondary phosphine (Ph_2PH), instead of a silylphosphine, was used as a phosphine source. In addition to the reported hydrophosphination procedures including radical addition (anti adducts) and metal-catalyzed addition (mainly syn adducts), this hydrophosphination provides a new method of highly selective alkenylphosphine synthesis with advantages from the applicability and selectivity point of view.

Experimental Section

General Procedure. To a solution of $[Rh(cod)Cl]_2$ (6 mg, 12.5 μmol) and MeOH (20 μL) in anhydrous benzene (2 mL) was added silver triflate (6 mg, 25 μmol) under argon. After the mixture was stirred for 20 min at room temperature, alkyne (0.50 mmol) and silylphosphine (0.6 mmol) were added successively. The mixture turned red with the addition of silylphosphine. The resulting mixture was heated under reflux until the color of the mixture turned from dark red to yellow (about 8−10 h). After the reaction mixture was concentrated, purification of the crude product by column chromatography on silica gel afforded the corresponding alkenylphosphine.

Acknowledgment. The authors wish to thank the Venture Business Laboratory of Ehime University for NMR measurements.

Supporting Information Available: Experimental details and characterization data for **3a**−**i**, **5**, and **7** and ^1H, ^{13}C, and ^{31}P NMR spectra of **3a**−**i**, **5**, and **7**. This material is available free of charge via the Internet at http://pubs.acs.org.

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