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Switch in Stereoselectivity Caused by the Isocyanide Structure in the Rhodium-Catalyzed Silylimination of Alkynes

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Supporting Information

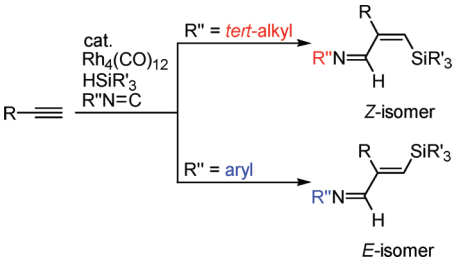
ABSTRACT: The reaction of terminal alkynes with hydrosilanes and *tert*-alkyl isocyanides in the presence of $Rh_4(CO)_{12}$ gives (*Z*)-*β*-silyl-α,*β*-unsaturated imines in good yields. On the other hand, the use of aryl isocyanides in place of *tert*-alkyl isocyanides leads to the formation of *E* isomers.

Recent advances have resulted in an expanded use of vinylsilanes as reagents in electrophilic substitution[1] and transition-metal-catalyzed cross-coupling reactions.[2] The regio- and stereoselective addition of silicon compounds (e.g., Si−E with E = H, Si, Ge, Sn, B, P, S, Se, Te, CN, etc.) to C≡C triple bonds in the presence of Lewis acids or transition-metal complexes is an efficient strategy for preparing stereodefined vinylsilanes.[3] A high degree of stereochemical control has been attained in the hydrosilylation of alkynes for selective production of both cis and trans addition products, depending on the reaction conditions used.[4] Other reactions usually proceed in a cis fashion, except for the trans carbosilylation of alkynes catalyzed by Lewis acids.[5] The reaction mechanism involves syn addition of either a Si−M bond or a M−E bond to the alkyne, followed by reductive elimination after oxidative addition of the Si−E bond to the transition metal to form a Si−M−E species. Treatment of alkynes with a combination of a hydrosilane and carbon monoxide also gives mainly cis addition products as the result of the addition of silyl and formyl groups across the C≡C triple bonds. This reaction is known as silylformylation of alkynes.[6]

Isocyanides, which are isoelectronic with CO, are often employed as synthetic surrogates of CO in the production of imine derivatives under acid or transition-metal catalysis.[7] Unlike CO, both the electronic and steric nature of isocyanides permit improvements in both product yield and selectivity and occasionally allow the course of the reaction to be controlled.[8,9] Herein we report on the rhodium-catalyzed reaction of alkynes with hydrosilanes and isocyanides to afford *β*-silyl-α,*β*-unsaturated imines. Interestingly, silylimination with aryl isocyanides leads to the formation of *E* isomers, while the use of *tert*-alkyl isocyanides gives *Z* isomers (Scheme 1).[10]

Treatment of phenylacetylene (**1a**, 1 mmol) with dimethylphenylsilane (2 mmol) and 1,1,3,3-tetramethylbutyl isocyanide (*tert*-octyl isocyanide, 2 mmol) in the presence of $Rh_4(CO)_{12}$ (0.015 mmol) as a catalyst in tetrahydrofuran (THF) at 70 °C for 30 min gave imine **2a** in 91% yield with 93% *Z* selectivity, as determined by ^{1}H NMR analysis of the reaction mixture (Table 1, entry 1). An attempt to isolate **2a** by bulb-to-bulb distillation under reduced pressure resulted in a decrease in the yield to 53%. Therefore, the imine was hydrolyzed to give the corresponding aldehyde **9a** without loss in the product yield or *E*/*Z* ratio (Scheme 2). Whereas $HSiEt_2Me$ also reacted to give (*Z*)-**2a′** stereoselectively (*E*/*Z* = 12/88) in 67% yield, the desired product was not obtained when $HSi(OMe)_3$ was used under the present reaction conditions.

Scheme 1. $Rh_4(CO)_{12}$-Catalyzed Reactions of Alkynes with Hydrosilanes and Isocyanides



In examining isocyanides other than *tert*-octyl isocyanide, we found that the stereoselectivity of the product could be switched depending on the substituent on the isocyanide nitrogen. Isocyanides bearing *tert*-alkyl groups, such as 1-adamantyl and *tert*-butyl isocyanides, also reacted with **1a** and $HSiMe_2Ph$ to predominantly give *Z* isomers, although the stereoselective outcome was decreased slightly in comparison with that of *tert*-octyl isocyanide (entries 2 and 3). The use of cyclohexyl and butyl isocyanides provided **5a** and **6a**, respectively, in good yields with a roughly equal mixture of (*E*)- and (*Z*)-imines (entries 4 and 5). In contrast, high *E* selectivity was attained when 2,6-dimethylphenyl isocyanide (xylyl isocyanide) or 2,6-diethylphenyl isocyanide was employed in the catalytic reaction (entries 6 and 7). In addition, hydrolysis of **7a** gave **9a** in 82% isolated yield with retention of the *E* selectivity (*E*/*Z* = 98/2).

Several types of alkynes were subjected to the catalytic reaction with $HSiMe_2Ph$ and either *tert*-octyl isocyanide or xylyl isocyanide in order to evaluate the scope and limitations of the present transformation, and the results are summarized in Table 2. Functional groups such as methoxy (**1c**), ester (**1d**), and trifluoromethyl (**1e**) groups at the para position of the aromatic ring were tolerated in the reaction, although electron-withdrawing substituents retarded the reaction rate (entries 5−10). A switch in *E*/*Z* selectivity for the product imines was also observed in reactions of other aryl-substituted alkynes with the same product ratio as was found for **1a**. The vinyl-substituted alkyne **1f** was reacted under each set of reaction conditions to

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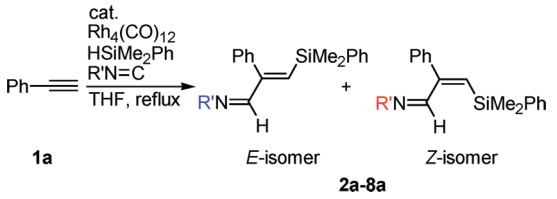
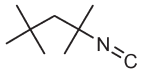
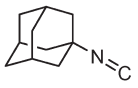
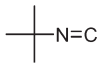
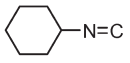
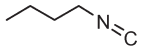
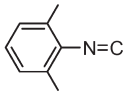
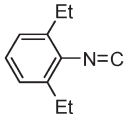
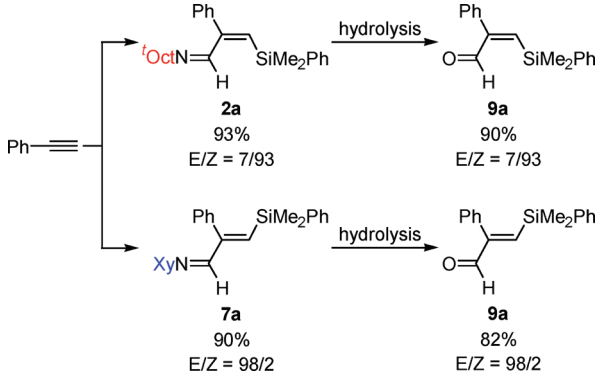
Table 1. $Rh_4(CO)_{12}$-Catalyzed Silylimination of 1a with $HSiMe_2Ph$ and Various Types of Isocyanides[a]



entry	R'N=C	time h	product[b] compd	yield %	E/Z
1[c]		0.5	**2a**	91	**7/93**
2		0.5	**3a**	83	11/89
3		1	**4a**	78	16/84
4		1	**5a**	83	43/57
5		1	**6a**	95	42/58
6		2	**7a**	90	**98/2**
7		20	**8a**	45	98/2

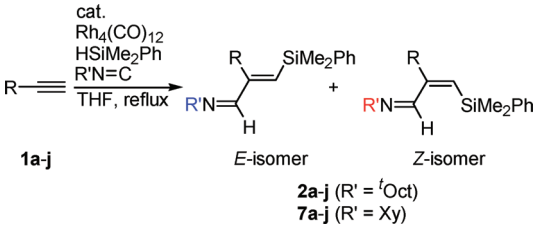
[a] Reaction conditions: **1a** (1 mmol), $HSiMe_2Ph$ (2 mmol), isocyanide (2 mmol), and $Rh_4(CO)_{12}$ (0.015 mmol) in THF (8 mL) at 70 °C. [b] Product yields and *E*/*Z* ratios were determined by ^1H NMR spectroscopy using 1,3,5-trimethoxybenzene as an internal standard. [c] Isolated yield was 53% (*E*/*Z* = 10/90) as the imine.

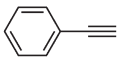
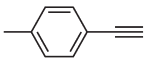
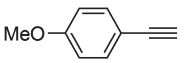
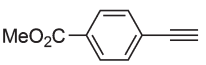
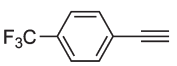
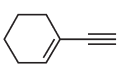
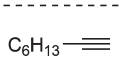
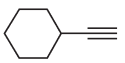
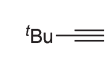
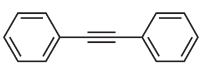
Scheme 2. Hydrolysis of Imines 2a and 7a to Aldehyde 9a



give (*Z*)-**2f** (entry 11) and (*E*)-**7f** (entry 12). The reaction of 1-octyne (**1g**) with $HSiMe_2Ph$ and *tert*-octyl isocyanide under the original reaction conditions afforded **2g** with moderate

Table 2. $Rh_4(CO)_{12}$-Catalyzed Silylimination of Alkynes with $HSiMe_2Ph$ and *tert*-Octyl Isocyanide or Xylyl Isocyanide[a]



entry	alkyne	R'	time h	product[b] compd	yield %	E/Z
1		^{t}Oct	0.5	**2a**	91	7/93
2	**1a**	Xy	2	**7a**	90	98/2
3		^{t}Oct	0.5	**2b**	95	7/93
4	**1b**	Xy	1	**7b**	92	98/2
5		^{t}Oct	0.25	**2c**	94	7/93
6	**1c**	Xy	0.5	**7c**	89	98/2
7		^{t}Oct	1	**2d**	91	7/93
8	**1d**	Xy	8	**7d**	73	98/2
9		^{t}Oct	1.5	**2e**	84	6/94
10[c]	**1e**	Xy	3	**7e**	75	98/2
11		^{t}Oct	0.5	**2f**	86	6/94
12	**1f**	Xy	4	**7f**	85	97/3
13		^{t}Oct	0.5	**2g**	88	30/70
14[d]	**1g**	^{t}Oct	24	**2g**	62	12/88
15		Xy	4	**7g**	86	93/7
16		^{t}Oct	0.5	**2h**	98	5/95
17	**1h**	Xy	4	**7h**	98	66/34
18		^{t}Oct	0.5	**2i**	88	0/100
19	**1i**	Xy	4	**7i**	85	15/85
20		^{t}Oct	3	**2j**	82	34/66
21	**1j**	Xy	12	**7j**	60[e]	37/63

[a] Reaction conditions: alkyne (1 mmol), $HSiMe_2Ph$ (2 mmol), isocyanide (2 mmol), and $Rh_4(CO)_{12}$ (0.015 mmol) in THF (8 mL) at 70 °C. [b] Product yields and *E*/*Z* ratios were determined by ^1H NMR spectroscopy using 1,3,5-trimethoxybenzene as an internal standard. [c] $Rh_4(CO)_{12}$ (0.02 mmol). [d] THF (1 mL) at 40 °C. [e] The hydrosilylation product was also obtained in 30% yield.

selectivity (*E*/*Z* = 30/70), but this was improved to 12/88 by decreasing the reaction temperature to 40 °C (entries 13 and 14). However, this protocol was not applicable to sterically demanding alkynes [e.g., *tert*-butylacetylene (**1i**)] or internal alkynes [e.g., diphenylacetylene (**1j**)] (entries 18−21).

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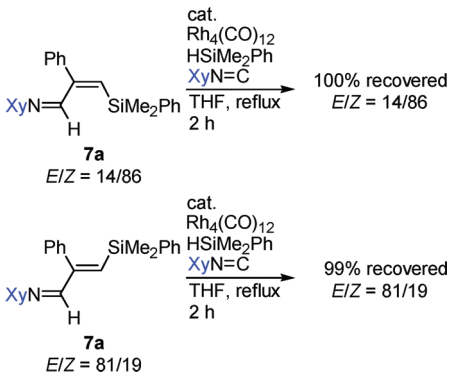
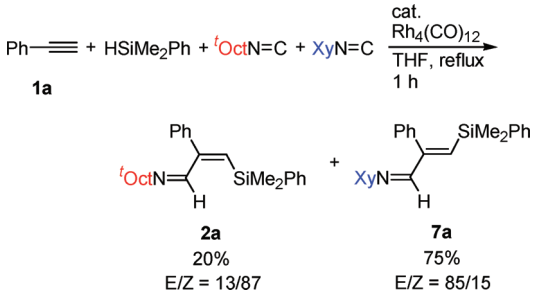
To examine the reaction mechanism and especially to gain information regarding the *Z*-to-*E* isomerization process, some additional experiments were carried out. The reaction mechanism for silylimination, which would be expected to be closely related to that for silylformylation, should essentially afford *Z* isomers. Thus, isolated *Z*-rich **7a** (*E*/*Z* = 14/86) was exposed to the standard reaction conditions in place of an alkyne in order to study the stability of the products. However no isomerization occurred, and 100% of the starting material was recovered. *E*-rich **7a** (*E*/*Z* = 81/19) also remained intact under the same reaction conditions (Scheme 3). These results suggest that *Z*-to-*E* isomerization likely occurs during the silylimination catalytic cycle, for example, via the formation of a zwitterionic carbene-metal[11] or a metallacyclopropene[12] intermediate derived from the (*Z*)-β-silylvinylmetal complex or via direct anti addition of the silylmetal species to an alkyne.[13]

Scheme 3. *E*/*Z* Stability of 7a



Scheme 4. Silylimination of 1a in the Presence of Equimolar Amounts of *tert*-Octyl Isocyanide and Xylyl Isocyanide



Ph—≡ + HSiMe2Ph + tOctN=C + XyN=C

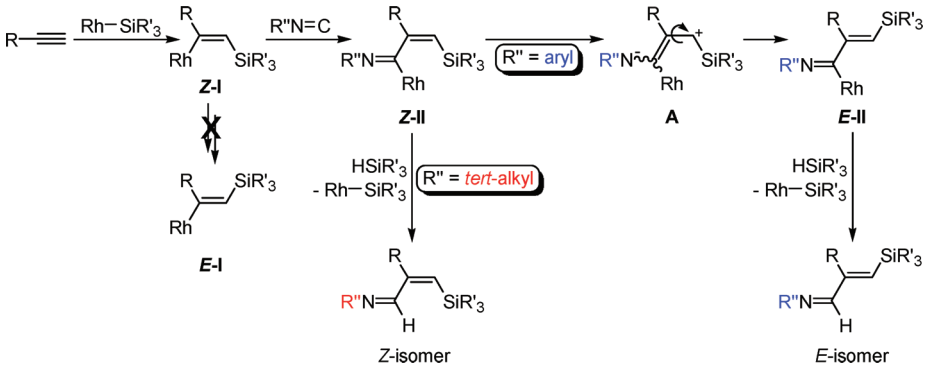
The reaction of **1a** in the presence of equimolar amounts of *tert*-octyl isocyanide and xylyl isocyanide was next examined to estimate the variation in the distribution of products. To our surprise, *E*-rich **7a** (*E*/*Z* = 85/15) was obtained as a major product along with *Z*-rich **2a** (*E*/*Z* = 13/87), indicating that the stereoselective preferences for both **2a** and **7a** in the reactions of **1a** with *tert*-octyl and xylyl isocyanide were maintained (Scheme 4). This observation indicates that the isomerization likely occurs after the formation of the iminometal species via the insertion of the isocyanide into the Rh−C bond.

A mechanistic rationale for the present catalytic reaction is proposed in Scheme 5. Formation of the Rh−Si species by the reaction of $Rh_4(CO)_{12}$ with a hydrosilane, followed by syn addition of the Rh−Si bond to an alkyne affords the (*Z*)-β-silylvinylrhodium species **Z-I**. Subsequent insertion of an isocyanide into the Rh−C bond forms the iminorhodium intermediate **Z-II**, which subsequently reacts with a hydrosilane to give the *Z* isomer with regeneration of the Rh−Si species when *tert*-alkyl isocyanides are employed. In case of the reaction with aryl isocyanides leading to the formation of *E* isomers, we propose that the zwitterionic intermediate **A** is formed in the isomerization of **Z-II** to **E-II**, with stabilization of the anion on the nitrogen by the electron-withdrawing aryl group.[14] It would appear that the reasonably good *E* selectivities in the reactions of aryl- and vinyl-substituted terminal alkynes with aryl isocyanides can be attributed to the stabilization of the vinyl intermediate **A** by conjugation with the unsaturated substituents. However, this does not account for the results obtained when primary- and secondary-alkyl-substituted isocyanides are used at the present stage.

In the competition experiment shown in Scheme 4, a mixture of (*E*)- and (*Z*)-**7a** was obtained as the main product, although the reaction with xylyl isocyanide alone was slower than that with *tert*-octyl isocyanide (Table 2, entries 1 and 2). One possible explanation for the results is that *tert*-octyl isocyanide is a better ligand than xylyl isocyanide in terms of accelerating the reaction, while on the other hand, the migration of the β-silylvinyl group in **Z-I** to the carbon atom of xylyl isocyanide coordinated on the rhodium center to give **Z-II** occurs more readily than in the case of *tert*-octyl isocyanide because of the electron-withdrawing nature of the aryl group on the isocyanide nitrogen.

In conclusion, we have reported on the discovery of an interesting stereochemical switch in the rhodium-catalyzed silylimination of alkynes to give vinylsilane derivatives. A new reaction

Scheme 5. Plausible Reaction Mechanism



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pathway involving the production of a zwitterionic species has been proposed to explain the formation of *E* isomers. Further investigations dealing with the relationship between the substituent on the isocyanide nitrogen and the product stereoselectivity, details of the reaction mechanism, and the synthetic utility of this stereoselective reaction are currently underway.

■ ASSOCIATED CONTENT

Supporting Information. Experimental procedures and characterization data for all new compounds. This material is available free of charge via the Internet at http://pubs.acs.org.

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