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Silane-Promoted Cycloisomerization of Functionalized 1,6-Dienes Catalyzed by a Cationic (π-Allyl)palladium Complex

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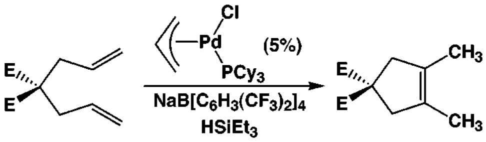
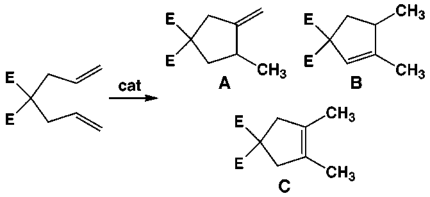
ABSTRACT



A 1:1 mixture of the (π-allyl)palladium complex (η^3-C_3H_5)Pd(Cl)PCy_3 and NaB[3,5-$C_6H_3(CF_3)_2$]$_4$ in the presence of $HSiEt_3$ catalyzed the cycloisomerization of functionalized 1,6-dienes to form 1,2-disubstituted cyclopentenes in good yield with high selectivity (typically >94%). The protocol tolerated a range of functional groups and substitution at one of the allylic carbon atoms.

The cycloisomerization of enynes employing Mo,[1] Ru,[2] Ti,[3] and especially Pd[4] catalysts has proven an efficient route toward the synthesis of functionalized carbocycles.[5] In contrast, diene cycloisomerization has remained less developed. For example, electrophilic d^0 Sc[6] and Zr[7] metallocene complexes readily catalyze the cycloisomerization of dienes to form methylenecycloalkanes. However, the utility of these procedures suffers from the limited functional group compatibility and excessive air and moisture sensitivity of the oxophilic catalyst. One approach toward ameliorating these limitations is through employment of a late-transition-metal catalyst. Unfortunately, early attempts to effect diene cycloisomerization employing a late-transition-metal catalyst required forcing conditions in an acidic medium.[8] However, the selective conversion of functionalized 1,6-dienes to methylenecyclopentanes (**A**) has recently been demonstrated by employing either a Ru[9] or a Ni[10] catalyst.[11] In contrast, the selective conversion of 1,6-dienes to 1-methyl- or 1,2-dimethylcyclopentenes (**B** or **C**) under mild conditions has not been demonstrated.[12] Here we report a palladium-catalyzed, silane-promoted protocol for the selective conver-



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(12) Rajanbabu has reported 74% selectivity (91% yield) for the conversion of dimethyl diallylmalonate to 4,4-dicarbomethoxy-1,2-dimethylcyclopentene catalyzed by a 1:2:2 mixture of [(η^3-C_3H_5)PdCl]$_2$, AgOTf, and P(4-C_6H_4OMe)$_3$.[10]

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sion of 1,6-dienes to 1,2-disubstituted cyclopentenes within minutes at room temperature under neutral conditions.

We recently reported several related procedures for the cyclization/hydrosilylation of 1,6- and 1,7-dienes catalyzed by cationic palladium phenanthroline and related complexes.[13] These complexes were initially targeted as diene cyclization catalysts due to their high reactivity with respect to olefin β-migratory insertion and/or σ-bond metathesis.[14,15] Similarly, the cationic (π-allyl)palladium complex $[(\eta^3\text{-}C_3H_5)Pd(OEt_2)PCy_3]^+[BAr_4]^-$ (Ar = 3,5-$C_6H_3(CF_3)_2$; **1**) is reactive toward olefin insertion and catalyzes the dimerization of functionalized olefins.[16] We therefore considered that **1** might also serve as a diene cyclization/hydrosilylation catalyst. However, reaction of dimethyl diallylmalonate (**2**) and triethylsilane (1.5 equiv) in the presence of **1** [generated in situ from a 1:1 mixture of (η^3-C_3H_5)Pd(Me)PCy_3 (**1a**) and $HBAr_4$·OEt_2 (**1b**);[16] 5 mol %] at room temperature for 10 min gave none of the expected cyclization/hydrosilylation product and instead yielded 4,4-dicarbomethoxy-1,2-dimethylcyclopentene (**3**) as the exclusive product in 89% yield and >97% isomeric purity (Scheme 1).

Scheme 1

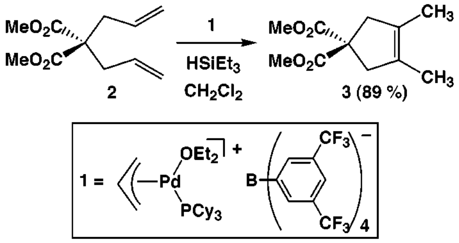
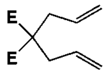
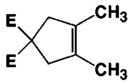
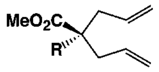
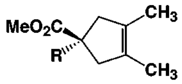
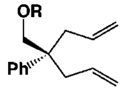
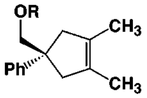
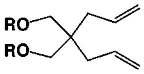
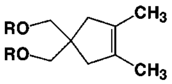
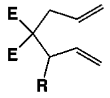
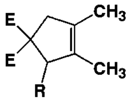
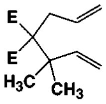
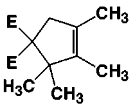
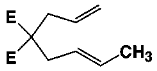
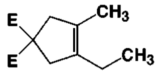


Table 1. Cycloisomerization of 1,6-Dienes Catalyzed by a 1:1 Mixture of (η^3-C_3H_5)Pd(Cl)PCy_3 (**1c**) and $NaBAr_4$ (Ar = 3,5-$C_6H_3(CF_3)_2$; **1d**) (5 mol %) in CH_2Cl_2 Containing $HSiEt_3$ for 15 min at 25 °C

entry	diene	carbocycle	yield (%)[a]	isomeric purity (%)[b]
				
1	E = CO_2Me		86	97
2	E = CO_2Bn		82	98
3	E = CO_2t-Bu		71	97
				
4	R = Ph		79	94
5	R = COMe		89	98
				
6	R = COMe		85	97
7	R = CO*t*-Bu		89	97
				
8	R = COMe		99	97
9	R = CO*t*-Bu		89	98
				
10	R = Me, E = CO_2Et		82	95
11	R = Ph, E = CO_2Me		71	97
				
12	E = CO_2Me		82	96
13				
	E = CO_2Me		84	76[c]

[a] Yield refers to isolated material of >95% purity. [b] Determined by capillary GC. [c] Minor isomer was 1,1-dicarbomethoxy-3-ethylidene-4-methylcyclopentane.

Halide abstraction from the palladium chloride complex (η^3-C_3H_5)Pd(Cl)PCy_3 (**1c**) with $NaBAr_4$ (**1d**) also generated an active cycloisomerization catalyst which converted **2** to **3** with a rate, yield, and selectivity comparable to the catalyst generated from **1a** and **1b** (Table 1, entry 1).[17,18] In addition, the halide abstraction route to catalyst generation benefited from the enhanced thermal stability and greater availability of the precatalysts.[16] However, a stoichiometric amount of triethylsilane was crucial for efficient cycloisomerization. In the absence of $HSiEt_3$, palladium-catalyzed isomerization of **2** occurred slowly over 12 h at room temperature to form a 6:5:1:1 mixture of **3**, 1,1-dicarbomethoxy-3-methyl-4-methylenecyclopentane,[10] and two unidentified isomers in 65% combined yield. Employment of <1 equiv of $HSiEt_3$ or employment of a bulkier silane led to a dramatic decrease in the efficiency of palladium-catalyzed diene cycloisomerization.[19]

The palladium-catalyzed protocol converted a range of functionalized 1,6-dienes to 1,2-disubstituted cyclopentenes

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(17) Halide abstraction employing $NaBAr_4$ has been shown to form cationic palladium complexes.[14c] Because no ether is present in the boronate salt, the exact structure of the cationic species generated from **1c** and **1d** is unknown.

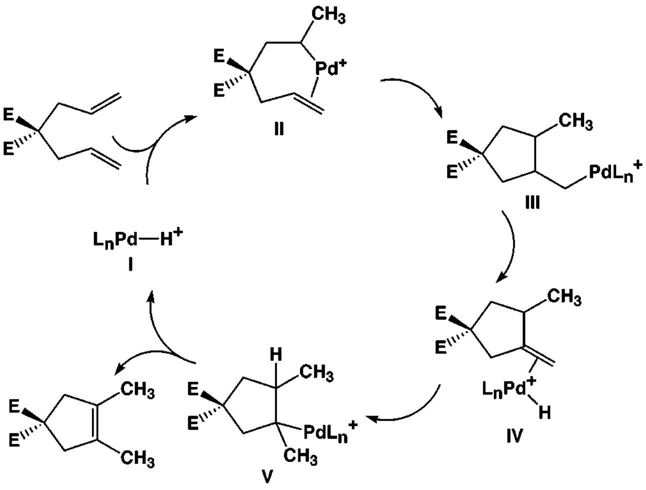
(18) Typical experimental procedure: **2** (100 mg, 0.47 mmol) and $HSiEt_3$ (80 mg, 0.70 mmol) were added sequentially via syringe to a solution of **1c** (10 mg, 0.022 mmol) and **1d** (24 mg, 0.024 mmol) in CH_2Cl_2 (8 mL) at 0 °C. The resulting yellow solution was stirred at room temperature for 15 min to form a dark brown solution. Solvent was evaporated under vacuum, and the oily residue was chromatographed (SiO_2, 12:1 hexane−EtOAc) to give **3** (89 mg, 89%) as a colorless oil.

(19) For example, dimethyl-*tert*-butylsilane failed to promote cycloisomerization, while employment of dimethylphenylsilane led to 58% yield for conversion of **2** to **3**.

in good yield with high selectivity (Table 1). For example, diesters (Table 1, entries 1−3), monoesters (Table 1, entries 4, 5), protected alcohols (Table 1, entries 6, 7), and protected diols (Table 1, entries 8, 9) underwent palladium-catalyzed cycloisomerization within 15 min at room temperature to form the corresponding cyclopentenes in >70% yield with ≥94% isomeric purity. In addition, dienes which possessed substitution at an allylic carbon atom underwent facile cycloisomerization in high yield and with good selectivity (Table 1, entries 10−12). Dienes which possessed a substituted olefin underwent rapid cycloisomerization in high yield, although considerable erosion of selectivity was observed (Table 1, entry 13).[20]

We propose a plausible mechanism for palladium-catalyzed diene cycloisomerization initiated by the cationic palladium hydride intermediate **I** (Scheme 2). β-Migratory insertion of an olefin into the Pd−H bond of **I** followed by insertion of the pendant olefin into the Pd−C bond of palladium alkyl olefin intermediate **II** could generate palladium cyclopentylmethyl intermediate **III**. β-Hydride elimination to form the palladium methylenecyclopentyl intermediate **IV** followed by reinsertion could form the palladium tertiary alkyl intermediate **V**. Subsequent β-hydride elimination of the tertiary β-hydrogen atom would form the observed cyclopentene and regenerate **I**.

Scheme 2



Triethylsilane presumably serves two key roles in the cycloisomerization process. Because $HSiEt_3$ dramatically increased the rate of cycloisomerization, the silane may facilitate formation of the active palladium hydride species **I**. The mechanism by which this may occur is unclear, as direct reaction of a hydrosilane with an electrophilic late-transition-metal alkyl complex typically leads to the formation of a metal silyl complex rather than a metal hydride complex.[15,21] In addition, because the selectivity of the process increased considerably in the presence of $HSiEt_3$, the silane may also facilitate the conversion of palladium alkenyl intermediate **IV** to palladium alkyl intermediate **V**.

In summary, a 1:1 mixture of (η^3-C_3H_5)Pd(Cl)PCy_3 (**1c**) and $NaBAr_4$ (**1d**) in the presence of $HSiEt_3$ catalyzed the cycloisomerization of functionalized 1,6-dienes to form 1,2-disubstituted cyclopentenes in good yield with high selectivity. The protocol tolerated a range of functionality and allylic substitution. We are currently working toward the development of more efficient diene cycloisomerization catalysts and toward elucidation of the role of silane in these isomerization reactions.

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

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[20] 1,7-Dienes and terminally disubstitued dienes failed to undergo cycloisomerization.

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