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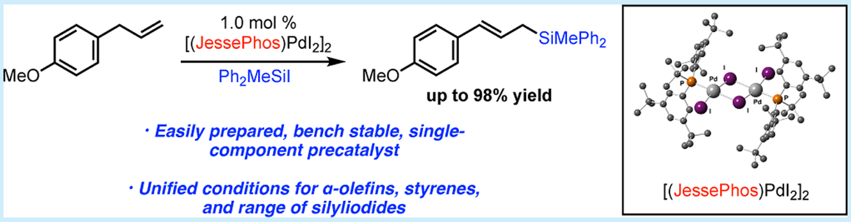
A Bench-Stable, Single-Component Precatalyst for Silyl–Heck Reactions

Sarah B. Krause, Jesse R. McAtee, Glenn P. A. Yap, and Donald A. Watson*

Department of Chemistry and Biochemistry, University of Delaware, Newark, Delaware 19716, United States

Supporting Information



ABSTRACT: Studies of the silyl-Heck reaction aimed at identifying active palladium complexes have revealed a new species that is formed in situ. This complex has been identified as the palladium iodide dimer, $[(\text{JessePhos})PdI_2]_2$, which has been found to be a competent single-component precatalyst for the silyl-Heck reaction. This complex is easily prepared and is temperature, moisture, and air stable. Additionally, this precatalyst provides higher activity and greater reproducibility compared to previous systems.

Unsaturated organosilanes, such as allyl- and vinylsilanes, are important intermediates in organic synthesis. These reagents serve as nucleophiles in a wide range of important carbon–carbon bond-forming reactions, are employed in cross-coupling reactions, and act as masking groups for a variety of heteroatomic functional groups (including alcohols, ketones, and vinyl fluorides).[1]

Over the past several years, our group has been investigating the preparation of both allyl- and vinylsilanes via the palladium-catalyzed silylation of alkenes using silyl electrophiles (silyl iodides and triflates).[2,3] Using palladium catalysis, we initially identified commercially available ^{t}BuPPh$_2$ (**L1**) as a modestly effective ligand in these silyl-Heck reactions (Figure 1). Subsequent studies led to the development of JessePhos (**L2**), which was shown to provide superior yields in the preparation of allylsilanes from terminal alkenes[4] and allowed the use of commercially available Pd_2dba_3 as the palladium precatalyst for the preparation of vinylsilanes from styrenes and styrene-like alkenes.[5]

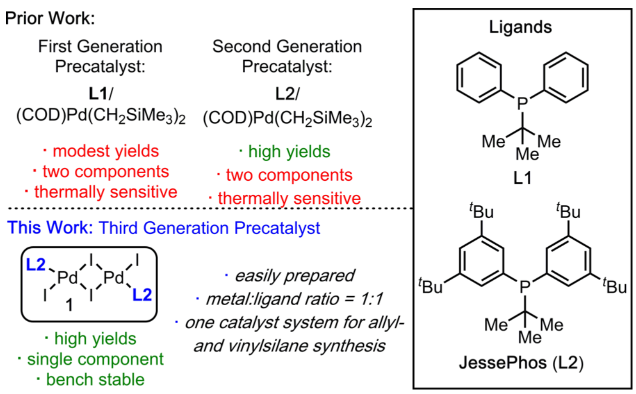
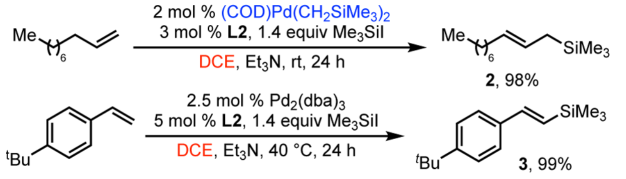


Figure 1. Evolution of Silyl–Heck catalyst systems.

Unfortunately, even with JessePhos, the formation of allylsilanes required the use of the thermally sensitive $(COD)Pd(CH_2SiMe_3)_2$ as the precatalyst to obtain optimal yields (Scheme 1).[4−6] While this latter precatalyst provides a workable solution, we considered the thermal sensitivity of $(COD)Pd(CH_2SiMe_3)_2$ to be an impediment to the implementation of this chemistry, and continued to search for catalysts that would provide a more "bench stable" method. Simultaneously, we also sought to understand the solvent dependencies in the reactions involving JessePhos. The formation of both allyl- and vinylsilanes were optimal in 1,2-dichloroethane (DCE), which is an unexpected solvent for what we believe to be a Pd(0)/Pd(II) catalytic cycle.

Scheme 1. Previously Optimized Conditions for Allyl- and Vinylsilane Synthesis Using Silyl–Heck Conditions[a]



[a] Previous best yields and conditions for α-olefins (ref 4) and styrenes (ref 5).

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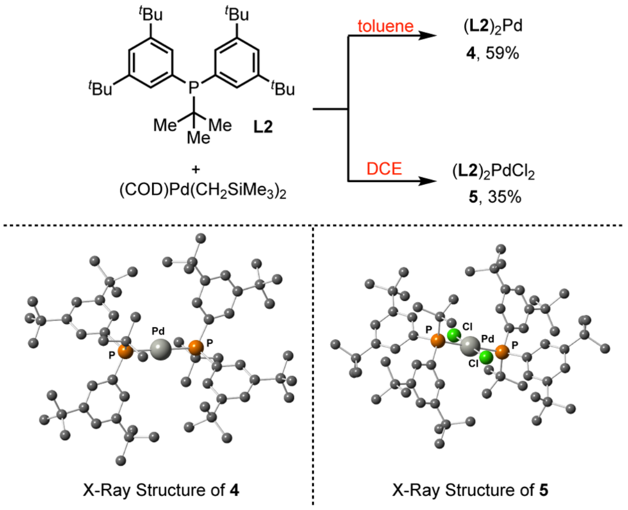
Herein we report our initial observations into the role of the chlorinated solvent in the silyl-Heck reaction. We have found that the previously employed combination of ligand and palladium precatalyst result in the rapid activation of the solvent to form a new Pd(II) complex, which in turn can react with Me_3Si–I to form a dimeric Pd(II) complex $[(\text{JessePhos})PdI_2]_2$ (**1**, Figure 1). We have found that **1**, which can also be readily prepared in a single step from commercial materials, is a bench-stable, single-component precatalyst that is highly effective for the formation of both allyl- and vinylsilanes from terminal alkenes. The key to the success of this complex appears to be due to the sterically enforced ligand to metal ratio of 1:1 imparted by the large iodide ligands. The development of this catalyst system, as well as direct comparison of its efficacy in silyl-Heck reactions to previous catalyst systems, is described below.

Our investigation began by studying the reaction of the precatalyst components previously used in allylsilane synthesis. As is expected from prior literature reports,[7] combining $(\text{COD})Pd(CH_2SiMe_3)_2$ and JessePhos (**L2**) in an inert solvent, such as toluene, led to clean formation of the Pd(0) complex $(\mathbf{L2})_2Pd$ (**4**, Scheme 2). This air-sensitive complex was isolated in 59% yield and was characterized by single-crystal X-ray diffraction (Scheme 2, bottom left). In contrast, the same reaction run in DCE provided the Pd(II) complex $(\text{JessePhos})_2PdCl_2$ (**5**) in 35% isolated yield. X-ray analysis of **5** established this as a monomeric chloride complex with two ligands per palladium atom (Scheme 2, bottom right).[8] It is evident from this result, and in accord with our expectations, that the initially formed palladium complex **4** is able abstract two chloride atoms from the solvent.

Scheme 2. Role of Solvent in Catalyst Formation



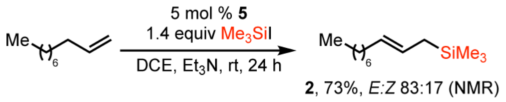
X-Ray Structure of **4**

X-Ray Structure of **5**

Complex **5** can also be prepared from $(\text{MeCN})_2PdCl_2$ and **L2** in high yield (eq 1). On the basis of our earlier report that complex **5** is an effective precatalyst in boryl–Heck reactions,[8] we decided to investigate its use in silyl-Heck reactions.

$$\mathbf{L2}\text{ (2 equiv)} \xrightarrow[\text{CH}_2\text{Cl}_2\text{, 30 min, rt}]{\text{1 equiv (CH}_3\text{CN)}_2\text{PdCl}_2} \underset{\mathbf{5}\text{, 92\%}}{(\mathbf{L2})_2\text{PdCl}_2} \qquad (1)$$

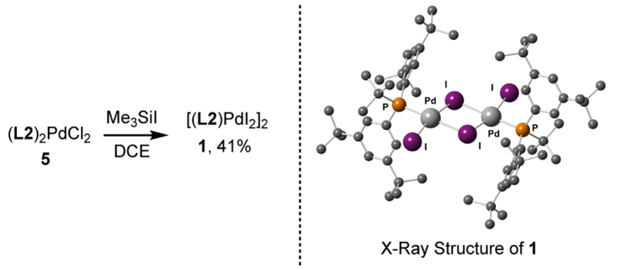
Using the reaction of 1-decene and Me_3SiI as a model system, 5 mol % of complex **5** proved to be only a modestly effective catalyst for the silyl-Heck reaction, providing the desired product **2** in only 73% assay yield with the mass balance being mainly unreacted starting material. This is significantly less efficient than the previously optimized conditions for this same reaction using the combination of 2 mol % $(\text{COD})Pd(CH_2SiMe_3)_2$ and 3 mol % **L2**.[4] Our prior studies strongly suggest that the active catalyst in silyl-Heck reactions are monoligated complexes supported by a single phosphine ligand, and that the reactions are highly sensitive to the ligand/Pd ratio. Optimal ligand/Pd ratios typically range between 1:1 to 1.5:1 ligand to metal, with significant decreases in catalytic efficiency observed when the ligand/Pd ratio is increased to 2:1 or higher. In this context, we attribute the relatively poor catalytic efficiency of complex **5** to the fact that it is a bis-ligated compound.



(2)

Next, to understand the catalytic relevance of complex **5** better, we sought to elucidate how this complex might be involved in the catalytic cycle. Those studies led us to examine the stoichiometric reaction of complex **5** with Me_3SiI in DCE (Scheme 3, left). Following the reaction by ^{31}P NMR revealed the rapid formation of a new palladium complex, along with traces of free ligand **L2**. ^{29}Si NMR also revealed the formation of Me_3SiCl. Isolation and characterization by X-ray diffraction revealed the complex to be the μ-iodo-Pd(II) dimer **1** (Scheme 3, right).[9] Presumably driven by the Si–Cl bond strength,[10] complex **5** undergoes halide metathesis with Me_3SiI to provide the $Pd(II)I_2$ complex and Me_3SiCl. Critically, because of the size of the iodo ligand, the complex sheds an extra phosphine ligand and is stabilized by the bridging halide centers.

Scheme 3. Identification of Complex 1

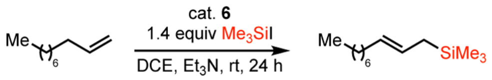


X-Ray Structure of **1**

Recognizing that complex **1** contains a ligand to metal ratio of 1:1, a ratio we found to be critical for highly reactive catalysts, we investigated its use in silyl-Heck reactions. Using the same model system as before, we found that at catalyst loadings of 1–2 mol %, complex **1** is highly efficient as a catalyst for the silyl-Heck reaction (Table 1, entries 2 and 3). At higher catalyst loadings isomerization of the starting alkene became competitive, and at lower catalyst loadings incomplete conversion was observed (entries 1 and 4). This is the first time that a highly efficient, single component precatalyst has been identified for the silyl-Heck reaction, which both eases reaction setup and leads to more reproducible results, as the ligand to metal ratio is dictated by the catalyst structure.

As least as important to the fact that **1** is a single component catalyst is that it is also completely bench stable. We have stored samples of the complex under air at room temperature, without special precautions, for over 30 months without

Table 1. Exploration of Complex 1 as a Precatalyst for the Silyl−Heck Reaction



2, *E*:*Z* 83:17

entry	**1** (mol %)	yield **2**[a] (%)
1	0.5	83
2	1.0	99
3	2.0	98
4	2.5	83

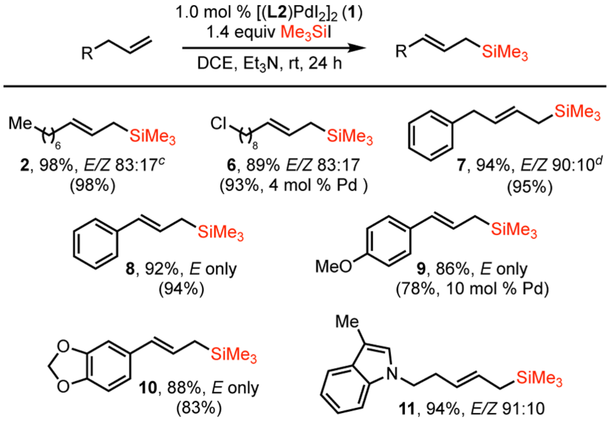
[a] Yield determined by ^{1}H NMR against an internal standard.

detectable decomposition. Moreover, we have found that the complex can be prepared in a single step from commercially available JessePhos and PdI$_2$ in near-quantitative yield (eq 3).[11] This synthesis makes this complex highly accessible and easy to use in silyl-Heck reactions.

$$\mathbf{L2} \xrightarrow[\text{PhMe, 85 °C, 30 min}]{\text{1 equiv PdI}_2} \underset{\mathbf{1},\ 97\%}{[(\mathbf{L2})\mathrm{PdI}_2]_2} \qquad (3)$$

To compare efficiency of the single component catalyst **1** directly, to our earlier catalytic systems, we invested the silyl-Heck reaction of a variety of α-olefin substrates (Scheme 4). In cases where we have reported the transformation under prior conditions, the previous yield is given in parentheses. For simple terminal alkenes (**2**, **6**, **7**) as well as allyl aromatic compounds (**8**−**10**), comparable (and in some cases higher) yields of allylsilane were observed. Notably, on a multigram scale, only 0.5 mol % precatalyst was required (see **2**). In all cases, the observed *E*/*Z* ratio of the allylsilane was nearly identical to previous conditions. Further, α-olefins bearing heterocycles (such as 3-methylindole) are also tolerated (**11**). It is notable that under the previously optimized conditions some of the examples required up to 10 mol % of Pd to obtain the reported yield. With the present system, 1 mol % of catalyst (2 mol % Pd) is effective for a wide range of substrates, suggesting that this catalyst system may in fact provide better reactivity than the previous conditions.

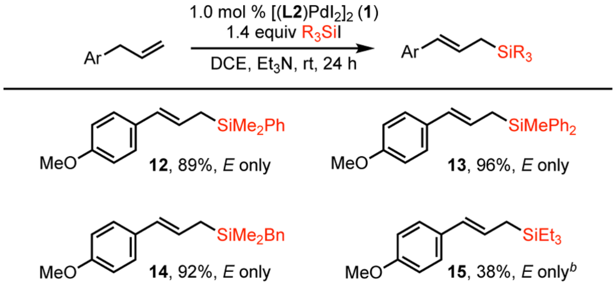
Scheme 4. Performance of Single-Component Catalyst 1 Compared to Previously Optimized Catalytic Conditions with α-Olefins[a,b]



[a] Isolated yields. [b] Parenthetical yields are for the same substrate and product using the conditions reported in ref 4 using 2−6 mol % **L2** and 2−4 mol % (COD)Pd(CH$_2$SiMe$_3$)$_2$ as catalyst. [c] 2.8 g scale; 0.5 mol % **1**. [d] Contains 5% of homoallylsilane, which is similar to the prior results.

Further supporting the superior activity of the single component catalyst **1**, larger silyl iodides are now competent substrates for the silyl-Heck reaction using α-olefins (Scheme 5). Previously, silyl iodides larger than Me$_3$SiI led to substantial alkene isomerization with alkenes bearing allylic hydrogen atoms.[12] With catalyst **1**, both aromatic- (**12**, **13**) and benzyl-substituted (**14**) silyl iodides led to allylsilanes in good yield without significant isomerization of the starting material. These are important substrates, as silanes bearing aromatic and benzylic groups are often superior to trimethylsilanes in a variety of downstream reactions, including oxidation and cross-coupling.[1f,13] Likewise, for the first time, we have been able to observe appreciable yield of the much more sterically demanding triethylsilane (**15**) using α-olefins.

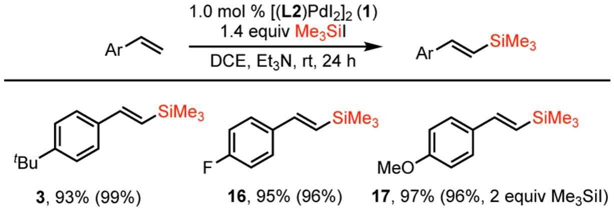
Scheme 5. Performance of Single-Component Catalyst 1 with Larger Silyl Iodides[a]



[a] Isolated yields. [b] 72 h.

Finally, we also investigated the use of complex **1** in the silylation of styrenes. Although the conditions reported in 2015 do not require a thermally sensitive precatalyst to obtain good yields in these transformations, a unified set of single-component conditions for both α-olefins and styrenes would simplify the utilization of the silyl-Heck reaction by others. Toward this end, we have found that the same conditions used for α-olefin silylation apply directly to the silylation of styrenes (Scheme 6). As shown above, using the single-component catalyst, we directly compared performance of several substrates to the previously best conditions. In all cases, similar yields of the product were observed, but all the reactions required less than half of the catalyst loading compared to the prior conditions. In some cases, less silyl iodide was also required. Overall, we believe that these results support the superiority of

Scheme 6. Performance of Single-Component Catalyst 1 Compared to Previously Optimized Catalytic Conditions with Styenes[a,b]



[a] Isolated yields. [b] Parenthetical yields are for the same substrate and product using the conditions reported in ref 5 using 5 mol % of **L2** and 2.5 mol % of Pd$_2$(dba)$_3$ as catalyst.

catalyst **1** compared to all previously reported catalysts for the silyl-Heck reaction.

In conclusion, through study of the fate of the catalytic additives under previously optimized conditions, we have discovered a new, single-component catalyst **1** that is both bench stable and highly effective in silyl-Heck reactions. The key to this finding was the discovery that complex **5** forms as a stable μ-bridged Pd(II)I_2 dimer with a 1:1 ligand to metal ratio using the large JessePhos ligand (**L2**). This new precatalyst appears to be the most effective system developed to date for the silyl-Heck reaction. It requires only low catalyst loading (0.5−1 mol %) and provides a unified set of conditions that are applicable to both α-olefin and styrene substrates. Further studies are underway to understand better the details of how this complex is reduced in situ to Pd(0), which will be reported in due course. However, in the meantime, catalyst **1** provides a very significant practical advantage that should greatly facilitate the implementation of silyl-Heck transformations in the preparation of unsaturated silanes.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.orglett.7b02807.

Crystallographic data for compound **1** (CIF)
Crystallographic data for compound **4** (CIF)
Experimental procedures and spectral data (PDF)

AUTHOR INFORMATION

Corresponding Author

*E-mail: dawatson@udel.edu.

ORCID

Donald A. Watson: 0000-0003-4864-297X

Notes

The authors declare no competing financial interest.

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