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COMMUNICATIONS

On the Pd-Catalyzed Vinylation of Aryl Halides with Tris(alkoxy)vinylsilanes in Water

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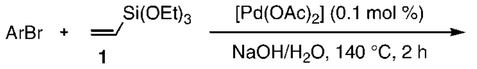
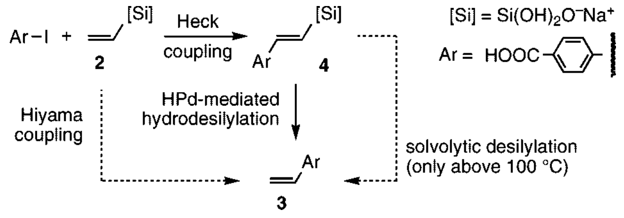
Many of the advances achieved in transition-metal-catalyzed organic transformations in water have been based on the modification of ligands or substrates to enhance their water solubility.[1] However, an understanding of the specific mechanisms in water is required for a rational optimization of processes.[2] The Pd-catalyzed cross-coupling of haloarenes and arylsilanes (the Hiyama reaction[3]) in water using tris(alkoxy)arylsilanes activated with NaOH was recently reported.[4] Vinyl analogues were subsequently applied to the vinylation of haloarenes under similar conditions.[5,6] Notably, most of the tested bromoarenes afforded styrenes almost quantitatively at high temperature with low loadings of palladium acetate (eq 1):[6] The excellent efficiency of these aqueous, ligand-free conditions allowed the performance of consecutive one-pot reactions and, in some cases, the isolation of products by mere filtration of the water solution. This synthetic simplicity prompted us to study its inner workings in more detail.



(1)

We selected for this study the vinylation of 4-iodobenzoic acid with **1** because it takes place homogeneously in water above pH 12.[7] The rapid hydrolysis of **1** under these conditions generates the water-soluble silanolate **2** (Scheme 1).[8,9] This reaction was monitored by ^{1}H NMR spectroscopy at 30 °C in NaOD/D_2O, where the formation of two vinylated arenes together with the evolution of ethene was observed (Figure 1a). The β-silylated styrene **4** results from a Heck reaction and is mostly formed at the start of the reaction along with significant amounts of ethene; styrene **3** can form by either the Hiyama route or HPd-mediated or solvolytic hydrodesilylation of **4**.[10] In this communication, we demonstrate that styrenes are mainly formed via Heck coupling followed by a combination of Pd-catalyzed and, at high temperature, solvolytic desilylation.

Scheme 1. Vinylation of 4-Iodobenzoic Acid in Water



The nondeuteration of **3** and ethene in D_2O proves that desilylation at 30 °C occurs only as part of the catalytic cycle, with the hydrogen atom proceeding from the Heck reaction. The key step involves the hydride intermediate **5** (Scheme 2), which should regenerate Pd^0 after olefin decoordination and HX elimination in the classical Heck cycle **a**. The competing desilylative route **b** consists of Pd−H readdition to the olefin followed by elimination of the silyl group.[10] The interpretation of the reaction profile is straightforward, assuming that under our conditions the HX elimination route **a** is secondary [see the Supporting Information (SI) for details] and *the Pd hydride complex is stable enough to allow olefin exchange and/or readdition* (routes **b** and **c**). At short reaction times, the large excess of vinyl silanolate **2** favors route **c**, and similar amounts of **4** and ethene are produced. The concentration of **4** reaches a plateau at values where olefin substitution is no longer thermodynamically favorable, at which point route **b** prevails. In accordance with this model, the formation of **3** is gradually suppressed as the excess of vinylating agent **2** is increased (Figure 1b).

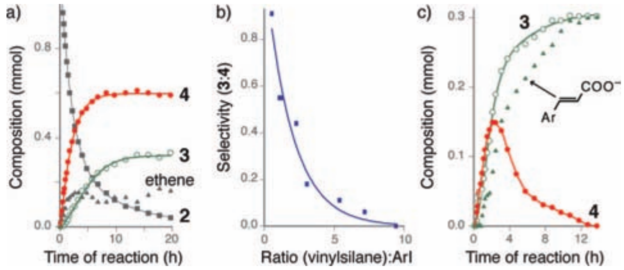
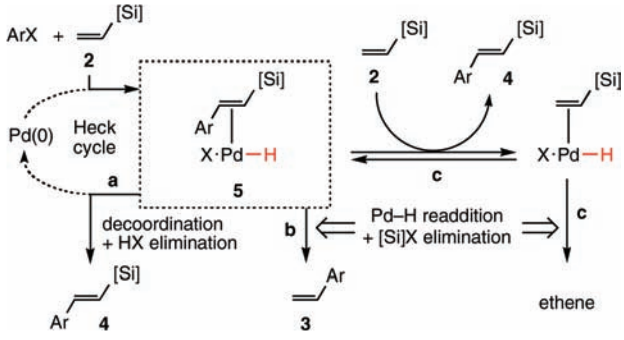


Figure 1. (a) Reaction profile obtained by ^{1}H NMR spectroscopy (the amount of ethene evolved was measured indirectly; see the SI) for the reaction of ArI (1.0 mmol), **1** (1.2 mmol), Pd(OAc)$_2$ (0.3 mol %), and NaOD (0.1 M) in D_2O. (b) Dependence of the selectivity on the vinylsilane excess. (c) Effect of the addition of acrylic acid on the reaction profile.

Scheme 2. Proposed Mechanism for the Coupled Heck Desilylation Reaction



Migration of the H atom initially at the arylated position of the olefin to the desilylated position via a PdH(olefin) intermediate can be intramolecular but also intermolecular because of the olefin exchange in route **c**. The addition of acrylate to the reaction medium confirmed such an intermolecular transfer (Figure 1c): the Heck coupling of acrylate and iodoarene generates extra PdH to complete the desilylation of **4** at the end of the reaction. The same reaction with acrylate-d_3 afforded a mixture of **3** (minor) and **3**-d_1 (major), the latter isotopologue coming from D transfer to **4** from the deuterated acrylate (eq 2).

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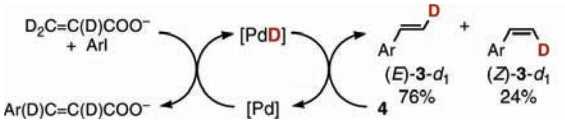
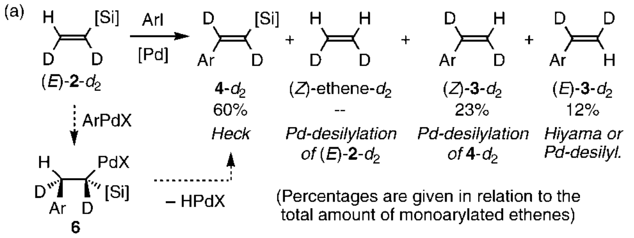


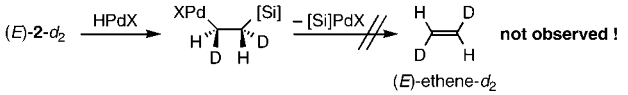
(2)

Next, we evaluated the point at which the distribution of products obtained from the partially deuterated vinylsilanolate (*E*)-**2**-d_2 becomes coherent with a Heck desilylation mechanism (Scheme 3a). The Heck product is almost exclusively the dideuterated β-silylated styrene **4**-d_2, as anticipated considering that **6** is the most sterically favorable intermediate for the β-H elimination step. As a result of the generation of HPdX rather than DPdX hydrides, the Pd-mediated desilylation of (*E*)-**2**-d_2 affords only dideuterated ethene. In this process, the cis configuration of the deuterium atoms is retained with remarkable stereoselectivity, giving (*Z*)-ethene-d_2 exclusively. This fact is important because *it rules out the involvement of a β-Si elimination in the mechanism for the desilylation step* (Scheme 3b).[11] The trans isotopomer (*Z*)-**3**-d_2 must therefore be obtained from *trans*-**4**-d_2 by the same configuration-retaining desilylation mechanism.

Scheme 3. Product Distribution Using a Partially Deuterated Silane

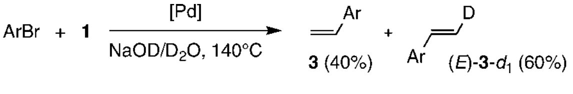


(b) Stereoisomer expected from a desilylation step via β-Si elimination



We can now address the question of the Heck desilylation versus the Hiyama route indicated in Scheme 1. The amount of (*E*)-**3**-d_2 formed (Scheme 3) establishes an upper limit of 12% for the minor Hiyama route. Moreover, a fraction of this styrene might proceed from a partial stereoselectivity of the Pd-mediated protodesilylation of **4**-d_2. The observation of **3**-d_1, which is formed as a 76:24 *E*/*Z* mixture via DPd desilylation of **4** (eq 2) supports this conclusion.

We finally tried to clarify the differences found between iodo- and bromoarenes and, more specifically, the fact that the reaction in eq 1 yields **3** quantitatively instead of a mixture of **3** and **4** at 120−140 °C. We observed that a pure sample of **4** in NaOD/D_2O was desilylated by the solvent in hours at the above temperature to give the monodeuterated styrene (*E*)-**3**-d_1. Moreover, the vinylation of ArBr in NaOD/D_2O afforded a 40:60 mixture of **3** and (*E*)-**3**-d_1 (eq 3). The same catalytic mechanism therefore operates for bromides and iodides, but **4**is thermally desilylated by the aqueous medium at the higher reaction temperature at which bromoarenes react.



(3)

In summary, we have provided an insight into the vinylation of aryl halides with tris(alkoxy)vinylsilanes in water under ligand-free conditions. Specifically, we have demonstrated that in spite of the high pH, the palladium hydride formed via Heck coupling is preferably transferred to the silyl olefins rather than to the NaOH solution. A key point is that this transfer can be either intra- or intermolecular and accounts for the low-temperature desilylation of the olefin, which does not occur through a β-silyl elimination step. An alternative desilylation mechanism might involve nucleophilic attack of the hydroxide anion at the silicon atom of a Pd-coordinated fragment.[12]

A corollary of this work is the stability of the hydride complexes toward the elimination of HI in a rather basic aqueous solution. Slow reaction rates in organic solvents have been correlated with a difficult reductive elimination of HX from [L_2PdHX] complexes.[13] Unfortunately, all our efforts to date to observe hydride species have been unsuccessful.[14]

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Supporting Information Available: Experimental procedures, product characterization, and reaction profiles. This material is available free of charge via the Internet at http://pubs.acs.org.

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(7) This pH value is essential for the observation of full conversions. The reaction can be activated with NaOH or with other bases such as sodium phosphate, whose Brönsted basicity is strong enough to attain pH > 12.
(8) Formation of small amounts of [$Si_2O_2(OH)_3(vinyl)_2$]$^-$ and traces of other oligomers were also observed above pH 12. For studies on the alkaline hydrolysis of RSi(OR′)$_3$ species, see: Pozdniakova, Y. A.; Lyssenko, K. A.; Korlyukov, A. A.; Blagodatskikh, I. V.; Auner, N.; Katsoulis, D.; Shchegolikhina, O. I. *Eur. J. Inorg. Chem.* **2004**, 1253–1261, and references therein.
(9) Silanolate **2** evolves to form water-insoluble species below pH 11.5−12. We are currently investigating whether the requirement of pH > 12 is associated with the chemical nature or the water solubility of **2**. Tetracoordinate silanolates have been introduced by Denmark and co-workers as activated substrates in Hiyama cross-coupling reactions. See: (a) Denmark, S. E.; Baird, J. D. *Chem.—Eur. J.* **2006**, *12*, 4954–4963, and references therein. (b) Denmark, S. E.; Butler, C. R. *J. Am. Chem. Soc.* **2008**, *130*, 3690–3704.
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(14) Under these ligand-free conditions, copious amounts of black Pd precipitation occur at the higher catalyst loadings needed for the observation of PdH resonances.

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