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Tetrahedron Letters 49 (2008) 3430–3432
Tetrahedron Letters

A one-pot efficient and fast Hiyama coupling using palladium nanoparticles in water under fluoride-free conditions

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Received 28 February 2008; revised 18 March 2008; accepted 21 March 2008
Available online 28 March 2008

Abstract

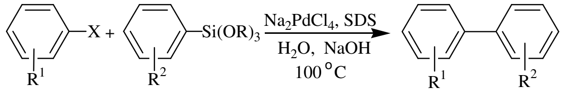
An efficient Hiyama cross-coupling of a wide variety of substituted aryl bromides and iodides with arylsilanes has been achieved at 100 °C in water through a simple one-pot operation using in situ generated palladium nanoparticles. This reaction is very fast (5 min) and has been performed in air under fluoride-free conditions, giving excellent chemoselectivity and high yields.

Keywords: Hiyama coupling; Palladium nanoparticle; Aryl bromide; Aryl silane; Biaryl

The palladium-catalyzed cross-coupling reaction to produce unsymmetrical biaryls is a useful protocol in organic synthesis and has wide applications in the synthesis of polymers, agrochemicals, and pharmaceutical intermediates.[1] The most frequently employed methods to perform this coupling reaction are Stille,[2] Suzuki–Miyaura,[3] and Hiyama[4] reactions. In spite of comparable excellent yields, high stereoselectivities, and superior functional group tolerance, the use of toxic tin reagents in Stille couplings, and difficulties in the preparation and purification of Suzuki boron reagents are the disadvantages. The ease of preparation and low toxicity of organosilane reagents has made the Hiyama coupling more attractive. Thus, several methods have been developed for this transformation using various Pd-catalysts in the presence of a ligand and fluoride derivatives.[5]

The use of metal nanoparticles as efficient catalysts in organic reactions has attracted considerable interest in the context of green chemistry because of their benign character and ease of preparation.[6] In addition, the high surface-to-volume ratio of nanoparticles provides larger number of active sites per unit area compared to their heterogeneous counterparts. Recently, two procedures involving preformed palladium-coated nickel nanoclusters[7a] and palladium nanoparticles[7b] have been reported. As a part of our continuing program to explore the novel applications of metal nanoparticles[8] we report here a one-pot fluoride-free Hiyama coupling of aryl bromides with arylsilanes using palladium(0) nanoparticles, prepared in situ from Na_2PdCl_4/SDS (sodium dodecyl sulfate) in water (Scheme 1).

The experimental procedure is very simple.[9] A mixture of aryl bromide and aryl siloxane in water was stirred at 100 °C (oil bath temp) in the presence of a catalytic amount of Na_2PdCl_4, SDS, and NaOH (3 M) for the required period of time. Standard work-up provided the product. Two surfactants, SDS and SBDS (sodium dodecylbenzene sulfonate), were investigated. SDS gave better yields and is also less expensive and easily available. The base, NaOH, was found to be the best compared to Na_2CO_3, $NaHCO_3$, KOH, and NaOAc. Details on the optimization of the reaction conditions are summarized in Table 1.



Scheme 1.

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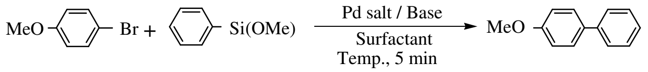
doi:10.1016/j.tetlet.2008.03.121

Table 1
Optimization of the catalyst and reaction conditions for the Hiyama coupling



Entry	Surfactant	Pd salt	Base	Temp (°C)	Yield (%)
1	SDS	1	NaOH	85	68
2	SDS	1	NaOH	100	87
3	SDS	2	NaOH	85	78
4	SDS	2	NaOH	100	92
5	SDBS	2	NaOH	100	75
6	SDS	2	KOH	100	88
7	SDS	2	KF	100	—
8	SDS	2	K_2CO_3	100	—
9	SDS	2	$NaHCO_3$	100	—
10	SDS	2	NaOAc	100	—

Pd Salt 1 = $PdCl_2$.
Pd Salt 2 = Na_2PdCl_4.

To determine the active catalytic species in this reaction, an extract from the reaction of 4-bromoanisole and phenyltrimethoxysilane after 3 min, when analyzed by UV (H_2O) spectroscopy, did not show the presence of a Pd(II) peak (Fig. 1). However, the TEM (transmission electron microscope) (Fig. 2) image and EDS (energy dispersive X-ray spectroscopy) (Fig. 3) confirmed the presence of Pd nanoparticles (3–6 nm). It is suggested that SDS served as the reductant as well as stabilizer in the formation of Pd nanoparticles.[10]

Several substituted aryl bromides underwent cross-coupling with phenyltrimethoxysilanes using this procedure to produce the corresponding biaryl derivatives. The results are summarized in Table 2. Trace amounts (2–5%) of dimeric products of arylsiloxane coupling were removed during the purification process. The reaction was uniform irrespective of the nature of the substituents (electron withdrawing or electron donating) on the aromatic ring. A wide range of substituents which included CHO, OMe, NO_2, COMe, F, and Cl were compatible with this procedure. As shown in Table 2, this procedure provides high chemoselectivity in reactions with other halo-substituted aryl compounds. Only bromo- and iodo-derivatives (Table 2, entries 15–18) participated in the reaction, leaving chloro and fluoro groups (entries 11 and 12) unaffected. Interestingly, aldehydes (entries 6 and 10) did not undergo metal-catalyzed nucleophilic addition with the aryltrimethoxysilane as has been observed in similar reactions.[11]

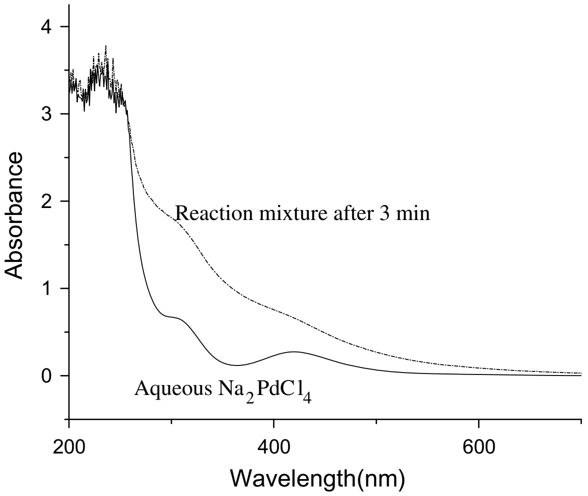


Fig. 1. UV spectra of palladium at different stages (0 and 3 min) of the reaction.

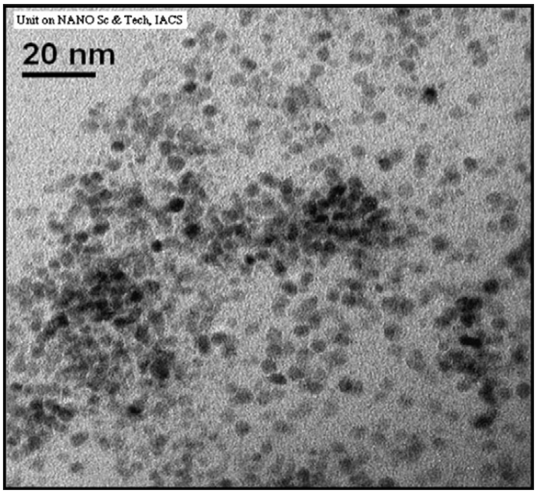


Fig. 2. TEM image of Pd nanoparticles formed in the reaction mixture.

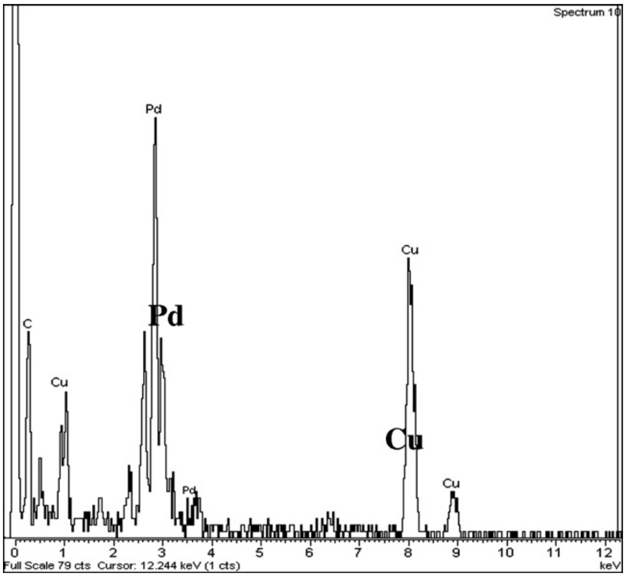
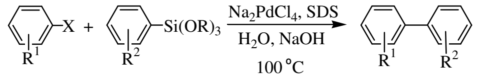


Fig. 3. Energy dispersive X-ray spectrum with the use of Cu-grid.

In general, the reactions are clean and high yielding. All the products were obtained in high purities. The aqueous layer containing the catalyst after work up was recycled for three subsequent runs with only a gradual loss of efficiency. It is believed that the reaction proceeds through the usual pathway of the Pd-catalyzed Hiyama coupling,[5f]

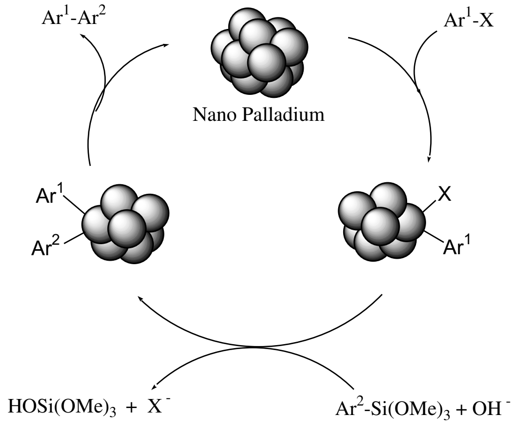
Table 2
Pd nanoparticle-catalyzed Hiyama cross-coupling of aryl bromides and iodides with arylsiloxanes



Entry	R^1	R^2	R	Time (min)	Yield[a] (%)	Ref.
1	H	H	Me	5	96	7b
2	2-Me	H	Me	5	92	7b
3	2-OMe	H	Me	5	90	7b
4	3-Me	H	Me	5	86	7b
5	3-OMe	H	Me	5	90	7b
6	3-CHO	H	Me	5	88	7b
7	4-Me	H	Me	5	94	7b
8	4-OMe	H	Me	5	92	7b
9	4-COMe	H	Me	5	95	7b
10	4-CHO	H	Me	5	88	7b
11	4-F	H	Me	5	92	12
12	4-Cl	H	Me	5	94	7b
13	4-Me	4-Me	Et	6	80	7b
14	3-OMe	4-Me	Et	6	80	13
15	3-NO_2	4-Me	Et	6	75	13
16	H	H	Me	5	94	7b
17	4-Me	H	Me	5	90	7b
18	3-NO_2	H	Me	5	93	7b

Entries 1–14, X = Br; 15–18, X = I.

[a] Isolated yields of purified products (^1H and ^{13}C NMR).



Scheme 2. Possible mechanism of cross-coupling reaction.

as outlined in Scheme 2. Sodium hydroxide works here as an alternative promoter[5g] to fluoride ions used in conventional procedures.[5]

In conclusion, this procedure has a marked distinction from other palladium nanoparticle-catalyzed processes,[7a,b] providing a one-pot, simple and fast (5 min) operation compared to other multi-step and lengthy reactions.[7a] Other significant advantages offered by this procedure are mild reaction conditions, no requirement of phosphine or imine ligands or a fluoride source, and the reaction occurs in water. To the best of our knowledge, this is the fastest Hiyama coupling of aryl bromides with arylsilanes to afford biaryl derivatives using palladium catalysis.

Acknowledgments

We are pleased to acknolwedge the financial support from DST, New Delhi [Grant No. SR/S5/GC-02/2006] for this investigation. R.D. and K.C. are thankful to CSIR for their fellowships.

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9. *Representative experimental procedure for the Hiyama coupling of bromobenzene with phenyltrimethoxysilane (Table 2, entry 1).* To a stirred mixture of Na_2PdCl_4 (4.5 mg, 1.5 mol %), SDS (57 mg, 0.2 mmol), and an aqueous solution of NaOH (2 mL, 3 M) was added bromobenzene (157 mg, 1 mmol) followed by phenyltrimethoxysilane (239 mg, 1.2 mmol). The reaction mixture was then stirred at 100 °C (oil bath temperature) for 5 min (TLC) and extracted with ethyl acetate (3 × 20 mL). The combined organic extract was washed with brine, dried over anhydrous Na_2SO_4, and evaporated to leave the crude product, which was purified by column chromatography over silica gel with hexane–ether (99:1) as eluent to furnish pure biphenyl as a white solid (148 mg, 96%). This procedure was followed for the synthesis of all the products listed in Table 2. Known compounds were identified by the comparison of their spectral data with those reported earlier (see references in Table 2).
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