Catalysis of the Heck-type reaction of alkenes with arylboronic acids by silica-supported rhodium: an efficient phosphine-free reusable catalytic protocol

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A 3-aminopropyl-functionalized silica-supported rhodium(0) catalyst (SiO_2–Rh^0) was prepared and employed in the Heck-type coupling of arylboronic acids and alkenes, affording good-to-excellent yields of substituted alkenes; the catalyst was recovered by filtration and reused for several cycles.

The rhodium-catalyzed conjugate addition of arylboronic acids to α,β-unsaturated carbonyl compounds is a well established methodology in modern organic synthesis,[1] but the related Heck-type olefination reaction was first reported in 2001 by Lautens *et al.*[2a] They have shown that a substrate incapable of enolization, such as styrene, affords the Heck-type product, whereas *ortho*- or *para*-vinylpyridines provide the conjugate adducts in the presence of $[Rh(COD)Cl]_2$/4,4′-(phenylphosphinidene)bis(benzenesulfonic acid)dipotassium salt (TPPDS). Later on, they widened the scope of their methodology to enolizable alkenes in a toluene–water (1 : 1) solvent system by using 2-(di-*tert*-butylphosphino)ethyltrimethylammonium chloride (*t*-Bu-amphos chloride) in place of the TPPDS ligand.[2b] Just after the report of Lautens *et al.*,[2a] Mori *et al.* reported a hydroxorhodium complex-catalyzed carbon–carbon bond forming reaction of silanediols with α,β-unsaturated carbonyl compounds. Heck-type products were obtained in anhydrous solvents, whereas in aqueous solvents, the Michael-type adduct was formed.[3] In 2003, Zou *et al.* reported the rhodium-catalyzed Heck-type reaction of arylboronic acids with α,β-unsaturated esters in a water–toluene biphasic medium.[4] All the protocols reported so far for the Heck-type coupling of alkenes with arylboronic acids by rhodium are homogeneous in nature and require an ancillary phosphine ligand. The major drawback of homogeneous catalysis is the need to separate the relatively expensive catalyst from the reaction mixture at the end of the process. One of the most promising solutions to this problem seems to be the immobilization of the soluble catalysts onto an insoluble matrix using a simplified protocol. So, to dispense with the use of ligands, as well as to achieve the reusability of the precious rhodium, it is highly desirable to design a ligand-free and recyclable heterogeneous system for this elegant coupling reaction.

Silica shows many advantageous properties, such as excellent chemical and thermal stability, high surface area, good accessibility and the fact that organic groups can be robustly anchored to the surface to provide catalytic centers.[5] By exploiting these advantages, we prepared a 3-aminopropyl-functionalized silica immobilized rhodium(0) catalyst (SiO_2–Rh^0) and subsequently tested it in the Heck-type arylation reaction of alkenes with arylboronic acids.

The SiO_2–Rh^0 catalyst was prepared by stirring 3-aminopropyl-functionalized silica gel (500 mg) at room temperature with an aqueous solution of $RhCl_3 \cdot xH_2O$ (30 mg in 200 mL) under a nitrogen atmosphere for about 10 min, followed by reduction with an excess amount of an aqueous solution of $NaBH_4$. Just after the addition of $NaBH_4$, the solution changed its colour from pink to black, confirming the reduction of rhodium(III) to rhodium(0). Finally, the catalyst was filtered and washed with water, followed by ether, to afford the black silica-immobilized rhodium(0) catalyst (SiO_2–Rh^0). The loading of rhodium was measured as 0.221 mmol g^{-1} (ICP-AES). TEM images of the SiO_2–Rh^0 showed the rhodium particles to be in the range 10–20 nm (Fig. 1).

The SiO_2–Rh^0 catalyst was used in the coupling of phenylboronic acid (**1a**) and *n*-butyl acrylate (**2a**) (Scheme 1) in a toluene/water (3 : 1) mixture under a nitrogen atmosphere for 24 h to afford *n*-butyl cinnamate (**3a**) in good yield (72%), along with a very small amount of the corresponding 1,4-Michael addition product (**4a**) (<1% as measured by ^1H NMR). **3a** was obtained in 82% yield when a **1a** : **2a** (1 : 3) mixture in toluene–water (5 : 1) was treated with 1.1 mol% catalyst at 100 °C for 10 h (Table 1, entry 1). A small amount of water is needed for the reaction to proceed,[6] and overall

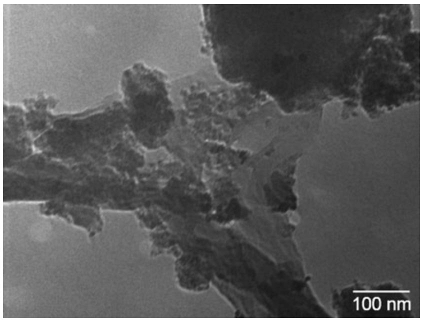

Fig. 1 TEM images of SiO_2–Rh^0 catalyst.

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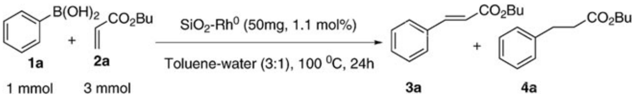
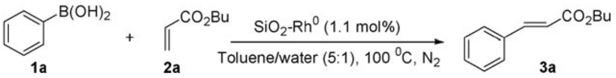
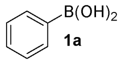
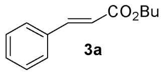
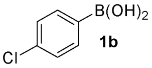
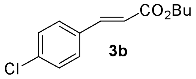
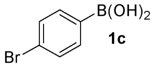
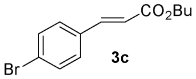
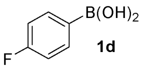
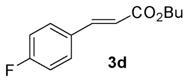
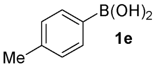
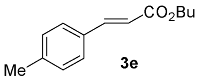
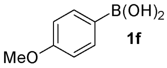
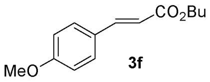
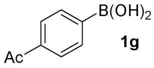
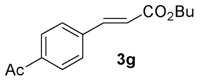
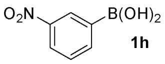
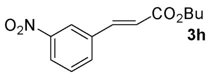
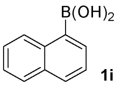
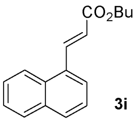


Scheme 1

Table 1 SiO_2–Rh^0-catalyzed coupling of arylboronic acids with *n*-butyl acrylate[a]



Entry	Arylboronic acid	Product	Time/h	Yield (%)
1	 **1a**	 **3a**	10	82, 10[b], 35[c]
2	 **1b**	 **3b**	18	78
3	 **1c**	 **3c**	18	80
4	 **1d**	 **3d**	24	72
5	 **1e**	 **3e**	8	84
6	 **1f**	 **3f**	8	88
7	 **1g**	 **3g**	24	75
8	 **1h**	 **3h**	24	80
9	 **1i**	 **3i**	14	88

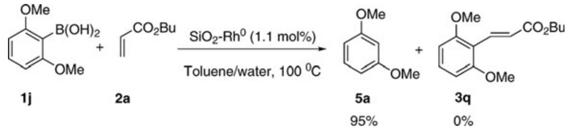
[a] Isolated yields. [b] 5% Rh/Al_2O_3 used as catalyst. [c] 1% Rh/SiO_2 used as catalyst.

yield decreases with the addition of bases.[7] We have performed the coupling of **2a** with various arylboronic acids, and the results are summarized in Table 1. From Table 1 it can be seen that steric hindrance, as well as electronic nature of the boronic acid, influence the outcome of the reaction. In general, arylboronic acids with an electron-withdrawing moiety reacted at a slower rate. There was no reaction when a bulky group was present at the *ortho*-position of the boronic acid. When *ortho*-tolylboronic acid was treated with **2a**, no product formation was observed after 24 h, but the boronic acid was completely consumed. When 2,6-dimethoxybenzeneboronic acid (**1j**) was employed in the reaction with **2a** (Scheme 2), after 48 h, only 1,3-dimethoxybenzene was isolated as the sole product in 95% yield.

To widen the scope of the current catalytic protocol, several alkenes were reacted with **1a** (Table 2). From Table 2 it can be seen that a sterically-hindered alkene gave a poor yield; 2-cyclohexenone did not yield any Heck product and only 5% conjugate addition product was observed by GC-MS. We tested a commercially available rhodium catalyst, namely 5% Rh/Al_2O_3, in the coupling of **1a** with **2a**, obtaining only 10% of **3a**. We have prepared a 1% Rh/SiO_2 catalyst without a spacer by impregnating SiO_2 (230–400 mesh size) with a solution of $RhCl_3$, followed by reduction with $NaBH_4$. The particle size was in the range 8–15 nm. We then tested 1% Rh/SiO_2 (1.1 mol%) in the same reaction, affording only 35% of the desired product. These observations prove the superiority of SiO_2–Rh^0 over 5% Rh/Al_2O_3 and 1% Rh/SiO_2, which may be attributed to the interphase nature of the SiO_2–Rh^0 catalyst.[8]

Based on the literature for homogeneous catalysis,[3,4,9] we assume that the reaction is catalyzed by a hydroxorhodium species, which is generated in the presence of water. To develop any heterogeneous catalyst, it is always necessary to know whether the reaction occurs on the solid surface or whether it is catalyzed by the dissolved metal in the liquid phase. To evaluate the heterogeneity of the SiO_2–Rh^0 catalyst, we conducted various experiments. Firstly, we checked the amount of leached Rh in the filtrate after the completion of the reaction; Rh was not detected in the filtrate by ICP spectroscopy (less than 0.1 ppm). Next, in the Heck-type reaction of phenylboronic acid (**1a**) with *n*-butyl acrylate (**2a**), the catalyst was removed after 2 h (yield 30%) by hot filtration and the reaction was continued using the filtrate for an additional 10 h. The Heck-type reaction did not occur after catalyst removal. Furthermore, the resultant filtrate was tested for rhodium by ICP spectroscopy; there being no leaching of Rh into the solution. The SiO_2–Rh^0 catalyst was also reused for 5 cycles (Table 3) with a slight decrease in activity; the rhodium content in the fresh and used catalyst after 5 cycles was found to be almost the same (Rh in the fresh catalyst: 0.221 mmol g^{-1}, and in the used catalyst after 5 cycles: 0.219 mmol g^{-1}). These studies clearly demonstrate that the rhodium is bound to the silica during the reaction and that the reaction proceeds on the heterogeneous surface.

In conclusion, we have prepared a silica-supported rhodium catalyst that was successfully used in the Heck-type coupling of alkenes with arylboronic acids in the absence of an external

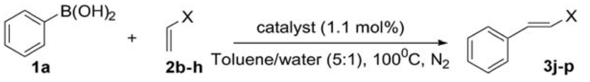


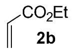
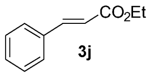
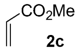
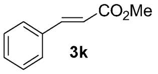
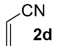
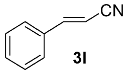
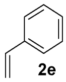
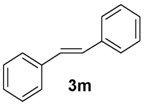
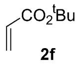
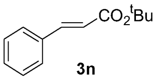
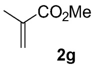
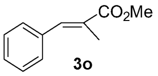
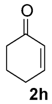
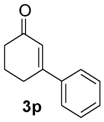
Scheme 2

phosphine ligand. The catalyst can be easily recovered by simple filtration and reused for several cycles with consistent activity.

We wish to thank the CSIR for financial support under the Task Force Project CMM-0006, and S.R. and M.R. thanks CSIR and UGC, respectively for providing research fellowship.

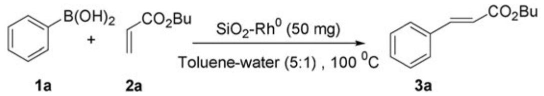
Table 2 SiO_2–Rh^0-catalyzed olefination of phenylboronic acid[a]



Entry	Olefin	Product	Time/h	Yield (%)
1	 **2b**	 **3j**	10	88
2	 **2c**	 **3k**	10	90
3	 **2d**	 **3l**	24	65[b]
4	 **2e**	 **3m**	18	72
5	 **2f**	 **3n**	15	84
6	 **2g**	 **3o**	24	12[c]
7	 **2h**	 **3p**	24	0

[a] Isolated yield. [b] 17% *cis* isomer observed by ^1H NMR. [c] GC yield, confirmed by GC-MS.

Table 3 Reusability study of SiO_2–Rh^0 catalyst in the Heck-type coupling of phenylboronic acid (**1a**) and *n*-butyl acrylate (**2a**)



Cycle	1	2	3	4	5	6
Time/h	10	10	10	12	12	15
Yield (%)	80	80	81	82	82	80

Experimental

General

3-Aminopropyl-functionalized silica gel, $RhCl_3$, the alkenes and arylboronic acids were purchased from Aldrich. 230–400 mesh size silica gel was purchased from Merck. All other reagents and solvents were procured from commercial sources. The particle size and external morphology of the samples were observed on a Philips TECNAI F12 FEI transmission electron microscope (TEM). ICP-AES analyses were performed using IRIS Intrepid II XDL ICP-AES (Thermo Electron Corporation). ^1H NMR spectra were determined on a Bruker spectrometer (300 MHz) with TMS as the internal standard.

Catalytic studies: Heck-type reactions of alkenes with arylboronic acids catalysed by SiO_2–Rh^0

In a typical experiment, 4-fluorophenylboronic acid (**1d**) (1 mmol), *n*-butyl acrylate (**2a**) (3 mmol), SiO_2–Rh^0 (50 mg, 1.1 mol%) and toluene–water (5 : 1) (3 mL) were combined in a 10 mL reaction vessel. The reaction mixture was stirred at 100 °C under nitrogen for a specified time. After completion of the reaction, as monitored by TLC, the catalyst was filtered off. The filtrate was diluted with ethyl acetate and washed with a 10% NaOH solution, followed by a saturated NaCl solution. The organic layer was concentrated under reduced pressure to afford the crude product. The crude product was purified by column chromatography using 2% ethyl acetate in hexane, and pure *n*-butyl 4-fluorocinnamate was obtained as a colorless liquid (160 mg, 72% yield). ^1H NMR (300 MHz, $CDCl_3$/ppm): 0.98 (3 H, t, J = 7.5 Hz), 1.38–1.51 (2 H, m), 1.63–1.74 (2 H, m), 4.18 (2 H, t, J = 6.8 Hz), 6.32 (1 H, d, J = 16 Hz), 7.06 (2 H, t, J = 9 Hz), 7.48–7.54 (2 H, m) and 7.60 (1 H, d, J = 16 Hz); ^{19}F NMR (300 MHz, $CDCl_3$/ppm): −113; EI-MS (*m*/*z*): 222 (M^+), 166, 149, 122, 102, 56 and 41.

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6 Yield of **3a**: Toluene = 10%; toluene–water 5 : 1 = 82%; toluene–water 3 : 1 = 72%; toluene–water 1 : 1 = 20%.

7 Yield of **3a**: K_2CO_3 (100 mol%) = 70%; NaOAc (100 mol%) = 72%; NaOH (100 mol%) = 62%.

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