

Palladium-containing perovskites: recoverable and reuseable catalysts for Suzuki couplings†

Martin D. Smith, Antonia F. Stepan, Chandrashekar Ramarao‡, Paul E. Brennan§ and Steven V. Ley*

University Chemical Laboratory, Department of Chemistry, Lensfield Road, Cambridge, UK CB2 1EW.
E-mail: svl1000@cam.ac.uk; Fax: +44 1223336442; Tel: +44 1223 336398

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Palladium-containing perovskites (LaFe_{0.57}Co_{0.38}Pd_{0.05}O₃) have been exploited as recoverable and reuseable catalysts in Suzuki coupling reactions; residual levels of Pd after removal of the catalyst by filtration are low (2 ppm) despite evidence that the reaction is occurring *via* a homogeneous process.

Perovskite-based catalysts are under investigation for use in automotive emissions control, and have been dubbed 'intelligent' by virtue of their ability to self-regenerate under oxidative and reductive conditions, whilst suppressing the growth of metallic Pd-particles.¹ These properties could promote activity and longevity in catalysts used in organic synthesis programmes where similar problems of catalyst deactivation are encountered.² It was thus considered that palladium-containing perovskites such as LaFe_{0.57}Co_{0.38}Pd_{0.05}O₃ could function as a new class of catalysts for cross coupling reactions. Initial investigations

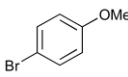
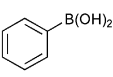
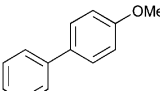
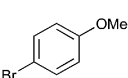
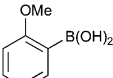
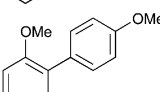

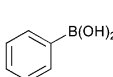
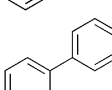

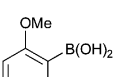
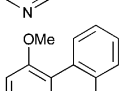
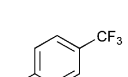
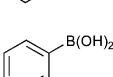
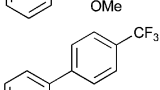
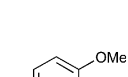
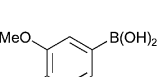
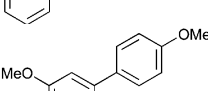
focussed on Suzuki reactions between aryl halides and boronic acids. Preliminary screening of solvents and reaction conditions demonstrated that aqueous alcohols were effective (non-aqueous solvent mixtures were unsuccessful) and that heating to 80 °C was sufficient for most substrates. Under these conditions, the coupling of aryl bromides in the presence of 0.05 mol% Pd catalyst and K₂CO₃ as base (K₃PO₄ and Cs₂CO₃ were also effective) proceeded smoothly to afford the requisite biaryls in high yields, Table 1. The catalyst can be removed from the reaction mixture by a simple filtration or decantation. Substituents in the *ortho* position were tolerated in both coupling partners without any undue increase in reaction time, or decrease in yields. The addition of tetra-*n*-butylammonium bromide³ (TBAB) proved only to be beneficial in a few difficult cases such as the coupling of 3,4,5-trimethoxyphenylboronic acid. In an attempt to ascertain the scope and limitations of the catalyst under these conditions, a reaction utilising 1 g of 4-methoxybromobenzene and 1 mg of catalyst (0.0038 mol% Pd) was attempted. This led to a 93% conversion (estimated by LC integration, 91% isolated yield) corresponding to a turnover number of 27000. Attempts to utilise vinyl boronic acids were unsuccessful when aryl bromides were used as coupling partners, but aryl iodides proved to be viable substrates for these transformations. This enabled the formation of the functionalised olefins described in Table 2. Similarly, sulfur-containing

† Electronic supplementary information (ESI) available: experimental details. See <http://www.rsc.org/suppdata/cc/b3/b308465e/>

‡ Current address: Avra Laboratories Pvt. Ltd., Avra House, 7-102/54, Sai Enclave, Habshiguda, Hyderabad-500 007, India.


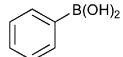
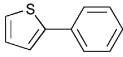
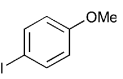
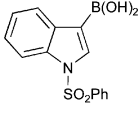
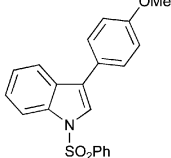
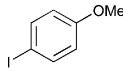
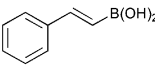
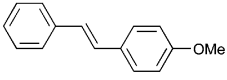
§ Current address: Amgen Inc., One Amgen Center Drive, Mailstop 29-1-B, Thousand Oaks CA, 91320, USA.

Table 1 Suzuki coupling reactions with aryl bromides^a

Aryl halide	Boronic acid	Product	Base	Additive	Mol% Pd	Time/h	Isolated yield (%)
			K ₂ CO ₃ Cs ₂ CO ₃	None None	0.05 0.0038	0.5 39	95 91
			K ₂ CO ₃	None	0.05	0.5	95
			K ₂ CO ₃	None	0.05	18	85
			K ₂ CO ₃	None	0.05	1	89
			K ₂ CO ₃	None	0.05	18	92
			K ₂ CO ₃ K ₂ CO ₃	TBAB None	0.05 0.05	18 18	93 60 ^b

^a Reagents and conditions: LaFe_{0.57}Co_{0.38}Pd_{0.05}O₃ (0.05 mol% Pd), IPA-H₂O (1 : 1, v/v), 80 °C, 3 eq. base, 1.5 eq. boronic acid. ^b Estimated conversion by ¹H NMR.

Table 2 Suzuki coupling reactions with aryl iodides ^a

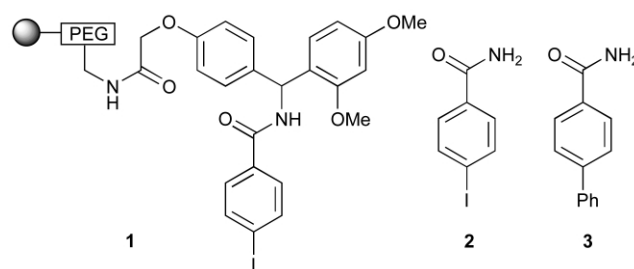
Aryl halide	Boronic acid	Product	Base	Additive	Mol% Pd	Time/h	Isolated yield (%)
			K ₂ CO ₃ K ₂ CO ₃	TBAB None	0.05 0.05	18 18	89 61
			K ₂ CO ₃ K ₂ CO ₃	TBAB None	0.05 0.05	18 18	70 70 ^b
			K ₂ CO ₃	None	0.05	18	92

^a Reagents and conditions: IPA–H₂O (1 : 1, v/v), 80 °C, LaFe_{0.57}Co_{0.38}Pd_{0.05}O₃, 1.5 eq. boronic acid, 3 eq. base. ^b Estimated conversion by ¹H NMR

compounds were investigated and were found to couple in high yields to aryl iodides, but not to aryl bromides. Application of standard conditions to the coupling of aryl chlorides proved troublesome, with heating at 80 °C yielding mixtures of products. However, it was found that the application of microwave heating at 135 °C cleanly facilitated the coupling of 4-nitrochlorobenzene in 71% yield. Coupling of deactivated aryl chlorides was less successful, affording 51% isolated yield for 4-chlorotoluene, and 26% yield for 4-chloroanisole, Table 3.

As the solid catalyst can be recovered easily, the feasibility of recovery and reuse of the catalyst was investigated utilising the coupling of phenylboronic acid and 4-bromoanisole as a test case. It was found that recovery can be achieved without compromising the operational simplicity of the procedure, and five catalyst runs were performed without any demonstrable loss of catalytic activity, Table 4.

The crude products of this reaction were analysed for Pd content by ICP-MS, which demonstrated that levels were uniformly low across four samples (filtration of both hot and cold reaction mixtures, with and without aqueous washing) ranging from 0.5–2.4 ppm. A comparison with Pd levels in the starting materials (0.3 ppm) demonstrates that these levels of palladium leaching are particularly low. In an attempt to ascertain whether the catalyst was operating by a homogeneous or heterogeneous mechanism, a three-phase test, Fig. 1, that has been elegantly applied to similar problems was utilised.⁴ This

**Fig. 1** Three-phase test

involved preparation of a solid-supported aryl iodide **1** on Novasyn TGR resin, as described.⁴

A control experiment under standard conditions (K₂CO₃, PhB(OH)₂, IPA–H₂O, 0.3 mol% Pd) resulted in quantitative recovery of the amido iodide **2** upon cleavage from the resin with TFA. In contrast, performing the same reaction in the presence of 4-bromoanisole led to significant coupling (estimated at 45% by ¹H NMR spectroscopy) to afford a mixture of the iodo amide **2** and the biaryl amide **3** upon cleavage. This suggests that the presence of an organohalide is necessary for the generation of a homogeneous catalyst. It thus appears that Pd-containing perovskites operate at least partially by a homogeneous mechanism. In the light of the ICP results – that indicate particularly low levels of residual palladium – this suggests that the catalyst may operate by a ‘release and capture’ mechanism, with the perovskite acting as a reservoir and scavenger for the active catalytic species, although this is yet to be confirmed.

In conclusion, it has been demonstrated that the perovskite LaFe_{0.57}Co_{0.38}Pd_{0.05}O₃ functions as an air-stable, reusable catalyst for Suzuki cross coupling reactions under mild conditions, with low levels of Pd leaching. Further reactions of this and other perovskites will be disclosed in due course.

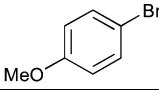
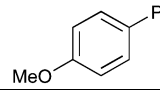
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Table 3 Suzuki coupling reactions with aryl chlorides^a

Entry	Transformation	Isolated yield (%)
1	R = NO ₂	71
2	R = Me	51
3	R = OMe	26

^a Reagents and conditions: 0.25 mol% Pd, IPA–H₂O (1 : 1, v/v), MW heating at 135 °C, 3 eq. Na₂CO₃, 1.5 eq. PhB(OH)₂, 1 h.

Table 4 Recycling experiments^a

Substrate:										
Run	1	2	3	4	5	1	2	3	4	5
Yield (%)	95	93	93	95	93	95	93	93	95	93
Time/h	1	0.6	2	1	1	1	0.6	2	1	1

^a Reagents and conditions: 0.05 mol% Pd, IPA–H₂O (1 : 1, v/v), 80 °C, 3 eq. K₂CO₃, 1.5 eq. PhB(OH)₂.

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