Heterogeneous Catalysis

Influence of the Base on Pd@MIL-101-NH₂(Cr) as Catalyst for the Suzuki–Miyaura Cross-Coupling Reaction

Fabian Carson,^[a, b] Vlad Pascanu,^[a, c] Antonio Bermejo Gómez,^[a, c, d] Yi Zhang,^[a, b] Ana E. Platero-Prats,^[a, b, c] Xiaodong Zou,^{*[a, b]} and Belén Martín-Matute^{*[a, c]}

Abstract: The chemical stability of metal–organic frameworks (MOFs) is a major factor preventing their use in industrial processes. Herein, it is shown that judicious choice of the base for the Suzuki–Miyaura cross-coupling reaction can avoid decomposition of the MOF catalyst Pd@MIL-101-NH₂(Cr). Four bases were compared for the reaction: K₂CO₃, KF, Cs₂CO₃ and CsF. The carbonates were the most active and achieved excellent yields in shorter reaction times than the fluorides. However, powder XRD and N₂ sorption measurements showed that the MOF catalyst was degraded

Introduction

Supported metal nanoparticles (NPs) are important as catalysts in research and industrial processes.^[1–5] The support hinders aggregation of the NPs and facilitates separation from the reaction media and recycling of the catalyst. Typical supports include carbons, polymers, metal oxides and aluminosilicates.^[6–9] However, tailoring the properties of the support for catalysis remains a challenge. Metal–organic frameworks (MOFs) have several advantages as supports for catalysis: high surface areas, controllable pore sizes and tuneable pore environments.^[10–13] Small, finely dispersed particles with high catalytic activity can be synthesised inside the MOF because the intrinsic framework pore shape and size restrict NP growth.^[14–26]

[a]	Dr.	. F. Car	rson,	V. Pasc	anu, l	Dr.	А.	Bei	mejo	o G	óme	2Z,	Y. Zł	nang,
	Dr.	. A. E. I	Plate	ro-Prats	, Prot	f. X	. Z	ou,	Pro	f. B.	Ма	artír	n-Ma	itute
	Be	rzelii C	Cente	r EXSELE	ENT or	n P	orc	ous	Mat	eric	ıls			
	Sto	ockhol	m Ur	niversity,	1069	11 9	Sto	ckh	olm	(Sv	ved	en)		
	E-r	nail: x	zou@	mmk.sı	ı.se									
		b	elen	@organ.	su.se									
	~	F (C		N 71	~		_	~		~		~	<i>c</i>	-

- [b] Dr. F. Carson, Y. Zhang, Dr. A. E. Platero-Prats, Prof. X. Zou Department of Materials and Environmental Chemistry Stockholm University, 106 91 Stockholm (Sweden)
- [c] V. Pascanu, Dr. A. Bermejo Gómez, Dr. A. E. Platero-Prats, Prof. B. Martín-Matute Department of Organic Chemistry Stockholm University, 106 91 Stockholm (Sweden)
- [d] Dr. A. Bermejo Gómez Current Address: AstraZeneca Translational Science Centre at Karolinska Institute, Stockholm, 171 65 (Sweden)
- Supporting information for this article is available on the WWW under http://dx.doi.org/10.1002/chem.201500843.

when carbonates were used but remained crystalline and porous with the fluorides. XANES measurements revealed that the trimeric chromium cluster of Pd@MIL-101-NH₂(Cr) is still present in the degraded MOF. In addition, the different countercations of the base significantly affected the catalytic activity of the material. TEM revealed that after several catalytic runs many of the Pd nanoparticles (NPs) had migrated to the external surface of the MOF particles and formed larger aggregates. The Pd NPs were larger after catalysis with caesium bases compared to potassium bases.

The palladium-catalysed Suzuki-Miyaura cross-coupling reaction is one of the most important and effective methods for C-C bond formation.^[27-29] It is used in industry to prepare a wide range of pharmaceuticals and fine chemicals.^[30-34] Many different forms of palladium can be used to catalyse the reaction, including molecular complexes,^[35] supported NPs^[36] and ligand-free palladium.[37] In many Suzuki-Miyaura reactions, the catalyst is in fact a precatalyst that is converted to the active form under the reaction conditions.[38] There has been much debate about the nature of the actual catalytic species and mechanism involved in reactions catalysed by Pd nanoparticles.^[38-41] For example, Rothenberg and co-workers found that Pd species leached from Pd NPs are the active catalytic species for Suzuki-Miyaura cross-coupling reactions at high temperatures in DMF.^[8,42,43] Similarly, Köhler and co-workers showed that dissolved molecular Pd is the catalytically active species when Pd/C is used as the catalyst at 120°C in N-methyl-2-pyrrolidone; Pd is then redeposited on the support at the end of the reaction.^[44] Pd dissolution and redeposition, which often occur during Suzuki-Miyaura and Heck reactions with Pd/C catalysts, result in eggshell catalysts with lower catalytic activity.[44-48] In contrast, Lee and co-workers used in situ X-ray absorption spectroscopy (XAS) to confirm that Pd NPs are not leached during catalysis at low temperatures in moderate-polarity solvents.^[49, 50] The mechanism therefore depends on several factors, such as the temperature, solvent, base, stabilising agent and support, among others, and different pathways may even operate simultaneously.

Although there have been reports on the role of the base in Suzuki–Miyaura reactions under homogeneous conditions,^[51,52] too little is understood about the effect of the base on the solid support in heterogeneous catalysis. The base (e.g., hy-

Chem. Eur. J. 2015, 21, 10896-10902

Wiley Online Library



droxide or fluoride) plays several roles in the catalytic cycle, such as formation of the key complex $[ArPd(Y)L_2]$ (Ar = aryl; L = ligand, e.g., PPh_3 ; $Y = OH^-$, F^-) that undergoes transmetallation with the boronic acid from $[ArPd(X)L_2]$ (X = I⁻, Br⁻, CI⁻) and formation of unreactive aryl boronates.^[51,52] The base can also interact with the solid support in a heterogeneous system. Because MOFs are constructed from metal ions or clusters and organic linkers connected by coordination bonds, they are often sensitive to certain reaction conditions. Whereas studies on the water stability of MOFs are abundant,^[53-56] similar systematic investigations of their stability with different bases (i.e., conditions relevant for Suzuki-Miyaura coupling reactions) are lacking. The behaviour of the support in catalysis is important to reduce metal leaching, which is essential for the synthesis of pharmaceuticals.^[57] Whereas most attention is generally paid to the activity of the catalyst, recyclability and stability of the support are also important. In many cases, stability of MOFs is a major factor preventing their use in industry.^[58–61]

There have been several studies on the synthesis of palladium NPs supported on MOFs and their application in the Suzuki–Miyaura cross-coupling reaction.^[22,24,62-68] MIL-101(Cr)^[69-73] is an attractive support for metal NPs due to its ex-

cellent chemical stability, high surface area, wide pore apertures and mesoporous cavities. Yuan et al. used Pd@MIL-101(Cr) as a catalyst with NaOMe in H₂O for Suzuki-Miyaura cross-coupling reactions, although reusability of the catalyst was only shown for the Ullmann coupling reaction.^[63] Huang et al. supported Pd on the surface of MIL-53-NH₂(Al) and demonstrated its recyclability for the coupling of *p*-bromobenzene with phenylboronic acid.^[64] The amino groups can stabilise the Pd NPs and prevent their aggregation. Interestingly, they observed that MIL-53-NH₂(Al) decomposed when NaOMe was used as base. Gascon and co-workers also observed decomposition of Pd@MIL-101(Cr) during Suzuki-Miyaura reactions when potassium carbonate was used in the presence of water or alcohols.^[65] We found that $Pd@MIL-101-NH_2(Cr)$ is a good and versatile catalyst for the Suzuki-Miyaura cross-coupling of (hetero)aryl boronic acids with (hetero)aryl halides in the presence of K₂CO₃ as base in aqueous solvent at room temperature.^[22,24] We also used Pd@MIL-101-NH₂(Cr) in a continuousflow setup to synthesise a wide range of biaryl compounds.^[24] Although the material retained high catalytic activity for ten cycles and palladium leaching was minimal (MIL-101-NH₂(Cr) acts as an efficient scavenger of Pd), the MOF structure had decomposed after catalysis. Avoiding collapse of the MOF can increase the potential catalytic activity of the material, particularly for use in a continuous-flow setup.

Herein, we report on the influence of the base on the stability of 8 wt% Pd@MIL-101-NH₂(Cr) in Suzuki–Miyaura cross-coupling reactions. We compared different anions (carbonates and fluorides) and cations (potassium and caesium) of the base and determined their effect on the catalytic activity, crystallinity, porosity and Pd distribution of Pd@MIL-101-NH₂(Cr). We used a combination of powder X-ray diffraction (PXRD), XAS, N₂ sorption and transmission electron microscopy (TEM) to study the material before and after catalysis.

Results and Discussion

The coupling of ethyl 4-bromobenzoate (**1 a**) with *p*-tolylboronic acid (**2 a**) in H₂O/EtOH (1:1 v/v) was chosen as a model reaction (Table 1). We initially used two equivalents of K₂CO₃ as the base due to the excellent results we previously reported (high conversions are achieved in short reaction times and the catalyst can be recycled up to ten times without significant loss of catalytic activity).^[22,24] For the chosen model system, excellent yields of the coupling product **3a** were obtained in short reac-



[a] Aryl bromide **1a-c** (0.6 mmol), boronic acid **2a-c** (0.9 mmol), base (1.2 mmol) and 8 wt% Pd@MIL-101-NH₂(Cr) (24 mg, 0.024 mmol, 3 mol% Pd) were suspended in a mixture of deionised H₂O (6 mL) and EtOH (6 mL) and the mixture stirred vigorously at 25 °C for 0.5 h or 2 h. [b] Yields of **3a-e** were determined by ¹H NMR spectroscopy from the crude reaction mixture by using 1,2,4,5-tetrachloro-3-nitrobenzene as internal standard. [c] For leaching evaluation, the reactions were repeated on a 0.1 mmol scale with respect to the aryl bromide **1a**. The reaction mixture was filtered and analysed by ICP-OES. [d] n.d. = not determined. [e] Reaction temperature: 40 °C.

Chem. Eur. J. 2015, 21, 10896-10902

www.chemeurj.org



tion times for three runs of 0.5 h each (Table 1, entries 1–3). Despite retaining high catalytic activity, the MOF was significantly less crystalline after the third run, as confirmed by PXRD (Figure 1 a). This partial decomposition could be attributed to the effect of the base K_2CO_3 . Cation and linker exchange can

patterns of Pd@MIL-101-NH $_2$ (Cr) after catalysis with KF confirmed that the MOF remained crystalline after three cycles (Figure 1 b).

We then performed the coupling of $1\,a$ and $2\,a$ with Pd@MIL-101-NH_2(Cr) and Cs_2CO_3 to determine the influence of

After run 3

After run 2

the Cs⁺ cation in the carbonate salt. Reactions with Cs₂CO₃ gave comparably high yields of 3a to those obtained with K₂CO₃ in the same reaction time of 0.5 h (Table 1, entries 8-10 versus 1-3). The PXRD patterns of Pd@MIL-101-NH₂(Cr) after catalysis with Cs₂CO₃ as base confirmed that the MOF lost crystallinity even faster when Cs₂CO₃ was used instead of K₂CO₃ (Figure 1 c versus a), which may be due to its stronger basicity, which leads to a higher concentration of hydroxide ions in the reaction media.

Next, we studied the effect of the countercation in the fluoride salt. The use of CsF instead of KF led to better activity, and the yield of **3a** increased to >99%after 2 h in the three cycles without any loss of activity (Table 1, entries 12–14). The ions of caesium salts generally have a lower degree of solvation and ion-pairing compared to other alkali metal salts, which may explain the higher activity of CsF compared to KF. As shown by the

(Figure 1 a). This partial decomposition could be attributed to We then per the effect of the base K₂CO₃. Cation and linker exchange can Pd@MIL-101-NH a Catalysis with K₂CO₃ as the base b Catalysis with KF as the base After run 2 After run 2 Before Catalysis



Figure 1. PXRD patterns of Pd@MlL-101-NH₂(Cr) a) before and after catalysis with K_2CO_3 as the base, b) after catalysis with KF as the base, c) after catalysis with Cs_2CO_3 as the base and d) after catalysis with CsF as the base.

occur in some MOFs even under mild conditions.^[76,77] Carbonates could coordinate to the metal component (chromium cluster) in the MOF and displace the ligand, resulting in framework decomposition.^[65,78] In addition, carbonates form hydroxides in aqueous media,^[79] which can destroy the MOF structure; tests with NaOH as the base for the catalytic reaction resulted in MOF decomposition,^[22] and aqueous NaOH has been used to digest MIL-101-NH₂(Cr).^[75] We previously found that organic nitrogen-containing bases result in significant Pd leaching and reduction during the catalytic activity of this material, presumably due to the high affinity of Pd for nitrogen ligands.^[22]

With these results in mind, we decided to test the cross-coupling reaction of **1a** and **2a** with KF as base (Table 1, entries 4–7). Fluoride salts are common bases for Suzuki–Miyaura cross-coupling reactions, and they have also been used to wash and activate MIL-101(Cr).^[71] The reaction with KF only reached 38% yield of **3a** after 0.5 h (Table 1, entry 4). On increasing the reaction time to 2 h, the yield increased to 66% for the first run and decreased to 60 and 47% for the second and third runs, respectively (Table 1, entries 5–7). The PXRD

PXRD data, the MOF retained its crystallinity after three runs with CsF (Figure 1 d).

All these data suggest that the structure of the MOF partially collapsed in the presence of carbonates (K₂CO₃ or Cs₂CO₃) but remained crystalline when fluorides (KF or CsF) were used. Whereas the cation did not affect the MOF structure, it did have an impact on the catalytic activity. Caesium carbonate resulted in less metal leaching (Cr and Pd) than potassium carbonate (Table 1). CsF gave higher yields than KF, similar to the higher catalytic activity of Cs₂CO₃ compared to K₂CO₃ previously reported.^[22] To further test the versatility of CsF as base, we also used less reactive, electron-rich bromo arenes 1b (p-Me) and 1c (p-OMe), which were coupled with 2a in H₂O/EtOH (1:1) for 2 h at room temperature to give 3b and 3c in good yields (93 and 78%, respectively; Table 1, entries 15 and 16). Even electron-deficient boronic acids **2b** and **2c** ($R^2 = p$ -CO₂Me and p-CHO, respectively), which are known to be less reactive, could be successfully used to obtain the desired biphenyls 3d and 3e in moderate to excellent yields (Table 1, entries 17 and 18).



Whereas the PXRD results imply loss of long-range order in the MOFs after catalysis with carbonate bases, the local coordination environment of chromium in the MOFs is unknown. Therefore, we carried out Cr K-edge XAS on the MOFs before and after catalysis, and the X-ray absorption near-edge structure (XANES) spectra are shown in Figure 2. The XANES spectra of Pd@MIL-101-NH₂(Cr) before and after catalysis with Cs₂CO₃ and CsF as bases are remarkably similar, which indicates that the trinuclear, trigonal {Cr₃OX(H₂O)₂(CO₂)₆} (X = OH⁻, F⁻) secondary building units of the MOF are still present in the poorly crystalline material.

To validate the structural stability of the MOF under the different reaction conditions, the porosity of the materials was ex-



Figure 2. Cr K-edge XANES spectra of Pd@MIL-101-NH₂(Cr) before and after catalysis with Cs_2CO_3 and CsF as the base.

with KF as the bas N₂ uptake (cm³ g⁻¹) uptake (cm³ g⁻¹) 60 0.2 0.1 p/p p/p° с d Catalysis with Cs₂CO₃ as the bas Catalysis with CsF as the base 1000 100 80 800 (cm³ g⁻¹) uptake (cm³ g⁻¹) 600 600 uptake 0.2 0.8 0.4 0.6 p/p' p/p

amined by N₂ sorption after the recycling studies with different bases (Figure 3). The surface areas and pore volumes are listed in Table 2. The BET surface area and pore volume of Pd@MIL-101-NH₂(Cr) were 2660 m²g⁻¹ and 1.43 cm³g⁻¹, respectively, before catalysis (Table 2, entry 1).

When carbonates were used as the base for the catalysis, the surface area decreased drastically to 30 and 60 m²g⁻¹ after three runs with K₂CO₃ (Figure 3a and Table 2, entry 4) and Cs₂CO₃ (Figure 3c and Table 2, entry 7), respectively. The pore volume also decreased to 0.05 cm³g⁻¹ for K₂CO₃ (Table 2, entry 4) and 0.09 cm³g⁻¹ for Cs₂CO₃ after three runs (Table 2, entry 7).

Table 2. Specific surface areas and pore volumes of $Pd@MIL-101-NH_2(Cr)$ before and after catalysis.								
Entry	Material after run no.	Base ^[a]	BET surface area [m ² g ⁻¹]	Pore volume [cm ³ g ⁻¹]				
1	0 ^[b]	-	2660	1.43				
2	1	K_2CO_3	1040	0.57				
3	2	K ₂ CO ₃	360	0.22				
4	3	K ₂ CO ₃	30	0.05				
5	1	Cs ₂ CO ₃	880	0.47				
6	2	Cs ₂ CO ₃	680	0.36				
7	3	Cs ₂ CO ₃	60	0.09				
8	1	KF	2200	1.12				
9	2	KF	2080	1.09				
10	3	KF	1950	0.98				
11	1	CsF	2340	1.20				
12	2	CsF	1990	1.01				
13	3	CsF	1820	0.94				
[a] The base used for catalysis. [b] Run 0 denotes Pd@MIL-101-NH2(Cr) before catalysis.								

On the other hand, when fluorides were used as bases for catalysis, the surface area only decreased to 1950 and 1820 m²g⁻¹ and the pore volume to 0.98 and 0.94 cm³g⁻¹ after three runs with KF (Figure 3b; and Table 2, entry 10) and CsF (Figure 3d; and Table 2, entry 13), respectively. The textural analysis supports the results from the PXRD Pd@MIL-101-NH₂(Cr) analysis: collapses when carbonates are used in aqueous media for the catalytic reaction, but remains porous when fluorides are used.

We then used TEM to investigate the effect of the base on the dispersion and size distribution of the Pd NPs in the MOF. TEM images of the MOFs before and after catalysis are shown in Figure 4. TEM analysis revealed that the Pd NPs before catalysis

Figure 3. N₂ adsorption (•) and desorption (\bigcirc) isotherms of Pd@MIL-101-NH₂(Cr) a) before and after catalysis with K₂CO₃, b) after catalysis with KF as the base, c) after catalysis with Cs₂CO₃ as the base and d) after catalysis with CsF as the base.

Chem. Eur. J. 2015, 21, 10896-10902

www.chemeurj.org



CHEMISTRY A European Journal Full Paper

were highly dispersed with an average particle size of 1 nm or less (Figure 4a and b). In all cases, the size and aggregation of the Pd NPs on the MOF increased after three runs of catalysis (Figure 4c–j). Interestingly, many of the Pd NPs were significantly larger after catalysis with caesium bases compared to potassium bases.

Electron tomography revealed that the larger Pd NPs were located on the external surface of the MOF (see video in Supporting Information). Although dissolution and redeposition of Pd NPs during Suzuki–Miyaura reactions has been observed with other solid supports, the influence of different bases on the distribution of Pd NPs has not been reported. The larger Pd NP size when caesium bases were used implies that more Pd migration took place. This can be related to the higher activity observed with caesium bases compared to potassium



Figure 4. TEM images of Pd@MIL-101-NH₂(Cr) a), b) before catalysis and after three runs of catalysis with c), d) K_2CO_3 , e), f) KF, g), h) Cs_2CO_3 and i), j) CsF as base.

bases, and suggests that homogeneous Pd species contribute significantly to the catalytic activity of Pd@MIL-101-NH₂(Cr) (see below). Amatore et al. found that under homogeneous conditions the countercation (when associated with OH⁻ and in DMF) affects the transmetallation step of the Suzuki-Miyaura reaction, and the reactivity decreases in the order: $nBu_4N^+ > K^+ > Cs^+ > Na^+$.^[80] Under our catalytic conditions, the effect of the countercation on the Pd distribution in the MOF is more important than its role in the catalytic cycle.

After catalysis with carbonate bases, Pd NPs that remain encapsulated in the MOF are inaccessible to reactants for further catalysis, because the support has lost its porosity. Therefore, catalysis will only take place on the MOF surface (or in solution). Despite this, the catalyst is still efficient for numerous substrates for a short-to-medium time period (i.e., when used in a continuous-flow process).^[81] Even though the MOF does not collapse with fluoride salts, some Pd migrates to the surface during catalysis and forms larger aggregates. This partial relocation of the active species opens the way for new catalytic pathways, but the substrates can still access the pores of the MOF, where catalysis can take place in a homogeneous or heterogeneous manner.^[38,42,43] As previously mentioned,^[22] leached Pd species can be responsible for the catalysis in Suzuki-Miyaura cross-coupling reactions. In Pd@MIL-101-NH₂(Cr), the small Pd NPs in the MOF can act as a reservoir of Pd atoms or ions, which subsequently form larger Pd NPs on the MOF surface.^[45] In this case, Pd@MIL-101-NH₂(Cr) effectively acts as a palladium scavenger after the coupling reaction is complete. Alternatively, catalysis can continue to function heterogeneously on the surface of the Pd NPs if the porosity of the framework is maintained. Nevertheless, the stability and lifetime of the catalyst are particularly important for use in continuousflow processes.[24]

Conclusion

The choice of base for the Suzuki-Miyaura cross-coupling reaction has an impact on the catalyst structure when palladium NPs encapsulated in MIL-101-NH₂(Cr) are used. Not only does it influence the catalytic activity, but also the stability of the framework. The use of carbonates (K₂CO₃ and Cs₂CO₃) as the base for the catalytic reaction leads to high yields in short reaction times, but also results in decomposition of the MOF. Importantly, by using fluorides as the base instead of carbonates, the crystallinity and porosity of the MOF are preserved under the reaction conditions tested here. Although the cross-coupling reaction requires longer times with the use of fluorides, the activity can be increased and controlled by using different countercations (Cs⁺ instead of K⁺) for the fluoride base. TEM analysis of the materials after catalysis indicated aggregation of Pd NPs on the surface of the MOF. Interestingly, the best results in catalysis are obtained with caesium bases, even though larger Pd NPs are formed. This is due to increased palladium migration and redeposition, and it indicates that homogeneous Pd species contribute significantly to the catalytic activity. In the Pd@MIL-101-NH₂(Cr) system, the anions have a large effect on the MOF structure, and they also influence

Chem. Eur. J. 2015, 21, 10896-10902

www.chemeurj.org



the catalysis. On the other hand, the cations have a larger impact on the catalysis outcome and the distribution of Pd NPs.

Stability is an important aspect if MOFs are to be used for large-scale catalytic setups, particularly for the industrial synthesis of pharmaceuticals, which requires catalysts with high activity and long half-life to avoid metal contamination and reduce waste and cost. Although the crystallinity and porosity of the MOF do not seem to influence the catalytic activity of the material, in catalytic processes in which the framework structure is crucial, such as size-selective catalysis, maintaining MOF crystallinity could be important. In addition, prolonging the lifetime of the catalyst may be a valuable approach in continuous-flow processes.

Experimental Section

Materials and equipment

All chemicals and reagents were used as received without further purification. PXRD data were collected on a PANalytical X'Pert PRO diffractometer with $\mathsf{Cu}_{K\alpha1}$ radiation in Bragg–Brentano geometry and recorded on a pixel detector at a speed of $2\theta/t = 0.1^{\circ} \text{min}^{-1}$. The samples were dispersed on zero-background Si plates with ethanol. N₂ sorption isotherms were measured at 77 K on a Micromeritics ASAP 2020 system. The samples were degassed under dynamic vacuum at 150 °C for 12 h prior to measurements. TEM observations were performed on a JEOL JEM-2100LaB₆ microscope operating at 200 kV. A tilt series of bright-field images were acquired over an angular range of $\pm 70^{\circ}$ with increments of 1.0°. The 3D reconstructions were carried out by using the weighted backprojection algorithm. Inductively coupled plasma-optical emission spectrometry (ICP-OES) was used for determination of chromium and palladium with a Varian Vista MPX ICP-OES instrument. Medac Ltd (UK) carried out the elemental analysis. ¹H NMR spectra were recorded at 400 MHz on a Bruker Advance spectrometer. Cr K-edge XAS was conducted at beamline B18, Diamond Light Source, UK, by using a Si(111) double-crystal monochromator and a nine-element Ge detector. The current of the storage ring was approximately 300 mA. Spectra were energy-calibrated to chromium foil (absorption edge taken at 5988.8 eV). MOF samples were ground with cellulose and pressed as pellets. XAS data processing was performed with the Athena software package.^[74]

General procedure for the Suzuki-Miyaura cross-coupling reaction

8 wt% Pd@MIL-101-NH₂(Cr) was prepared according to literature procedures.^[22,65,71] Aryl bromide (**1a–c**, 0.6 mmol), boronic acid (**2a–c**, 0.9 mmol), base (1.2 mmol) and 8 wt% Pd@MIL-101-NH₂(Cr) (24 mg, 0.024 mmol, 3 mol% Pd) were suspended in a mixture of deionised H₂O (6 mL) and EtOH (6 mL) in a sealed 20 mL vial and stirred vigorously at 25 °C for 0.5 h or 2 h. The solid was collected by centrifugation and washed with EtOH (10 mL), EtOAc (2× 10 mL) and H₂O (2×10 mL). The combined phases were separated and the aqueous phase was washed with EtOAc (2×10 mL). The combined organic phases were dried over MgSO₄ and filtered. The volatile materials were removed under reduced pressure. Yields were determined by ¹H NMR spectroscopy of the crude reaction mixture against 1,2,4,5-tetrachloro-3-nitrobenzene as an internal standard.

Acknowledgements

This project was supported by the Swedish Research Council (VR) and the Swedish Governmental Agency for Innovation Systems (VINNOVA) through the Berzelii Center EXSELENT, the Knut and Alice Wallenberg Foundation through the project grants 3DEM-NATUR and Catalysis in Selective Organic Synthesis, and by the MATsynCELL project through the Röntgen Ångström Cluster. B.M.-M. also thanks VINNOVA for a VINNMER grant. We are grateful to Dr. Andrew Dent for XAS measurements at beamline B18, Diamond Light Source, UK, under the Rapid Access Proposal SP12120.

Keywords: cross-coupling • heterogeneous catalysis • metal– organic frameworks • nanoparticles • palladium

- [1] M. Moreno-Mañas, R. Pleixats, Acc. Chem. Res. 2003, 36, 638-643.
- [2] D. Astruc, F. Lu, J. R. Aranzaes, Angew. Chem. Int. Ed. 2005, 44, 7852– 7872; Angew. Chem. 2005, 117, 8062–8083.
- [3] J.-P. Corbet, G. Mignani, Chem. Rev. 2006, 106, 2651-2710.
- [4] A. Balanta, C. Godard, C. Claver, Chem. Soc. Rev. 2011, 40, 4973-4985.
- [5] Y. Xia, H. Yang, C. T. Campbell, Acc. Chem. Res. 2013, 46, 1671-1672.
- [6] M. Králik, A. Biffis, J. Mol. Catal. A 2001, 177, 113-138.
- [7] G. G. Wildgoose, C. E. Banks, R. G. Compton, *Small* **2006**, *2*, 182–193.
- [8] L. D. Pachón, G. Rothenberg, Appl. Organomet. Chem. 2008, 22, 288– 299.
- [9] R. J. White, R. Luque, V. L. Budarin, J. H. Clark, D. J. Macquarrie, Chem. Soc. Rev. 2009, 38, 481–494.
- [10] S. Kitagawa, R. Kitaura, S. Noro, Angew. Chem. Int. Ed. 2004, 43, 2334– 2375; Angew. Chem. 2004, 116, 2388–2430.
- [11] J. L. C. Rowsell, O. M. Yaghi, *Microporous Mesoporous Mater.* 2004, 73, 3– 14.
- [12] G. Férey, Chem. Soc. Rev. 2008, 37, 191–214.
- [13] S. M. Cohen, Chem. Rev. 2012, 112, 970-1000.
- [14] M. Meilikhov, K. Yusenko, D. Esken, S. Turner, G. Van Tendeloo, R. A. Fischer, *Eur. J. Inorg. Chem.* 2010, 3701–3714.
- [15] C. Janiak, J. K. Vieth, New J. Chem. 2010, 34, 2366–2388.
- [16] G. Lu, S. Li, Z. Guo, O. K. Farha, B. G. Hauser, X. Qi, Y. Wang, X. Wang, S. Han, X. Liu, J. S. DuChene, H. Zhang, Q. Zhang, X. Chen, J. Ma, S. C. J. Loo, W. D. Wei, Y. Yang, J. T. Hupp, F. Huo, *Nat. Chem.* **2012**, *4*, 310–316.
- [17] A. Dhakshinamoorthy, H. Garcia, *Chem. Soc. Rev.* **2012**, *41*, 5262–5284.
- [18] A. Aijaz, Q. Xu, J. Phys. Chem. Lett. 2014, 5, 1400-1411.
- [19] Q.-L. Zhu, Q. Xu, Chem. Soc. Rev. 2014, 43, 5468-5512.
- [20] J. Liu, L. Chen, H. Cui, J. Zhang, L. Zhang, C.-Y. Su, Chem. Soc. Rev. 2014, 43, 6011-6061.
- [21] C. Rösler, R. A. Fischer, CrystEngComm 2015, 17, 199-217.
- [22] V. Pascanu, Q. Yao, A. Bermejo Gómez, M. Gustafsson, Y. Yun, W. Wan, L. Samain, X. Zou, B. Martín-Matute, *Chem. Eur. J.* **2013**, *19*, 17483–17493.
- [23] V. Pascanu, A. Bermejo Gómez, C. Ayats, A. E. Platero-Prats, F. Carson, J. Su, Q. Yao, M. À. Pericàs, X. Zou, B. Martín-Matute, ACS Catal. 2014, 4, 472–479.
- [24] V. Pascanu, P. R. Hansen, A. Bermejo Gómez, C. Ayats, A. E. Platero-Prats, M. J. Johansson, M. À. Pericàs, B. Martín-Matute, *ChemSusChem* 2015, *8*, 123–130.
- [25] Z. Guo, C. Xiao, R. V. Maligal-Ganesh, L. Zhou, T. W. Goh, X. Li, D. Tesfagaber, A. Thiel, W. Huang, ACS Catal. 2014, 4, 1340–1348.
- [26] X. Li, Z. Guo, C. Xiao, T. W. Goh, D. Tesfagaber, W. Huang, ACS Catal. 2014, 4, 3490–3497.
- [27] N. Miyaura, A. Suzuki, Chem. Rev. 1995, 95, 2457-2483.
- [28] L. Yin, J. Liebscher, Chem. Rev. 2006, 106, 133-173.
- [29] J. C. H. Lee, D. G. Hall, in *Metal-Catalyzed Cross-Coupling Reactions and More* (Eds.: A. de Meijere, S. Bräse, M. Oestreich), Wiley-VCH, Weinheim, 2014, pp. 65–132.
- [30] S. Kotha, K. Lahiri, D. Kashinath, Tetrahedron 2002, 58, 9633-9695.
- [31] M. R. Kumar, K. Park, S. Lee, Adv. Synth. Catal. 2010, 352, 3255-3266.

Chem. Eur. J. 2015, 21, 10896-10902

www.chemeurj.org

10901

© 2015 Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim



CHEMISTRY A European Journal Full Paper

- [32] Y. Gull, N. Rasool, M. Noreen, F.-H. Nasim, A. Yaqoob, S. Kousar, U. Rashid, I. H. Bukhari, M. Zubair, M. S. Islam, *Molecules* 2013, *18*, 8845– 8857.
- [33] G. Xu, W. Fu, G. Liu, C. H. Senanayake, W. Tang, J. Am. Chem. Soc. 2014, 136, 570-573.
- [34] A. B. Patel, K. H. Chikhalia, P. Kumari, Med. Chem. Res. 2014, 23, 2338– 2346.
- [35] M. Miura, Angew. Chem. Int. Ed. 2004, 43, 2201–2203; Angew. Chem. 2004, 116, 2251–2253.
- [36] D. Astruc, Inorg. Chem. 2007, 46, 1884-1894.
- [37] T. Maegawa, Y. Kitamura, S. Sako, T. Udzu, A. Sakurai, A. Tanaka, Y. Kobayashi, K. Endo, U. Bora, T. Kurita, A. Kozaki, Y. Monguchi, H. Sajiki, *Chem. Eur. J.* 2007, 13, 5937–5943.
- [38] N. T. S. Phan, M. Van Der Sluys, C. W. Jones, *Adv. Synth. Catal.* **2006**, *348*, 609–679.
- [39] J. Le Bars, U. Specht, J. S. Bradley, D. G. Blackmond, Langmuir 1999, 15, 7621–7625.
- [40] A. Biffis, M. Zecca, M. Basato, Eur. J. Inorg. Chem. 2001, 5, 1131-1133.
- [41] A. F. Schmidt, A. A. Kurokhtina, Kinet. Catal. 2012, 53, 714-730.
- [42] M. B. Thathagar, J. E. ten Elshof, G. Rothenberg, Angew. Chem. Int. Ed. 2006, 45, 2886–2890; Angew. Chem. 2006, 118, 2952–2956.
- [43] A. V. Gaikwad, A. Holuigue, M. B. Thathagar, J. E. ten Elshof, G. Rothenberg, *Chem. Eur. J.* 2007, 13, 6908–6913.
- [44] K. Köhler, R. G. Heidenreich, S. S. Soomro, S. S. Pröckl, Adv. Synth. Catal. 2008, 350, 2930–2936.
- [45] K. Köhler, R. G. Heidenreich, J. G. E. Krauter, J. Pietsch, Chem. Eur. J. 2002, 8, 622–631.
- [46] R. G. Heidenreich, J. G. E. Krauter, J. Pietsch, K. Köhler, J. Mol. Catal. A 2002, 182–183, 499–509.
- [47] F. Y. Zhao, M. Shirai, Y. Ikushima, M. Arai, J. Mol. Catal. A 2002, 180, 211– 219.
- [48] G. M. Scheuermann, L. Rumi, P. Steurer, W. Bannwarth, R. Mülhaupt, J. Am. Chem. Soc. 2009, 131, 8262–8270.
- [49] A. F. Lee, P. J. Ellis, I. J. S. Fairlamb, K. Wilson, *Dalton Trans.* 2010, 39, 10473-10482.
- [50] P. J. Ellis, I. J. S. Fairlamb, S. F. J. Hackett, K. Wilson, A. F. Lee, Angew. Chem. Int. Ed. 2010, 49, 1820–1824; Angew. Chem. 2010, 122, 1864– 1868.
- [51] C. Amatore, A. Jutand, G. Le Duc, Chem. Eur. J. 2011, 17, 2492-2503.
- [52] C. Amatore, A. Jutand, G. Le Duc, Angew. Chem. Int. Ed. 2012, 51, 1379– 1382; Angew. Chem. 2012, 124, 1408–1411.
- [53] J. B. DeCoste, G. W. Peterson, H. Jasuja, T. G. Glover, Y. Huang, K. S. Walton, J. Mater. Chem. A 2013, 1, 5642–5650.
- [54] J. E. Mondloch, M. J. Katz, N. Planas, D. Semrouni, L. Gagliardi, J. T. Hupp, O. K. Farha, Chem. Commun. 2014, 50, 8944–8946.
- [55] J. R. Karra, H. Jasuja, Y.-G. Huang, K. S. Walton, J. Mater. Chem. A 2015, 3, 1624–1631.
- [56] K. Tan, N. Nijem, Y. Gao, S. Zuluaga, J. Li, T. Thonhauser, Y. J. Chabal, *CrystEngComm* **2015**, *17*, 247–260.

- [57] C. E. Garrett, K. Prasad, Adv. Synth. Catal. 2004, 346, 889-900.
- [58] U. Mueller, M. Schubert, F. Teich, H. Puetter, K. Schierle-Arndt, J. Pastré, J. Mater. Chem. 2006, 16, 626–636.
- [59] J. Canivet, A. Fateeva, Y. Guo, B. Coasne, D. Farrusseng, Chem. Soc. Rev. 2014, 43, 5594-5617.
- [60] N. C. Burtch, H. Jasuja, K. S. Walton, Chem. Rev. 2014, 114, 10575-10612.
- [61] T. Devic, C. Serre, Chem. Soc. Rev. 2014, 43, 6097-6115.
- [62] F. X. Llabrés i Xamena, A. Abad, A. Corma, H. Garcia, J. Catal. 2007, 250, 294–298.
- [63] B. Yuan, Y. Pan, Y. Li, B. Yin, H. Jiang, Angew. Chem. Int. Ed. 2010, 49, 4054–4058; Angew. Chem. 2010, 122, 4148–4152.
- [64] Y. Huang, Z. Zheng, T. Liu, J. Lü, Z. Lin, H. Li, R. Cao, Catal. Commun. 2011, 14, 27–31.
- [65] J. Juan-Alcañiz, J. Ferrando-Soria, I. Luz, P. Serra-Crespo, E. Skupien, V. P. Santos, E. Pardo, F. X. Llabrés i Xamena, F. Kapteijn, J. Gascon, J. Catal. 2013, 307, 295 304.
- [66] A. S. Roy, J. Mondal, B. Banerjee, P. Mondal, A. Bhaumik, S. M. Islam, Appl. Catal. A 2014, 469, 320–327.
- [67] M. Zhang, J. Guan, B. Zhang, D. Su, C. T. Williams, C. Liang, Catal. Lett. 2012, 142, 313–318.
- [68] M. Zhang, Y. Gao, C. Li, C. Liang, Chin. J. Catal. 2015, 36, 588-594.
- [69] G. Férey, C. Mellot-Draznieks, C. Serre, F. Millange, J. Dutour, S. Surblé, I. Margiolaki, *Science* 2005, 309, 2040–2042.
- [70] A. Henschel, K. Gedrich, R. Kraehnert, S. Kaskel, Chem. Commun. 2008, 4192–4194.
- [71] D. Hong, Y. K. Hwang, C. Serre, G. Férey, J. Chang, Adv. Funct. Mater. 2009, 19, 1537–1552.
- [72] Y. Pan, B. Yuan, Y. Li, D. He, Chem. Commun. 2010, 46, 2280-2282.
- [73] S. Bhattacharjee, C. Chen, W.-S. Ahn, RSC Adv. 2014, 4, 52500-52525.
- [74] B. Ravel, M. Newville, J. Synchrotron Radiat. 2005, 12, 537–541.
 [75] S. Bernt, V. Guillerm, C. Serre, N. Stock, Chem. Commun. 2011, 47, 2838–
- 2840.
- [76] M. Kim, J. F. Cahill, H. Fei, K. A. Prather, S. M. Cohen, J. Am. Chem. Soc. 2012, 134, 18082–18088.
- [77] P. Á. Szilágyi, P. Serra-Crespo, I. Dugulan, J. Gascon, H. Geerlings, B. Dam, CrystEngComm 2013, 15, 10175 10178.
- [78] J. Gascon, A. Corma, F. Kapteijn, F. X. Llabrés i Xamena, ACS Catal. 2014, 4, 361–378.
- [79] C. Amatore, G. Le Duc, A. Jutand, Chem. Eur. J. 2013, 19, 10082-10093.
- [80] C. Amatore, A. Jutand, G. Le Duc, Chem. Eur. J. 2012, 18, 6616-6625.
- [81] In a continuous-flow setup under similar conditions, after a period of relative stability and high activity (48–66 h), the catalyst was deactivated, and this led to high levels of metal leaching and amorphisation of the MOF. The deactivation of the catalyst occurred even more rapidly when more highly functionalised substrates were used.

Received: March 2, 2015 Published online on June 23, 2015