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Straightforward installation of carbon-halogen, carbon-oxygen and carbon-carbon bonds within metal-organic frameworks (MOF) via palladium-catalysed direct C-H functionalization[†]

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The straightforward C-H functionalization of UiO-67-dcppy materials was realized by a Pd-catalysed PSM. This novel protocol provides an efficient method for the synthesis of various functionalized MOFs, which have shown promising adsorbent ability in removing phenolic contaminates from water.

Crystalline metal-organic frameworks (MOFs) have become particularly attractive for a wide range of applications such as gas storage,^{1a,b} separation,^{1c} biomedicine,^{1d} heterogeneous catalysis,^{1e} and other technologies.^{1f,g} The development of efficient methods for the construction of various types of functionalized MOFs is highly important.² Recently, post-synthetic modifications (PSM) of known MOFs have emerged as important tools for broader introduction of functional groups into MOFs,³ in particular, which have also been achieved to produce functional materials with improved catalytic⁴ and gas sorption properties.⁵ Despite these advancements in PSM approaches, a large proportion of these methods depends on the interconversions of functional groups (e.g. amine,^{6a,b} hydroxyl,^{6c} azide, 6d and aldehyde 6e), which are greatly limited by the requirement of pre-formed functionality of MOFs, thereby promoting us to develop novel PSM methods for the straightforward functionalization of MOFs.

Recently, MOFs with open coordination sites have been shown to efficiently bind to various metal ions via PSM protocols, providing a useful platform for the development of coordination chemistry and

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Fig. 1 (A) The post-synthetic cyclometalation in previous work; (B) the proposed cyclopalladation intermediate within UiO-67-dcppy.

heterogeneous catalysts (Fig. 1A).⁷ In particular, the usage of 2-phenylpyridine-5,4'-dicarboxylic acid (H₂dcppy) as a building block is much more preferable for the preparation of efficient single-site MOF catalysts through the organometallic cyclometalation (i.e. iridium and ruthenium).8 However, to our knowledge, the C-H functionalization of MOFs assisted by a directing group with transition metal catalysis has not been disclosed so far.

Although Glorius and co-workers have recently reported pioneering work on the direct palladium-catalysed C-H phenylation of an indole-derived UMCM-1-type MOF,9 there are still some challenges needed to be addressed, such as the limited scope in terms of MOFs (only one example) and the long reaction time (seven days). Therefore, based on the mode of cyclometalation within MOFs and owing to the use of 2-phenylpyridine as an effective directing group in Pd-catalysed C-H activation in homogenous systems,¹⁰ we envisioned that MOFs bearing 2-phenylpyridine as a building linkage would be the potential precursors for C-H functionalization via a cyclopalladation intermediate (Fig. 1B). Herein, we reported the first example of a convenient PSM protocol of UiO-67-dcppy materials via a facile palladium-catalysed carbon-halogen, carbonoxygen and carbon-carbon bond-forming functionalization, affording chemically stable, highly porous and functionally diverse collection of MOFs (Scheme 1).

To validate the feasibility of the proposed PSM process, three Zr-cluster-based MOFs bearing the 2-phenylpyridine moiety (i.e. UiO-67-dcppy, 2-Me-UiO-67-dcppy and 3-Me-UiO-67-dcppy) were synthesized via solvothermal reaction,¹¹ since this class of MOFs have exhibited particularly attractive features including chemical and thermal stability and large apparent surface areas.¹² Powder

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Scheme 1 PSM of UiO-67-dcppy materials via Pd-catalysed C-H activation.

X-Ray Diffraction (PXRD) and Brunauer-Emmett-Teller (BET) surface analyses clearly demonstrate that the resultant UiO-67type materials are highly porous crystalline which are isostructural with UiO-67 materials (Fig. S1[†] and Table S2[†]).¹² Then, these UiO-67-dcppy materials were used as substrates for Pd-catalysed C-H activation/C-X halogenation according to reported procedures for homogenous C-H activation reactions.13 The reaction of UiO-67-dcppy and N-bromosuccinimide (NBS) using 20 mol% of $Pd(OAc)_2$ as the catalyst with acetic acid as the additive was conducted in acetonitrile at room temperature for 24 hours (Table S3,† entry 1) and afforded the desired brominated product (2-Br-UiO-67-dcppy) on a proximal C-H site of 2-phenylpyridine, albeit with low conversion (16%), which was quantified and characterized using ¹H NMR analysis of digested solution. Next, the screening of solvents (i.e. 1,4-dioxane, DCE, DMF, Table S3[†]) for the reaction reveals that DMF was the optimal one, affording a good yield of 2-Br-UiO-67-dcppy (21%) and 2,6-diBr-UiO-67-dcppy (75%) (Table S3,† entry 6 and Fig. 2). In contrast, no desired product was observed in the absence of Pd catalysis, indicating that palladium is essential for this reaction (Table S3,† entry 4). The different loadings of Pd(OAc)₂ were examined, and it was found that 20 mol% of $Pd(OAc)_2$ gave the best result. In addition to NMR analysis, other evidence for successful bromination on



Fig. 2 ¹H-NMR data of the organic linker of the digested post-modified UiO-67-dcppy materials; di-substituted product (+), mono-substituted product (*) and the remaining starting material (#).

UiO-67-dcppy was provided by the presence of typical C–Br stretching vibrations (783 cm⁻¹) in IR spectra (Fig. S2†) and molecular ion peaks of [Hdcppy-Br]⁻ (m/z 320) and [Hdcppy-diBr]⁻ (m/z 400) in negative mass spectra of digested solution.

Most importantly, the superior catalytic C–H bromination performance and reactivity of UiO-67-dcppy derivatives were observed as compared with that of H₂dcppy as the substrate under the homogeneous reaction conditions (42% yield of 2-Br-H₂dcppy without 2,6-diBr-H₂dcppy) (Fig. S3†). It should be noted that no brominated product was obtained by using a non-porous amorphous Zr-based powder (Fig. S1† and Table S2†)¹⁴ as the substrate under the standard conditions (Fig. S3†). Such drastic difference could be attributed to their intrinsic topology and porosity for efficiently substrate and catalysis binding and interaction in the porous cage.¹⁵

To further investigate the scope of application, we set out to explore the scope of this protocol with respect to chlorinated agent (N-chlorosuccinimide, NCS) and other UiO-67-dcppys. To our delight, a good yield of desired chlorinated products 2-Cl-UiO-67-dcppy (26%) and 2,6-diCl-UiO-67-dcppy (70%) on a proximal C-H site of 2-phenylpyridine were obtained with NCS as the chlorinated agent at 60 °C (Table 1, entry 2 and Fig. 2). Moreover, mono-halogenated products 2-CH₃-UiO-67-dcppy and 3-CH₃-UiO-67-dcppy with up to almost complete regioselectivity were afforded with 2-Me-6-Br-UiO-67-dcppy, 3-Me-6-Br-UiO-67dcppy and 2-Me-6-Cl-UiO-67-dcppy in good yields of 46%, 85% and 68%, respectively (Table 1, entries 3-5 and Fig. 2). The highly regioselective features of C-H halogenation would be possibly attributed to the steric hindrance originating from the substituent side of the 2-phenylpyridine linker during the formation of a cyclometalated intermediate within MOF lattices, thereby avoiding the generation of the di-halogenated products.

Owing to the excellent reactive nature of UiO-67-dcppy in C–H halogenation, we then tested the C–H oxidative functionalization of UiO-67-dcppy. Initially, UiO-67-dcppy was treated with $Pd(OAc)_2$ (20 mol%) and $PhI(OAc)_2$ (5 equiv.) in DMF. It was found that the reaction could proceed, and a small amount of the desired

Table 1 The Pd-catalysed C–X (*i.e.* Cl and Br), C–O and C–C bond-forming functionalization of UiO-67-dcppy materials

Entry	UiO-67-dcppy materials	Substrate	Yield ^e (%)	
			mono-	di-
1 ^{<i>a</i>}	UiO-67-dcppy	NBS	21	75
2^{b}	UiO-67-dcppy	NCS	26	70
3 ^{<i>a</i>}	2-Me-UiO-67-dcppy	NBS	46	_
4^a	3-Me-UiO-67-dcppy	NBS	85	_
5^{b}	2-Me-UiO-67-dcppy	NCS	68	_
6 ^{<i>c</i>}	UiO-67-dcppy	$PhI(OAc)_2$	_	75
7^d	UiO-67-dcppy	PhB(OH) ₂	20	_

^{*a*} UiO-67 materials (0.1 mmol), Pd(OAc)₂ (20 mol%), NBS (0.5 mmol) and HOAc (0.5 mmol) in DMF (1.0 mL) at r.t. (\sim 25 °C) for 24 hours. ^{*b*} UiO-67 materials (0.1 mmol), Pd(OAc)₂ (20 mol%), NCS (0.5 mmol) and HOAc (0.5 mmol) in DMF (1.0 mL) at 60 °C for 24 hours. ^{*c*} UiO-67-dcppy (0.1 mmol), Pd(OAc)₂ (20 mol%), PhI(OAc)₂ (0.5 mmol) in DCE (1.0 mL) at 80 °C for 12 hours. ^{*d*} UiO-67-dcppy (0.1 mmol), Pd(OAc)₂ (30 mol%), BQ (0.3 mmol), PhB(OH)₂ (0.3 mmol), DMF (1.0 mL) at 100 °C for 24 hours. ^{*c*} The conversion was determined by ¹H NMR analysis of digested solution.

di-acetoxylated product was obtained (15%). After optimizing the reaction conditions, the yield of the desired product via the C-H oxidative PSM protocol could be improved by using DCE in place of DMF as solvent, affording 2,6-diOAc-UiO-67-dcppy in a good yield (75%, Table 1, entry 6 and Fig. 2). Additionally, the IR spectra of 2,6-diOAc-UiO-67-dcppy with C-H stretching vibrations (2800–3000 cm⁻¹) and the characteristic C=O stretching vibrations $(\sim 1770 \text{ cm}^{-1})$ clearly demonstrated the efficient introduction of an acetoxyl group (CH₃CO) via the current PSM approach (Fig. S2⁺). The negative ion mass spectrum of digested 2,6-diOAc-UiO-67dcppy gave a value of m/z 358, which is consistent with the presence of a molecular ion peak of [Hdcppy-diOAc]-. Furthermore, it is of interest to note that chelation-directed C-H activation could be extended to C-C bond-forming PSM of UiO-67-dcppy with slight modification of the reaction conditions. Our preliminary results showed that the reaction of UiO-67-dcppy with phenylboronic acid (3 equiv.) in the presence of $Pd(OAc)_2$ (30 mol%) and 1,4-benzoquinone (3 equiv.) in DMF gave desired coupling product 2-Ph-UiO-67-dcppy with relatively low yield (20%, Table 1, entry 7 and Fig. 2), which is currently under further optimization in our laboratory.

The resultant functionalized MOFs after PSM were shown to possess the same structure and comparable thermal stability to that of parent UiO-67-dcppy as evidenced by PXRD (Fig. 3), Brunauer-Emmett-Teller (BET) surface area analysis (Table S4[†]), thermogravimetric analysis (TGA, Fig. S4[†]), scanning electron microscopy (SEM) images (Fig. S5†). It is demonstrated that the crystallinity of the functionalized UiO-67-dcppy materials remains reserved, although the decreased crystallinity of UiO-67dcppy-OAc was observed, which was confirmed by drastic BET surface decrease from 2281 to 380 cm² g⁻¹ (Table S4^{\dagger}) possibly owing to slightly harsh conditions using acetic acid and higher temperature (80 °C). The chemical stability of these functionalized UiO-67-dcppy derivatives was also found to be quite similar to UiO-67-dcppy, with good tolerance to polar solvents including methanol, ethanol, acetone and DMF. Compared with that of parent Uio-67-dcppy materials, the C-H functionalized Uio-67dcppys showed a significant decrease of the BET surface area. The larger molecular volume of the acetoxy group as compared with the chloro group led to more decreased BET surface area of



Fig. 3 PXRD patterns of the parent and C-H functionalized UiO-67-dcppy materials.

2,6-diOAc-Uio-67-dcppy than that of 2,6-diCl-Uio-67-dcppy (Table S4;† BET surface areas of 380 *vs.* 930 m² g⁻¹). However, inductively coupled plasma-mass spectrometry (ICP-MS) analysis of the obtained UiO-67-dcppy-Br showed the presence of a small amount of palladium residue (2.8 wt%), which will further require much efforts to overcome this problem. Overall, all of the functionalized MOFs are still highly porous and crystalline even after post-synthetic modification, indicating that all of them would provide a useful platform for the further development of their potential applications in the field of materials.

Considering the fact that pyridine-based polymers can serve as good adsorbents for phenolic compounds,16 which are considered as one of the most important sets of organic contaminants,¹⁷ the obtained functionalized UiO-67 materials were also evaluated for their adsorbent ability in removing phenolic compounds from water (Fig. S6A⁺). Owing to the electronically distinct effect of different functionalized groups incorporated onto the wall of UiO-67-dcppy, these MOFs showed different adsorbent capacity of phenol, and UiO-67-dcppy-Br was the best one with an adsorption capacity of 45 mg g^{-1} . More significantly, the adsorption capacities of UiO-67-dcppy-Br for phenol derivatives bearing electron-withdrawing groups dramatically increased to 112, 205 and 361 mg g⁻¹ (Fig. S6B⁺) for 4-Cl-phenol, 4-nitro-phenol and 2-nitro-phenol, respectively, possibly owing to the enhanced acidity of hydroxyl groups of phenols. Furthermore, the treatment of 2-nitro-phenol solution (50 mg L^{-1} , 10 mL) with UiO-67-dcppy-Br (100 mg) for 3 hours resulted in excellent removal efficiency (96.2%) (Fig. S6C⁺), demonstrating the potential practical application of UiO-67-dcppy-Br for cleaning hazardous materials from contaminated water.

We have presented here the first example of a convenient PSM protocol for Pd-catalysed C–H functionalization within MOF lattices *via* a cyclopalladation strategy, leading to direct installation of C–X (*i.e.* chloro and bromo), C–O and C–C bonds onto the linker of MOFs. The superior catalytic C–H bromination performance and reactivity of UiO-67-dcppy were observed, suggesting that C–H functionalization of MOFs would be an intriguing late-stage functionalization approach as advantageous alternative to traditional interconversions of functional groups in PSM of MOFs. More significantly, the resulting UiO-67-dcppy-Br has shown remarkable adsorbent ability of the phenol derivatives bearing electron-withdrawing groups from contaminated water. Further studies on a wider range of applications of these functionalized MOFs are currently in progress in our laboratory.

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Notes and references

 (a) M. P. Suh, H. J. Park, T. K. Prasad and D. W. Lim, *Chem. Rev.*, 2012, **112**, 782; (b) K. Sumida, D. L. Rogow, J. A. Mason, T. M. McDonald, E. D. Bloch, Z. R. Herm, T. H. Bae and J. R. Long, *Chem. Rev.*, 2012, **112**, 724; (c) J. R. Li, J. Sculley and H. C. Zhou, *Chem. Rev.*, 2012, **112**, 869; (d) P. Horcajada, R. Gref,
T. Baati, P. K. Allan, G. Maurin, P. Couvreur, G. Ferey, R. E. Morris
and C. Serre, *Chem. Rev.*, 2012, **112**, 1232; (e) J. Lee, O. K. Farha,
J. Roberts, K. A. Scheidt, S. T. Nguyen and J. T. Hupp, *Chem. Soc. Rev.*, 2009, **38**, 1450; (f) L. E. Kreno, K. Leong, O. K. Farha,
M. Allendorf, R. P. Van Duyne and J. T. Hupp, *Chem. Rev.*, 2012, **112**, 1105; (g) C. Y. Lee, O. K. Farha, B. J. Hong, A. A. Sarjeant,
S. T. Nguyen and J. T. Hupp, *J. Am. Chem. Soc.*, 2011, **133**, 15858.

- 2 (a) H. Furukawa, K. E. Cordova, M. O'Keeffe and O. M. Yaghi, *Science*, 2013, 1230444; (b) F. A. Paz, J. Klinowski, S. M. Vilela, J. P. Tome, J. A. Cavaleiro and J. Rocha, *Chem. Soc. Rev.*, 2012, **41**, 1088.
- 3 S. M. Cohen, Chem. Rev., 2012, 112, 970.
- 4 (a) K. K. Tanabe and S. M. Cohen, Angew. Chem., Int. Ed., 2009,
 48, 7424; (b) C. D. Wu and W. Lin, Angew. Chem., Int. Ed., 2007,
 46, 1075.
- 5 R. B. Getman, Y. S. Bae, C. E. Wilmer and R. Q. Snurr, *Chem. Rev.*, 2012, **112**, 703.
- 6 (a) C. Volkringer and S. M. Cohen, Angew. Chem., Int. Ed., 2010,
 49, 4644; (b) L. Gao, C. Y. Li, H. Yung and K. Y. Chan, Chem. Commun., 2013, 49, 10629; (c) L. Ma, J. M. Falkowski, C. Abney and W. Lin, Nat. Chem., 2010, 2, 838; (d) C. Liu, T. Li and N. L. Rosi, J. Am. Chem. Soc., 2012, 134, 18886; (e) A. Huang, W. Dou and J. Caro, J. Am. Chem. Soc., 2010, 132, 15562.
- 7 (a) E. D. Bloch, D. Britt, C. Lee, C. J. Doonan, F. J. Uribe-Romo, H. Furukawa, J. R. Long and O. M. Yaghi, *J. Am. Chem. Soc.*, 2010, 132, 14382; (b) K. Manna, T. Zhang and W. Lin, *J. Am. Chem. Soc.*, 2014, 136, 6566; (c) M. J. Ingleson, J. P. Barrio, J.-B. Guilbaud, Y. Z. Khimyak and M. J. Rosseinsky, *Chem. Commun.*, 2008, 2680; (d) X. Zhang, F. X. Llabrés i Xamena and A. Corma, *J. Catal.*, 2009, 265, 155; (e) H. Feia and S. M. Cohen, *Chem. Commun.*, 2014,

50, 4810; (f) L. Li, S. Tang, C. Wang, X. Lv, M. Jiang, H. Wu and X. Zhao, *Chem. Commun.*, 2014, **50**, 2304.

- 8 (a) P. V. Dau, M. Kim and S. M. Cohen, *Chem. Sci.*, 2013, 4, 601;
 (b) C. Wang, Z. Xie, K. E. deKrafft and W. Lin, *J. Am. Chem. Soc.*, 2011, 133, 13445.
- 9 (a) J. Wencel-Delord and F. Glorius, *Nat. Chem.*, 2013, 5, 369–375;
 (b) T. Droge, A. Notzon, R. Frohlich and F. Glorius, *Chem. Eur. J.*, 2011, 17, 11974.
- (a) T. W. Lyons and M. S. Sanford, *Chem. Rev.*, 2010, **110**, 1147;
 (b) R. Giri, B. F. Shi, K. M. Engle, N. Maugel and J. Q. Yu, *Chem. Soc. Rev.*, 2009, **38**, 3242.
- 11 M. J. Katz, Z. J. Brown, Y. J. Colon, P. W. Siu, K. A. Scheidt, R. Q. Snurr, J. T. Hupp and O. K. Farha, *Chem. Commun.*, 2013, **49**, 9449.
- 12 (a) J. H. Cavka, S. Jakobsen, U. Olsbye, N. Guillou, C. Lamberti, S. Bordiga and K. P. Lillerud, J. Am. Chem. Soc., 2008, 130, 13850; (b) V. Guillerm, F. Ragon, M. Dan-Hardi, T. Devic, M. Vishnuvarthan, B. Campo, A. Vimont, G. Clet, Q. Yang, G. Maurin, G. Ferey, A. Vittadini, S. Gross and C. Serre, Angew. Chem., Int. Ed., 2012, 51, 9267.
- (a) P. L. Arnold, M. S. Sanford and S. M. Pearson, J. Am. Chem. Soc., 2009, 131, 13912; (b) D. Kalyani, A. R. Dick, W. Q. Anani and M. S. Sanford, Org. Lett., 2006, 8, 2523.
- 14 Such a non-porous amorphous Zr-based powder was obtained *via* the solvothermal method without usage of con. HCl as an additive.
- 15 T. Murase, Y. Nishijima and M. Fujita, J. Am. Chem. Soc., 2012, 134, 162.
- (a) N. Sahiner, O. Ozay and N. Aktas, *Chemosphere*, 2011, 85, 832;
 (b) N. Kawabata and K. Ohira, *Environ. Sci. Technol.*, 1979, 13, 1396.
- 17 (a) A. Kumar, S. Kumar, S. Kumar and D. V. Gupta, *J. Hazard. Mater.*, 2007, **147**, 155; (b) M. C. Burleigh, M. A. Markowitz, M. S. Spector and B. P. Gaber, *Environ. Sci. Technol.*, 2002, **36**, 2515.