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Functional MOFs

Metal–Organic Framework Regioisomers Based on Bifunctional Ligands**

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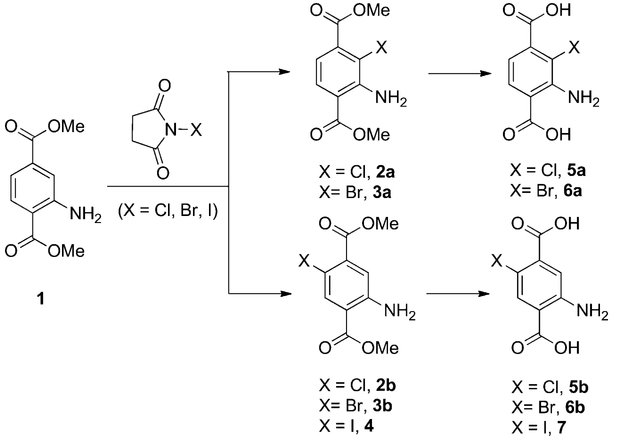
Metal–organic frameworks (MOFs) are crystalline, hybrid materials that consist of inorganic connecting nodes and organic linker molecules. MOFs are attractive materials for applications in gas adsorption,[1] separations,[2] catalysis,[3] and other technologies[4] because of their high porosity, thermal stability, and chemical tunability. The ability to utilize different organic ligands in MOFs is particularly advantageous, as it allows for the introduction of a wider variety of functional groups into the pores of the MOF when compared to other porous, crystalline solids. The use of postsynthetic modification (PSM) has provided broader access to functional groups within MOFs.[5,6] Both solvothermal and PSM routes have demonstrated that multifunctional or "multivariate" MOFs can be prepared, with more than one functional group displayed within the MOF pores.[7–13] In these multifunctional MOF materials, the relative abundance of different ligands (and hence different functional groups) can be controlled, but not the distribution nor spatial orientation of the functional groups with respect to each other. To truly achieve the next level of tailored, multi-purpose materials,[14] control over the relative position of different functional groups would be required. Herein, we describe the first class of bifunctional MOF "ligand regioisomers" and show that even these subtle changes can result in materials with dramatically different physical properties.

Recently, framework isomers of MOFs have been classified into three major groups: interpenetrated, conformational, and orientation isomers—which all describe different structures comprised of the same ligand and metal ion composition.[15] These isomers tend to have different properties from each other, albeit sometimes minor. MOFs derived from different ligands are referred to as "ligand-originated isomers". Although many different ligands have been investigated for MOF formation, we are unaware of any systematic studies of ligand-originated isomers that arise from differences is regiochemical isomerism in a multifunctional ligand. In the studies presented here, the first MOF regioisomers are described and it is found that these regioisomers manifest themselves as distinct conformational isomers with notably different physical properties. Furthermore, these studies are the first to control the position of targeted functional groups in a porous, crystalline material.

We chose a previously unreported class of bifunctional amino-halo benzene dicarboxylates (NH_2X-BDC, where X = Cl, Br, or I) as the building blocks for MOF regioisomers. Independently, amino and halide groups are well-known in MOFs,[5,16] and PSM routes for both amino and halide groups have been reported,[13] leaving open the possibility of PSM on MOF regioisomers. The target ligands were synthesized by halogenation of dimethyl-2-amino terephthalate (**1**) using *N*-halosuccinimides (NCS, *N*-chlorosuccinimide; NBS, *N*-bromosuccinimide; NIS, *N*-iodosuccinimide; Table 1 and Scheme S1 in the Supporting Information).[17] Depending on the *N*-halosuccinimide used, it was possible to obtain two different regioisomers that could be isolated by column chromatography. Electronic effects dictate that the *ortho*- and *para*-positions, relative to the amino group, will be preferentially halogenated over the *meta*-position. In addition, steric considerations would suggest that the *para*-position might be more accessible than the *ortho*-position. Indeed, chlorination with NCS gave a nearly equal mixture of the *ortho*- (**2a**) and

Table 1: Preparation of bifunctional amino-halo BDC ligands.[a]



X	Yield of *ortho*-halogenation[b]	Yield of *para*-halogenation[b]
Cl	**2a**, 34%	**2b**, 44%
Br	**3a**, 16%	**3b**, 57%
I	0%	**4**, 47%

[a] Reaction conditions for halogenation: **1** (5 mmol) and NCS (5.5 mmol) in isopropyl alcohol (100 mL) under reflux; **1** (10 mmol) and NBS (11 mmol) in chloroform (150 mL) at room temperature; **1** (1 mmol) and NIS (1.1 mmol) in acetic acid (20 mL) at room temperature. [b] Yields of isolated products.

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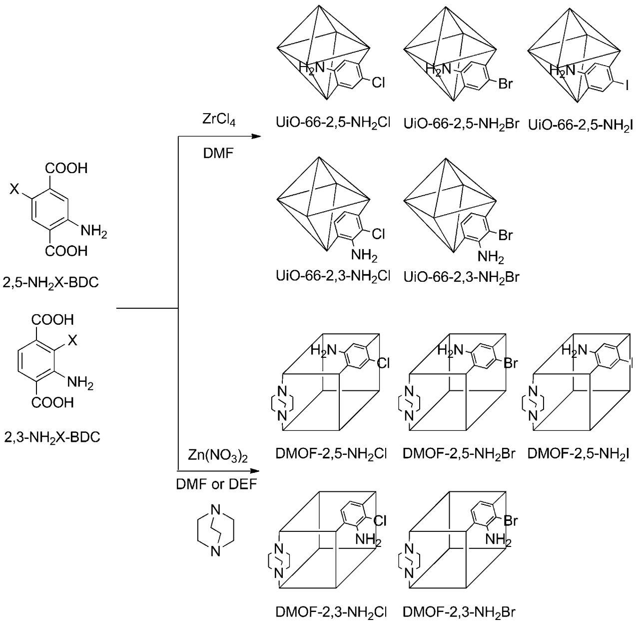
para-isomers (**2b**; Table 1, Scheme S1, Figure S1). By comparison, bromination with NBS gave predominantly the *para*-isomer (**3b**) with only trace amounts of the *ortho*-isomer (**3a**), consistent with the increased steric demand of the bromo-substituent (Figure S2). Bromination of aniline produces only *p*-bromoaniline,[18] making the isolation of *ortho*-isomer as a minor product quite surprising. Finally, iodination gave exclusively the *para*-isomer (**4**, Table 1, Scheme S1, Figure S3). The *ortho*- and *para*-bifunctional amino-haloester intermediates were hydrolyzed under mild conditions to obtain the desired 2-amino-3-halobenzenedicarboxylic acid (2,3-NH_2X-BDC) or 2-amino-5-halobenzenedicarboxylic acid (2,5-NH_2X-BDC) ligands, respectively (Table 1). All of the aforementioned compounds were characterized by ^1H NMR and ESI-MS (Figures S3–S5), and the structure of intermediate **3b** was determined by single-crystal X-ray diffraction (Figure S6, Table S1).

Using this series of bifunctional ligands both Zr^{IV}- and Zn^{II}-based MOFs were synthesized. The Zr^{IV}-based UiO-66, (UiO = University of Oslo) is a rigid, chemically robust MOF with the empirical formula $Zr_6(OH)_4O_4(BDC)_6$.[19] UiO-66-2,3-NH_2X or UiO-66-2,5-NH_2X were synthesized by combining the appropriate bifunctional BDC ligand with $ZrCl_4$ in *N*,*N*-dimethylformamide (DMF) and heating the mixture to 120 °C for 24 h (Scheme 1). The resulting microcrystalline powders were shown to possess the same structure as the parent UiO-66 material as evidenced by power X-ray diffraction (PXRD, Figure 1). The chemical stability of these bifunctional UiO-66 derivatives was found to be quite similar to UiO-66, with good tolerance to polar solvents including water, methanol, ethanol, dichloromethane, and DMF. The materials also displayed thermal stability comparable to other UiO-66 derivatives, as confirmed by thermogravimetric analysis (TGA, Figure S7).



Scheme 1. Synthesis of bifunctional, regioisomeric MOFs.

^1H NMR spectra and ESI-MS analysis after digestion of the MOFs under acidic conditions indicate that the bifunctional ligands remained intact in all UiO-66-2,3-NH_2X and UiO-66-2,5-NH_2X materials (Figures S8–S11). The UiO-66-2,5-NH_2I material produced at 120 °C showed a byproduct in the ^1H NMR spectra. We presumed this impurity arose from greater lability of the iodo group when compared to the bromo or chloro groups at elevated temperatures. To obtain a higher quality material, the synthesis temperature was reduced to 80 °C and acetic acid was employed as a modulator.[20] This resulted in a material with few impurities that still displayed a good PXRD pattern (Figure S8 and Figure 1). Importantly, ^1H NMR analysis of this material showed no evidence of trapped acetic acid.

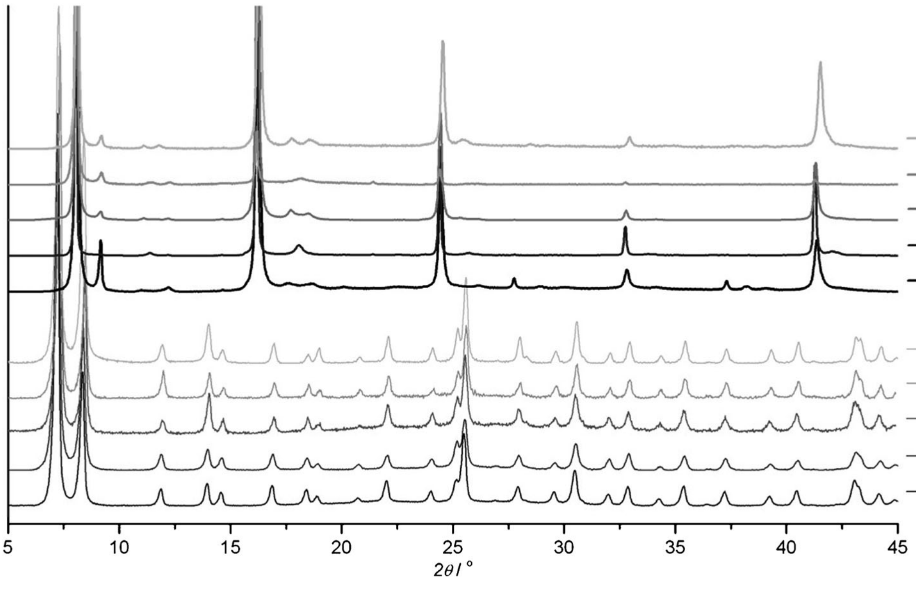


Figure 1. PXRD patterns of bifunctional UiO-66 and DMOF regioisomers.

The compatibility of the bifunctional ligands with other MOF topologies was confirmed by preparing a series of semi-flexible, Zn^{II}-based MOFs. DMOF-1 (DMOF = dabco MOF) is a 3D porous material constructed from Zn^{II}-based paddle-wheel secondary building units (SBUs), BDC, and pillaring 1,4-diazabicyclo[2,2,2]octane (dabco) ligands (Scheme 1).[21] DMOF-2,3-NH_2X or DMOF-2,5-NH_2X was obtained by combining 2,3-NH_2X-BDC or 2,5-NH_2X-BDC with $Zn(NO_3)_2$ and dabco in DMF or DEF (*N*,*N*-diethylformamide). As with the UiO-66 series, all five different bifunctional DMOFs (DMOF-2,3-NH_2X and DMOF-2,5-NH_2X) were readily obtained under solvothermal conditions as evidenced by PXRD (Figure 1). The ^1H NMR spectra after digestion of the crystals show that both the bifunctional ligand and dabco were present in all DMOF-2,3-NH_2X and DMOF-2,5-NH_2X samples with the ratio between the BDC and dabco ligands confirmed to be 2:1 in every case (Figure S12). ESI-MS and TGA analysis also verified the composition and stability of these regioisomer MOFs (Figures S13–S16).

Examination of the gas sorption behavior of these materials revealed substantial differences in behavior based on the MOF topology and regioisomerism. In the relatively rigid UiO-66 derivatives, Brunauer–Emmett–Teller (BET) surface areas differed little between regioisomers falling in the range of 600–900 $m^2 g^{-1}$ (Table S2). In contrast, the DMOF derivatives displayed dramatically different gas sorption properties depending on the regioisomer. All of the DMOF-2,5-NH_2X materials were nearly non-porous to N_2 (6–61 $m^2 g^{-1}$). However, the DMOF-2,3-NH_2X frameworks show large surface areas with N_2; BET surface areas of $(1169 \pm 152)\ m^2 g^{-1}$ and $(527 \pm 105)\ m^2 g^{-1}$ were obtained for DMOF-2,3-NH_2Cl and DMOF-2,3-NH_2Br, respectively (Table S2). The differences in gas sorption phenomena are well illustrated by the full N_2 isotherms performed at 77 K as

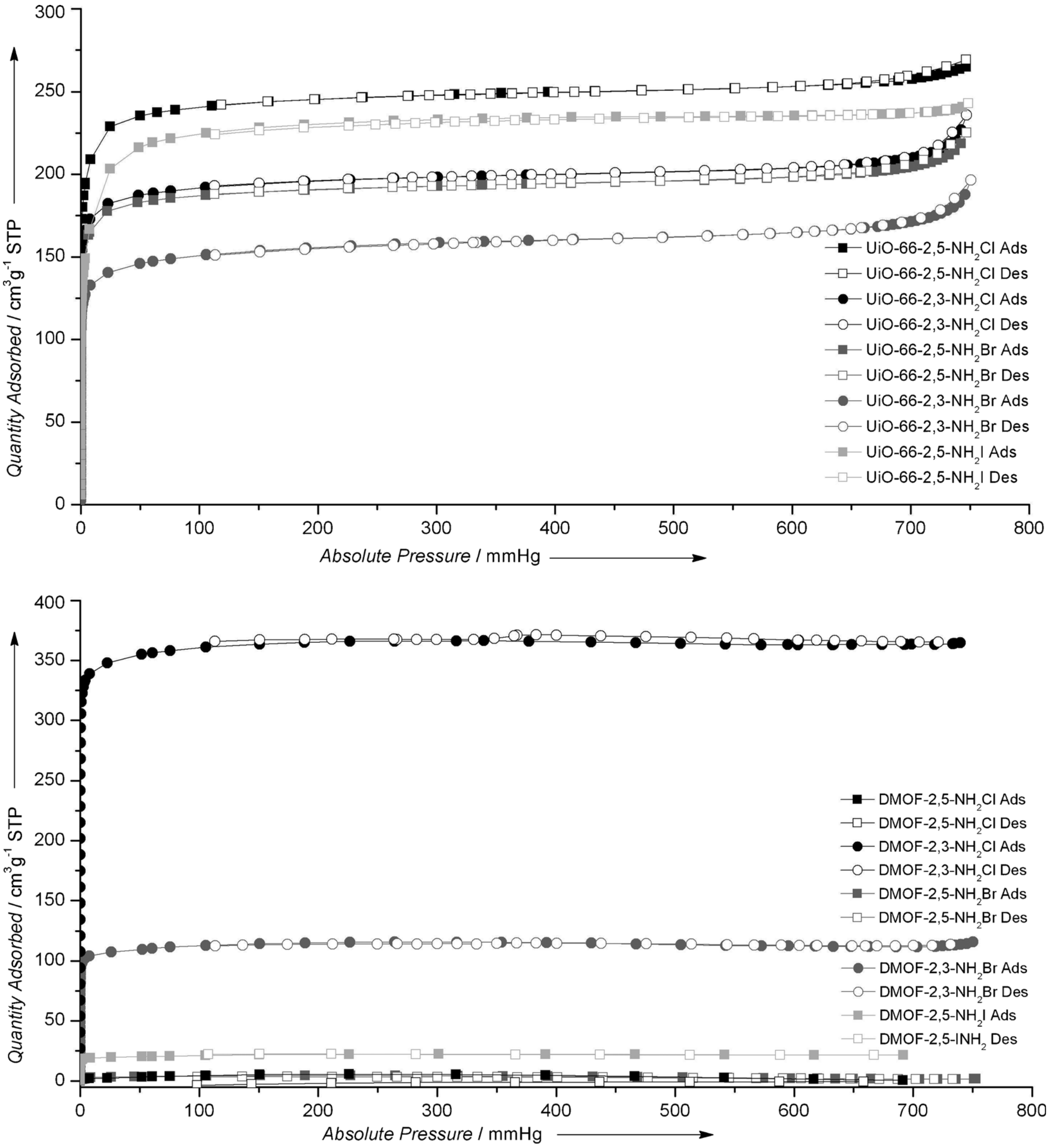


Figure 2. N_2 isotherms (77 K) of bifunctional UiO-66 (top) and DMOF (bottom) regioisomers. Adsorption and desorption traces are indicated by filled and open symbols, respectively.

shown in Figure 2. Since the bulk porous structure and the kinetic radius of functional group atoms are similar, we attribute the differences in gas sorption to the difference in the position of the functional groups (i.e. regioisomerism) and the impact this has on the structural flexibility of the framework.

As previously reported, the DMOF system exhibits flexibility;[21–23] indeed, functional group introduction via PSM can affect the flexibility of the DMOF lattice.[24] With this in mind, we attribute the low porosity of DMOF-2,5-NH_2X to the flexibility of the framework adopting a narrow pore form.[25] This is consistent with a recent report showing a 2,5-alkyl ether functionalized DMOF is non-porous to N_2.[26] Single-crystal X-ray diffraction data suggest that DMOF-2,5-NH_2X is flexible and can form a narrow pore form, while DMOF-2,3-NH_2X cannot (Figure 3). The structure of DMOF-2,3-NH_2Cl taken from either DMF or $CHCl_3$ mother liquor shows a square (type-α)[23] lattice isomer (Figure S17, S18, Table S3). In contrast, the structure of DMOF-2,5-NH_2Cl from DMF shows a square (type-α) lattice, but when taken from a $CHCl_3$ mother liquor displays a rhomboid (type-β)[23] structure (Figure S19, S20, Table S4), illustrating that DMOF-2,5-NH_2Cl displays flexibility depending on the guest molecule. The same difference in structural behavior is also found for DMOF-2,3-NH_2Br and DMOF-2,5-NH_2Br (Figure S21, Table S5, S6), where only DMOF-2,5-NH_2Br displays a rhomboid (type-β) lattice when taken from $CHCl_3$ (Figure S21 and S22). Because all of the MOFs are activated for gas sorption from $CHCl_3$, the X-ray data would suggest that the DMOF-2,3-NH_2X materials are inflexible and remain in a large pore, square (type-α) lattice, while the DMOF-2,5-NH_2X materials collapse to a narrow pore form as evidenced by the formation of the rhomboid (type-β) lattice. This hypothesis is further supported by changes in the low angle PXRD spectra of these materials. The lowest angle reflection in both DMOF-2,5-NH_2Cl and DMOF-2,5-NH_2Br shift to higher angles after activation (i.e. evacuation of solvent) indicating a change in structure to a narrow pore form. However, DMOF-2,3-NH_2Cl and DMOF-2,3-NH_2Br showed no shift in this reflection, indicating that these frameworks are rigid and largely unchanged upon solvent loss (Figure S23). These findings suggest that differences in framework flexibility originate from the regioisomerism of the ligand functional groups.

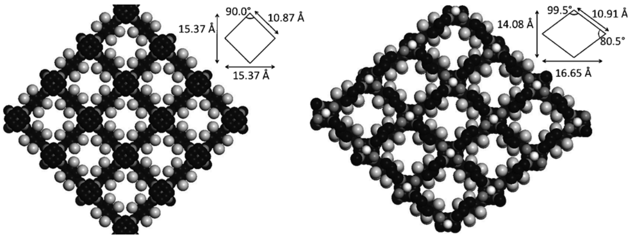


Figure 3. Crystal structures of DMOF-2,3-NH_2Cl (left) and DMOF-2,5-NH_2Cl (right) taken from $CHCl_3$ viewed along the *c*-axis.

In conclusion, five new amino-halo bifunctional BDC ligands have been prepared and used to produce new regioisomers of the Zr^{IV}-based UiO-66 and Zn^{II}-based DMOF materials. While the rigid UiO-66 derivatives show little differences in surface area, the DMOF regioisomers result in distinct conformational isomers with vastly different surface areas. While DMOF-2,3-NH_2X systems adopt a square (type-α) lattice isomer with high surface areas, the DMOF-2,5-NH_2X materials are flexible, as demonstrated by the crystallization of a rhomboid (type-β) phase, and ultimately a non-porous form upon desolvation. These findings reveal the previously unrecognized importance of regioisomerism in MOFs.

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