Postsynthetic Modification of Metal-Organic Frameworks

Senior Thesis

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by
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ABSTRACT

Postsynthetic Modification of Metal-Organic Frameworks

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Metal-organic frameworks (MOFs) are porous, crystalline materials with the potential to act as supports for heterogeneous catalysis. Owing to the presence of tunable organic linkers, these materials can be functionalized to support catalytically active metals. Many MOFs exhibit poor chemical and thermal stability, making them ill-equipped for heterogeneous catalysis. However, the MFU and UiO families of MOFs have been shown to exhibit high degrees of chemical, thermal, and structural stability. The first part of this thesis focuses on the synthesis of amine-functionalized organic linkers for the synthesis of new MFU and UiO MOFs. We have successfully synthesized dipyrazolate linkers \((\text{Me}_2\text{pyz})_2\text{biPh}\) \([(\text{Me}_2\text{pyz})_2\text{biPh} = 4,4'\text{-bis}(3,5\text{-dimethyl}-1\text{H}-\text{pyrazol-4-y1})-1,1'\text{-biphenyl}]\) and \((\text{Me}_2\text{pyz})_2\text{biPh-NO}_2\) \([(\text{Me}_2\text{pyz})_2\text{biPh-NO}_2 = 4,4'\text{-}(2\text{-nitro-[1,1'-biphenyl]-4,4'-diy1]}\text{bis}(3,5\text{-dimethyl}-1\text{H}-\text{pyrazole})\) or assembly of MFU frameworks. The second part of the thesis describes the synthesis of UiO-67 types MOFs with amine-functionalized 4,4'-biphenyl dicarboxylate linkers. Incorporation of these linkers into MFU and UiO frameworks will allow us to use post-synthetic modification as a means of incorporating catalytically active metals and examine their potential for heterogeneous catalysis.
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CHAPTER 1

Introduction
1.1 Metal Organic Frameworks

Metal-organic frameworks (MOFs) are coordination polymers constructed from organic linkers and metal clusters, or secondary building units (SBUs), that form 1-, 2-, or 3-dimensional structures. The metal nodes are connected by organic linkers containing coordinating functional groups, typically carboxylate or pyridine groups (Figure 1). Certain classes of MOFs can exhibit good thermal and chemical stability. Additionally, MOFs can have very high internal surface areas (upwards of 7,100 g²m⁻¹) and large pores or channels. As a result of their ability to maintain permanent porosity upon desolvation, these materials have been studied for applications in heterogeneous catalysis, gas storage and separation.

![Figure 1. Representation of common SBUs, linkers (left) and metal-organic framework (right).](image)

Many industrial processes favor heterogeneous catalysts owing to their high activity and ease of product separation. While homogeneous catalysts generally do no offer the same degree of stability, ligand design can be used to tune both the steric and electronic properties of
the catalysts, leading to improved activity and selectivity.\textsuperscript{17-18} MOFs can be used as supports for catalytically active species, resulting in materials that have the stability and recyclability of heterogeneous catalysts as well as the activity and selectivity of homogeneous analogues. Unfortunately, many MOFs are sensitive to moisture in the air or collapse upon evacuation of host molecules from the pore, limiting their applicability as supports for catalytic active sites.\textsuperscript{19} Collapse of the framework results in loss of usable surface area, blocking substrate access to the catalytic active species within the MOF.

MOF materials constructed from dipyrazolate linkers have demonstrated high degrees of chemical and thermal stability relative to many carboxylate-based materials.\textsuperscript{14, 20} For example, MOF-5 is a dicarboxylate-based MOF with Zn$_4$O SBUs. (Figure 2, left) The Zn-O bonds are hydrolyzed by moisture in the air, which makes this material difficult to handle outside of a glovebox. However, MFU-1, a dipyrazolate MOF containing an analogous Co$_4$O SBU (Figure 2, right) is stable to adventitious moisture. The pyrazolate ligands are softer ligands than carboxylates, resulting in stronger metal-ligand bonds with the late transition metals often used for MOF assembly. The MFU-1 framework offers the attractive features of MOF-5, such as permanent porosity and high surface area, with the added benefit of being air-stable. This makes pyrazolate MOFs attractive as supports for heterogeneous catalysis.
Figure 2. Zn₄(O)(1,4-benzenedicarboxylate)₃ (MOF-5) structure and Zn₄O SBU (left) Co₄(O)[1,4-benzenedi(3,5-dimethylpyrazolate)]₃ (MFU-1) structure and Co₄O SBU (right).

Air-stable, pyrazolate-based MOFs MFU-1 and MFU-2 have been synthesized from Co²⁺ and (Me₂pyz)₂Ph [(Me₂pyz)₂Ph = 1,4-bis(3,5-dimethyl-1H-pyrazol-4-yl)benzene] (Scheme 1).²⁻³ These materials retain porosity upon evacuation of guest molecules from the pores, are stable to 400 °C, and exhibit high internal surface areas (~1500 m²g⁻¹), making them promising candidates as supports for heterogeneous catalysis.²⁻³
Scheme 1. (i) 4.5 eq CoCl$_2$·6H$_2$O, 0.01 mL 1M HCl, DMF, room temp to 120 °C, 0.15 °C/min, 4 d (ii) 6 eq Co(NO$_3$)$_2$·6H$_2$O, DMF, room temp to 120 °C, 0.15 °C/min, 10 h.

Pryazolate MOFs are not the only air and moisture stable MOFs that have been reported. The UiO family of MOFs contain hexanuclear Zr oxide SBUs (Scheme 2, right). These clusters consist of six zirconium atoms linked by four μ$_3$-oxygens, four μ$_3$-hydroxyls, and 12 carboxylate ligands associated with an organic linker. This family of MOF is extremely stable to water and other protic solvents, since Zr-O bonds in the UiO SBU are stronger than the Zn-O bonds in MOF-5. Zr$^{4+}$ is a hard transition metal ion that binds tightly to oxygen. UiO-67, containing [BPDC]$^{2-}$ ([BPDC]$^{2-}$ = 4,4'-biphenyldicarboxylate) linkers, exhibits a high internal surface area (~2500 m$^2$ g$^{-1}$) as well as excellent thermal (through 400 °C) and chemical stability (Scheme 2).$^{4-5,21-22}$ The stability of this material toward water and other protic solvent, as well as aqueous acid and base make it a promising support material for heterogeneous catalysis.
Scheme 2. (i) ZrCl₄, AcOH, DMF, 120 °C, 24 h.

2.2 Designing MOFs as Hybrid Catalysts: Homogeneous vs. Heterogeneous Catalysis

Mesoporous silica and activated carbon are widely used supports for heterogeneous catalysts due to their high surface areas and stability in a variety of chemical and thermal environments.⁹⁻¹², ²³⁻²⁴ They can be functionalized by addition of catalytic active dopants. A well known example of this principle is activated carbon acting as a support for Pd(0). Increased activity of Pd/C verses Pd metal is the result of increased surface area.²⁵⁻²⁶ Similarly, MOFs can also be used as supports for catalytically active species. An advantage of MOFs relative to other heterogeneous supports is that the pore size of the framework can be tuned by variation of the organic linker, therefore a more selective channel size can be obtained for the desired application or catalyst species.²⁷

On the other hand, homogeneous catalysts can be tuned to allow high catalytic activity and selectivity through ligand design, which can allow for the use of lower catalyst loading.¹⁷⁻¹⁸ Homogenous catalysts reside in the same phase as the reactants, therefore they are not easily separated from products nor recycled. However, homogenous catalysts can be immobilized on insoluble polymers or silica.¹¹ Catalyst immobilization combines the positive aspects of both types of catalysts: the activity and selectivity of homogeneous catalysts and the stability and
recyclability of heterogeneous catalysts. MOFs are attractive supports for these types of systems, given their pore size and functional group tenability, allowing a variety of catalytic species to be incorporated into their frameworks for a variety of chemical transformations.

Catalytically active species can be incorporated into MOFs in several ways: catalyst encapsulation, activation of a metal node, or incorporation of a catalytic active site at the organic linker (Figure 3).\textsuperscript{1,7-8,19,28} Catalyst encapsulation occupies pore space, which can limit substrate diffusion. Additionally, catalyst leeching may occur. Catalysis may also occur at a metal structural node (SBU). While this does not consume internal surface area, the approach is limited by the identity of the metal at the SBU. During a catalytic cycle, substrate binding or redox reactions can compromise the structural integrity of the framework. By incorporating a catalytically active site as part of an organic linker, catalyst leeching and framework degradation may be suppressed. Catalyst incorporation into an organic linker can be achieved through \textit{de novo} synthesis or postsynthetic modification (PSM) of an existing framework.

\begin{center}
\textbf{Figure 3.} Three modes of incorporation of catalytically active sites in MOFs.
\end{center}
2.3 Postsynthetic Modification (PSM) and Mixed-Linker MOFs

Postsynthetic Modification (PSM) is a strategy that involves functionalization of the MOF structure after assembly. This pathway allows for the installation of functional groups that would otherwise not survive the harsh conditions associated with MOF synthesis. PSM has been accomplished by three methods, each named for the type of bond broken or formed during the modification: formation of a covalent bond (covalent PSM), dative PSM formation of a metal-ligand bond (dative PSM), and postsynthetic deprotection (PSD).\textsuperscript{29}

Covalent PSM forms a new covalent bond, generally at a functional group attached to the organic linker. These modifications have been made in MOFs containing amine, aldehyde, azide, or alkyne-functionalization.\textsuperscript{7, 19, 29} As an example, amine-functionalized MOFs can react with aldehydes containing pendant electron donor groups via imine condensations to form chelating ligands, which can then be used to capture non-framework metals for catalysis (Figure 4).

![Figure 4. Strategy for covalent PSM of amine-functionalized MOFs with aldehydes, where Y = ligand donor group.](image)

Examples of PSM have largely focused on amine- or aldehyde-functionalized MOFs. IRMOF-3, a material assembled from 2-amino-1,4-benzenedicarboxylate (BDC-NH\textsubscript{2}) and Zn\textsubscript{4}O SBU\textsubscript{s}, has been shown to react with salicyaldehyde. The resulting imine can act as a chelating ligand and effectively binds vanadium.\textsuperscript{20} These resulting chelating ligands and non-framework
metals are suspended in the framework pores and block substrate success to sites within the material. Thus, the number of catalyst active sites must often be reduced to accommodate incoming substrates (Figure 5). If substrates cannot enter the pores of a MOF, then the catalytic activity of the material will decrease.

![Diagram of catalyst crowding](image)

**Figure 5.** Representation of catalyst crowding.

Catalyst crowding can be alleviated in post-synthetically modified MOFs by synthesizing mixed-linker or multivariate MOFs (MTV-MOFs). Solution or solid-state NMR spectroscopy can be used to determine the ratio of linkers in a mixed-linker MOF by integration of the resulting spectra. NMR spectroscopy shows a significant advantage over single-crystal X-ray diffraction, as mixed-linker MOFs are inherently more disordered and their structure will be more difficult to refine. Additionally, MOFs synthesized from purely organic linkers, containing only C, H, O, and N, may not be electronically unique enough to quantify linker ratios in the framework. 7,30-31

As an example of mixed-linker MOFs in the literature, Hupp and coworkers have synthesized a hydrogen-bond-donating mixed-linker UiO-67 MOF catalyst, containing a mixture of [BPDC]²⁻ and urea-functionalized dicarboxylate struts. Solution-state ¹H NMR analysis of a digested MOF samples was used to determine the ratio of urea-functionalized linkers to [BPDC]²⁻. The mixed-linker MOF was shown to have improved catalytic activity for the Henry
reaction over both the parent MOF, containing only urea-functionalized linkers, and the homogenous catalyst. The mixed-linker MOF allowed for site isolation of the catalytically active species and an increase in accessible surface area for substrate diffusion, both of which resulted in the improved catalytic activity.\textsuperscript{22}

More recently, Kuhn and coworkers have reported the PSM of a mixed-linker, amine-functionalized UiO-67 derivative with salicyaldehyde. \textsuperscript{13}C magic-angle spinning NMR (MAS NMR) analysis of MOF samples was used to determine the ratio of amine-functionalized linkers to [BPDC]\textsuperscript{2-}. The product salicylimine chelates [MoO\textsubscript{2}(acac)\textsubscript{2}] (acac = acetylacetonate) and the resulting material is catalytically competent for olefin epoxidation.\textsuperscript{21}

2.4 Objectives

The objective of the work described in this thesis is the postsynthetic modification of amine-functionalized, mixed-linker MOFs as a means of incorporating catalytically active, non-framework metals for catalysis. Specifically, we have focused on materials constructed from dicarboxylate and dipyrazolate linkers that demonstrate high chemical and thermal stability. Given their high surface area, thermal stability, and stability to moisture in the air, we have modeled our pyrazolate frameworks after MFU-1 and MFU-2 and our carboxylate frameworks after UiO-67.\textsuperscript{2-5,22}

Additionally, we were interested in using biphenyl linkers in our syntheses. Synthesis of biphenyl derivatives of MFU-1 and MFU-2 leads to materials with increased pore size and surface areas, allowing for efficient postsynthetic modification (Figure 6). Additionally, increased pore space will allow for increased substrate diffusion within the framework to catalyst active site.
Another goal of this work was to functionalize our MOFs with phosphine chelating groups (Figure 7). Phosphines are soft ligands and strong σ-donors and have been used extensively in homogenous catalysis. However, given their sensitivity to oxygen, phosphine moieties are difficult to directly incorporate into MOFs via solvothermal synthesis. Using a PSM approach, we set out to generate an amine-functionalized MOF and use a phosphinoaldehyde to generate chelating phosphine-imine groups (Figure 7). This aldehyde is derived from an air-stable cyclic phosphonium salt reported in the literature that has been used in the template synthesis of Fe(II) complexes containing tridentate P–N–S, P–N–P, P–N–N and tetradentate P–N–N–P ligands. We hypothesized that the resulting imine would chelate a variety of soft, non-framework metals to afford catalytically active MOFs.

![Figure 6](image1.png)

**Figure 6.** Target amine-functionalized biphenyl linker (right).

![Figure 7](image2.png)

**Figure 7.** Strategy for incorporation of phosphine and secondary metal via PSM.
Chapter 2 describes the synthesis of the \((\text{Me}_2\text{pyz})_2\text{biPh}\) \((2) \ (\text{Me}_2\text{pyz})_2\text{biPh} = \text{4,4}'\text{-bis}(3,5\text{-dimethyl-1H-pyrazol-4-yl})\text{-1,1'}\text{-biphenyl}\) for use as an organic linker in MOF assembly. Following the successful design of the linker, this dipyrazole was used to synthesize isoreticular analogous of MFU-1 and MFU-2. The new MFU-1 based material, \(\text{Co}_4(\text{O})[(\text{Me}_2\text{pyz})_2\text{biPh}]_3\) \((7)\), was characterized by powder X-ray diffraction, single crystal X-ray diffraction, thermogravimetric analysis (TGA), and \(\text{N}_2\) gas sorption to understand its structure, porosity, and stability. However, further work with this material has been hampered by the poor reproducibility of the synthesis.

Chapter 3 describes the synthesis and characterization of a reported mixed-linker Uio-67 MOF \(\text{Zr}_6(\text{O})_4(\text{OH})_4([\text{BPDC}]^2^-)_{6-x}([\text{BPDC}-\text{NH}_2]^2^-)_x\) \((\text{BPDC}-\text{NH}_2)^2^- = 2\text{-amino-[1,1'}\text{-biphenyl]}\text{-4,4'}\text{-dicarboxylate}\). Attempts at postsynthetic modification to introduce chelating phosphine groups into this framework were unsuccessful.
CHAPTER 2

Dipyrazolate Metal-Organic Frameworks
2.1 Objective

The goal of my project was to synthesize a mixed-linker, pyrazolate MOF incorporating amine-functionalized linkers in order to install chelating phosphinoimine groups via postsynthetic imine condensation. Such a modification would allow for chelation of catalytically active, non-framework metals. Pyrazolate-based organic linkers were chosen due to the resulting MOF’s increased structural stability relative to carboxylate analogues.29, 31

We aimed to synthesize biphenyl analogues of MFU-1 and MFU-2, with the intention of obtaining materials with increased internal surface area, while retaining similar thermal and chemical stability. We also hypothesized that mixed-linker pyrazolate MOFs could be synthesized with amine-functionalized linkers and PSM strategies could be used to introduce chelating groups and catalytically active metal species.

2.2 Synthesis of pyrazolate linkers (Me$_2$pyz)$_2$biPh and (Me$_2$pyz)$_2$biPh-NO$_2$

The synthesis of (Me$_2$pyz)$_2$biPh (2) was carried out as shown in Scheme 3. Cu-catalyzed Ullmann coupling of acetylacetone with 4,4’-diiodobiphenyl afforded compound 1 in 60% yield. A characteristic resonance for the enolic-proton appears at 16.71 ppm in d$_6$-DMSO. Upon reaction with hydrazine, compound 1 was converted to dipyrazole 2 in 90% yield.

Scheme 3. (i) CuI, l-proline, K$_2$CO$_3$, DMSO, 90 °C, 4 h (ii) H$_2$NNH$_2$, EtOH, reflux, 12 h.
Attempts to mono-nitrate 2 resulted in mixtures of the dinitrated products 3.1 and 3.2 shown in Scheme 4. A small amount of symmetric product (3.1) was isolated by precipitation with acetone and was characterized by analysis of the $^1$H NMR spectra. $^1$H NMR analysis of the products obtained from the acetone filtrate revealed a 3:2 mixture of 3.2 to 3.1. This procedure produced inconsistent results and the desired, mono-nitrated product could not be obtained.

![Scheme 4](image)

Scheme 4. (i) HNO$_3$/H$_2$SO$_4$, 0 °C, 1 h.

The mono-nitrated dipyrazole 6 was synthesized as shown in Scheme 5. Reaction of 4,4’-dibromobiphenyl with HNO$_3$ cleanly generated 4,4’dibromo-2-nitro-biphenyl (3). A subsequent Cu-catalyzed halogen exchange of 3 using NaI afforded 4,4’-diiodo-2-nitro-biphenyl (4) in 90% yield. An Ullmann coupling of 4 with acetylacetonate generated compound 5 at a 30 % yield. Reaction of 5 with hydrazine afforded the desired dipyrazole ligand 6 in 90% yield.

![Scheme 5](image)

Scheme 5. (i) HNO$_3$/H$_2$SO$_4$, AcOH, 110 °C, 2 h (ii) NaI, CH$_3$NHCH$_2$CH$_2$NHCH$_3$, Cul, dioxanes, reflux, 2 days (iii) Cul, l-proline, K$_2$CO$_3$, DMSO, 90 °C, 24 h (iv) H$_2$NNH$_2$, EtOH, reflux, 12 h.
The Ullmann coupling step showed a dependence on the quality of the CuI used. Trace metals grade (99.99%) CuI stored in the glovebox gave poor yields. However, when the high purity CuI was removed from the glovebox and left open to air for about 20 minutes, the yield of 5 increased from 20% to 40%. The use of rigorously deoxygenated DMSO also significantly improved the yield of this reaction. From these results, it is postulated that a small amount of CuO might be beneficial for this reaction to proceed, but too much results in significantly decreased catalytic activity.

2.3 Solvothermal Synthesis and Characterization of Co\(^{2+}\) MOFs

Dipyrazole 2 was used to synthesize the MOF Co\(_4\)(O)[(Me\(_2\)pyz)\(_2\)biPh]\(_3\) (7), as shown in Scheme 6. Dipyrazole ligand 2 was dissolved in DMA with heat and solid Co(NO\(_3\))\(_2\)·6H\(_2\)O was added to the solution upon cooling. The reaction vessel was sealed and heated at 130 °C for five days to afford blue cubic crystals of 7. Single crystals of 7 were recovered, and the structure of the MOF was determined by single crystal X-ray diffraction. The bulk crystallinity of the sample was confirmed by comparing the experimental PXRD pattern with the pattern simulated from the single crystal structure (Figure 10).
Scheme 6. (i) Co(NO$_3$)$_2$·6H$_2$O, DMA, slow ramp 0.1 °C/min to 130 °C, 5 days.

Figure 10. Experimental and simulated PXRD patterns of 7.

The thermal stability of 7 was studied by thermogravimetric analysis (TGA) (Figure 11). The TGA curve showed an initial mass loss over the temperature range 50-65 °C. Given the low temperature, this mass loss is attributed to evaporation of residual solvent on the surface of the
crystals. A subsequent mass loss from 85-200 °C is attributed to solvent loss from inside the pores. Based on this data, the empirical formula of MOF 7, including guest solvent molecules, has been assigned as Co₄(O)[(Me₂pyz)₂biPh]₃·23 DMA. No weight loss occurred between 200 and 550 °C and full decomposition occurred at 650 °C. This suggests that 7 is stable at high temperatures, making it a good candidate as a thermally stable support for heterogeneous catalysis.

Figure 11. Thermogravimetric analysis data for 7.

Upon scaling up the synthesis of 7, a mixed phase material (7-Is) was obtained. The PXRD pattern of this material shows a peak at 2θ = 5° that does not appear in the original sample (7), implying that this scaled up reaction did not yield a phase pure material (Figure 12). A sample of 7-Is was desolvated by heating to 150 °C under vacuum (10⁻⁴ torr) for 36 h. The PXRD pattern of the resulting materials shows retention of the impurity at 5 ° (Figure 12). Nevertheless, PXRD suggests that 7 is the major component of the material and it was used for a subsequent N₂ adsorption experiment.
Based on the TGA data, a sample of 7-ls was heated to 150 °C under high vacuum to remove guest solvent molecules. A subsequent N₂ adsorption experiment (77K) revealed that compound 7 maintains N₂-accessible porosity. The data was analyzed to give a calculated BET surface area of 2696 m²g⁻¹ (Figure 13). The permanent porosity and large surface area of 7 makes it a good candidate as a support for heterogeneous catalysis. The N₂ adsorption isotherm appears to show two different slopes in the low-pressure region, which could be indicative of the
two different phases observed via PXRD. Alternatively, the material could contain two different pore sizes, defined by defect sites or variations in coordination environments.

![Figure 13. N\textsubscript{2} adsorption isotherm for 7.](image)

The hydrolytic stability of 7 was investigated by suspending samples in three different solvents: ethanol, 50:50 ethanol/H\textsubscript{2}O, and H\textsubscript{2}O. After 24 h, powder X-ray diffraction analysis of these materials showed complete degradation of the framework (Figure 14). This was not observed for the analogous material MFU-1, which showed stability in ethanol for up to 96 h and solvent mixtures containing up to 30 vol % H\textsubscript{2}O.\textsuperscript{2} Based on this data, attempts to use MOF 7 as a support for heterogeneous catalysis might be limited to aprotic solvents.
While early syntheses of 7 resulted in a crystalline phase, later attempts using identical reaction conditions resulted in formation of dark blue films (7.1) (Figure 15). Reactions parameters were varied extensively to attempt to reform the desire MOF phase consistently. We varied ligand concentration, Co$^{2+}$ source, Co$^{2+}$ equivalencies, acid modulators, and reaction vessel with no success. We hypothesized that the reproducibility issues were due to poor ligand solubility. Consequently, we looked to a more soluble dipyrazole ligand to synthesize our framework.

**Figure 14.** PXRD patterns of 7 after soaking in solvents for 24 h: 50:50 H$_2$O/EtOH (blue), H$_2$O (green), and EtOH (orange).
Nitratated dipyrazole 6 exhibits better solubility than 2 in organic solvents. Thus, we considered that the increased solubility may facilitate the reproducible synthesis of a Co MOF analogous to 7. Indeed, the reaction of 6 with Co(NO$_3$)$_2$·6H$_2$O in DMA, as shown in scheme 7, afforded Co$_4$(O)[(Me$_2$pyz)$_2$biPh-NO$_2$]$_3$ (8) as a blue powder. Powders of 8 were determined to be analogous to 7 by comparison of experimental PXRD data. MOF 8 could be scaled up (8-I$_s$) and the desired phase was retained (Figure 16)
Scheme 7. (i) Co(NO$_3$)$_2$·6H$_2$O, DMA, 120 °C, 4 days.

Figure 16. PXRD patterns of as-synthesized 7 (red), 8 (blue) and scaled up 8-Is (green).

Unfortunately, while the initial syntheses of 8 resulted in isolation of microcrystalline powders, later attempts under identical conditions once again resulted in dark blue films. This suggests that the initial hypothesis may have been incorrect. However, there may be an impurity
carried through from ligand synthesis that assists the formation of the desired crystalline phase. The quality of the pyrazole 6 was notably different in the later syntheses of films. Compound 6 was rigorously cleaned to remove residual solvents and impurities, and MOFs synthesized from this “clean” ligand resulted in films.

**2.4 Solvothermal Synthesis and Characterization of Zn$^{2+}$ MOF**

![Scheme 8](image)

**Scheme 8.** (i) Zn(NO$_3$)$_2$·6H$_2$O, 1M HCl, DMF, room temp to 130 °C at 0.1 °C/min, 5 days.

Solvothermal reaction of 2, Zn(NO$_3$)$_2$·6H$_2$O, and 1M HCl in DMF afforded 9 as an off-white, microcrystalline powder as shown in Scheme 8. PXRD analysis of 9 suggests that it is an isoreticular analogue of MFU-2. The reported structure of MFU-2 was used as a starting point to construct a model of an isoreticular analogue containing the extended linker (9). The PXRD pattern simulated from this model closely matched the experimental pattern obtained for 9 (Figure 17).
Unfortunately, the synthesis of this phase could not be reproduced. In attempts to reproduce the synthesis, reaction parameters such as the reaction vessel, zinc source, solvent composition, and ligand concentration were varied. However, these attempts were all unsuccessful, leading us to again speculate that an impurity may be assisting the formation of the framework.

2.5 Summary

We successfully synthesized two new dipyrazole linkers, (Me$_2$pyz)$_2$biPh (2) and (Me$_2$pyz)$_2$biPh-NO$_2$ (6). Future work will need to be done to complete the synthesis of (Me$_2$pyz)$_2$biPh-NH$_2$. Three new MOFs, Co$_4$(O)[(Me$_2$pyz)$_2$biPh]$_3$ (7), Co$_4$(O)[(Me$_2$pyz)$_2$biPh-NO$_2$]$_3$ (8), and Zn[(Me$_2$pyz)$_2$biPh]$_3$ (9) were synthesized and characterized by PXRD. MOF 7 was further characterized by single crystal X-ray diffraction, TGA, and N$_2$ gas adsorption experiments. Unfortunately, the syntheses of these MOFs were not reproducible, even after
screening variations of the metal source, solvent, ligand concentration, acid modulators, and reaction vessel. It is possible that an impurity from the ligand synthesis is carried through to the MOF synthesis and assists in templating the material.
2.7 Experimental

General Considerations

4,4’-diiodobiphenyl\textsuperscript{34} and 4,4’-dibromo-2-biphenyl\textsuperscript{35} were synthesized following literature procedures. Other reagents were purchased from Sigma Aldrich, Alfa Aesar, or Fisher Scientific and used as received. Anhydrous DMSO was purchased from Acros Organic and used as received. DMF, DMA, ethanol, methanol, ethyl acetate, dioxanes, were used as received unless otherwise noted. Acetylacetonate was refluxed over P\textsubscript{2}O\textsubscript{5} and fractionally distilled before use. Air-sensitive compounds were handled under a N\textsubscript{2} atmosphere using standard Schlenk techniques. Sealed tubes used for MOF synthesis were prepared by soaking in 2M KOH for 20 minutes, rinsing with water, soaking in 2M HCl for 20 minutes, rinsing with water, rinsing with acetone, and then oven drying overnight.

Instrumental Methods

Solution-state NMR spectra were measured using either a Varian Inova or MR 400 MHz spectrometer (400 MHz operating frequency for \textsuperscript{1}H, 101 MHz operating frequency for \textsuperscript{13}C). For \textsuperscript{1}H and \textsuperscript{13}C\{\textsuperscript{1}H\} NMR spectra, the solvent resonance was referenced as an internal standard.

Routine powder X-ray diffraction patterns for phase identification were collected on a Rigaku Miniflex 600 diffractometer using Nickel-filtered Cu-K\textalpha radiation (\(\lambda = 1.5418\) Å). The 2θ angle was varied from 3 to 45 degrees at a rate of 5 °/min. Dry samples were loaded onto a glass slide open to air. The crystal structure of 7 was collected on the 11.3.1 beamline at the Lawrence Berkeley National Lab Advanced Light Source. Thermogravimetric analysis was conducted on a Q500 TGA from TA instruments. Samples were air dried on filter paper for at least 15 minutes prior to analysis. Samples were heated from room temperature to 700 °C at a ramp rate of 5 °C/min. N\textsubscript{2} adsorption isotherms were measured at 77K (liquid nitrogen bath)
using a Micromeritics 3Flex Surface Characterization Analyzer. Prior to analysis, samples (100-200 mg) were heated under vacuum until the outgas rate was less than 2 mTorr/minute.

**Experimental**

\( (3Z,3'Z)-3,3'-(1,1'-biphenyl-4,4'-diyl)bis(4-hydroxypent-3-en-2-one) \) (1) \( \rightarrow \) \( 4,4' \)-diiodobiphenyl (3.00 g, 7.39 mmol), \( \text{L-proline} \) (341 mg, 2.96 mmol, 0.4 eq), and \( \text{K}_2\text{CO}_3 \) (8.00 g, 59.1 mmol, 8 eq) were added to an oven-dried Schlenk flask. Anhydrous DMSO (40 mL) was added via syringe. The solution was degassed with nitrogen with stirring for at least 20 minutes. Acetylacetone (4.50 mL, 44.4 mmol, 6 eq) and CuI (282 mg, 1.48 mmol, 0.2 eq) were added and the reaction was left to stir under nitrogen for 4 h at 90 °C. The flask was cooled to room temperature and was poured over 2M HCl (~40 mL). The resulting solution was allowed to stir for 20 minutes or until it appeared transparent. The products were extracted with EtOAc (5\( \times \)25mL), washed with brine, and dried over MgSO\(_4\). The resulting red solution was concentrated to a dark oil *in vacuo*. Upon the addition (5-7 mL), the desired product precipitated as a tan powder. The product was collected by vacuum filtration and the resulting powder was recrystallized from MeOH. (2.6 g, 60% yield) \( ^1\text{H} \) NMR (400 MHz, CDCl\(_3\)): \( \delta \) 16.71 (s, 2H, enolic-H), 7.66 (d, \( J = 7.6 \), 4H, Ar-H), 7.27 (d, \( J = 8.4 \), 4H, Ar-H), 1.95 (s, 12H, Me). \( ^{13}\text{C}\{^1\text{H}\} \) NMR: \( \delta \) 190.9 (s, 4C, CO), 139.5 (s, 2C, Ar-C), 136.2 (s, 2C, Ar-C), 131.6 (s, 4C, Ar-C), 127.4 (s, 4C, Ar-C), 114.7 (s, 2C, quaternary C), 24.2 (s, 4C, Me-C).

\( 4,4'\)-bis(3,5-dimethyl-1H-pyrazol-4-yl)-1,1'-biphenyl (2) - Compound 1 (1.50 g, 4.28 mmol, 1 eq) was suspended in EtOH (60 mL). Hydrazine (0.520 mL, 10.7 mmol, 2.5 eq), was added to this solution and the reaction mixture was heated to reflux for 16 hr. The desired product
precipitated as a white solid that was insoluble in EtOH, and was recovered via vacuum filtration. (1.29 g, 92% yield) \(^1\)H NMR (400 MHz, d\(_6\)-DMSO): \(\delta\) 12.30 (s, 2H, NH), 7.73 (d, \(J=7.6\) Hz, 4H, Ar-H), 7.39 (d, \(J=8.0\) Hz, 4H, Ar-H), 2.24 (s, 12H, pyz-CH\(_3\)). \(^{13}\)C{\(^1\)H} NMR: \(\delta\) 145.8 (s, 4C, CN), 142.4 (s, 2C, Ar-C), 138.2 (s, 2C, Ar-C), 134.3 (s, 4C, Ar-C), 131.7 (s, 4C, Ar-C), 121.7 (s, 2C, quaternary C), 16.8 (s, 4C, pyz-CH\(_3\)).

**Attempted nitration of 2** (3.1, 3.2) – Dipyrazole 2 (250 mg, 0.73 mmol, 1 eq) was dissolved in H\(_2\)SO\(_4\) (4 mL) at room temperature. The ligand solution was cooled to 0 °C. A solution of HNO\(_3\) (0.080 mL, 1.8 mmol, 2.5 eq) and H\(_2\)SO\(_4\) (2 mL) was prepared and added dropwise to the cooled ligand solution over the course of 30 min. The reaction was allowed to proceed at < 5 °C for 30 min. The solution was then poured over ice and neutralized with NaOH. The resulting yellow precipitate was isolated via vacuum filtration. The solid was washed with acetone and filtered again. 3.1 was somewhat insoluble in acetone and was isolated on filter paper (38 mg, 12 % yield). \(^1\)H NMR (400 MHz, d\(_6\)-DMSO): \(\delta\) 8.10 (s, 2H, Ar-H), 7.79 (d, \(J=7.6\) Hz, 2H, Ar-H), 7.56 (d, \(J=8.0\) Hz, 2H, Ar-H), 2.56 (s, 12H, Me-H). 3.2 was very soluble in acetone and removal of the solvent via rotary evaporation afforded a yellow solid that was a 2:3 mixture of 2.1 and 2.2. \(^1\)H NMR (400 MHz, d\(_6\)-DMSO): \(\delta\) 8.07 (s, 1H, Ar-H), 8.00 (s, 1H, Ar-H), 7.78-7.71 (m, 3H, Ar-H), 7.54 (d, \(J=8.0\) Hz, 1H), 2.32 (s, 6H, Me-H), 2.07 (s, 6H, Me-H).

4,4'-diiodo-2-nitro-1,1'-biphenyl (3) - 4,4'-dibromo-2-nitro-biphenyl (2.0 g, 5.6 mmol, 1 eq) and NaI (3.36 g, 22.4 mmol, 4 eq) were added to an oven-dried Schlenk flask. Anhydrous 1,4-dioxane (38 mL) was added to the flask via syringe. This solution was degassed with N\(_2\) for at least 20 min. N, N’-dimethylethlyenediamine (120. µL, 1.12 mmol, 0.2 eq) and CuI (107 mg, 0.560 mmol, 0.10 eq) were added to the flask and the reaction mixture was stirred at reflux under
nitrogen for 72 hours. The resulting solution was then diluted with 30% ammonia hydroxide, poured into water, extracted with EtOAc (5×25 mL), washed with brine, and dried over MgSO₄. The resulting yellow solution was then diluted with 30% ammonia hydroxide, poured into water, extracted with EtOAc (5×25 mL), washed with brine, and dried over MgSO₄. The resulting yellow solution was concentrated via rotary evaporation to afford a bright yellow solid, which required no further purification. (2.2 g, 89% yield) ¹H NMR (400MHz, CDCl₃): δ 8.19 (s, 1H, Ar-H), 7.94 (dd, 1H, Ar-H), 7.76 (dd, 1H, Ar-H), 7.13 (d, 2H, Ar-H), 7.02 (d, 2H, Ar-C). ¹³C {¹H} NMR: δ 149.1 (s, Ar-C), 141.4 (s, Ar-C), 137.9 (s, Ar-C), 136.0 (s, Ar-C), 134.8 (s, Ar-C), 133.0 (s, Ar-C), 132.8 (s, Ar-C), 129.5 (s, Ar-C), 94.7 (s, Ar-C), 92.3 (s, Ar-C).

(3Z,3′Z)-3,3′-(2-nitro-[1,1′-biphenyl]-4,4′-diyl)bis(4-hydroxypent-3-en-2-one) (4) - 3 (1.00 g, 2.21 mmol, 1 eq), L-proline (101 mg, 0.880 mmol, 0.4 eq), and K₂CO₃ (2.50 g, 17.7 mmol, 8 eq) were added to an oven-dried Schlenk flask. Dry DMSO (20 mL) was added via syringe. The solution was degassed with nitrogen for at least 20 min. Acetylacetone (1.40 mL, 13.3 mmol, 6 eq) and CuI (84 mg, 0.44 mmol, 0.2 eq) were added to the solution and the reaction mixture was stirred under N₂ at 90 °C for at least 18 h. The flask was cooled to room temperature and was poured over 1M HCl (~100 mL). The resulting solution was allowed to stir for 20 minutes or until it appeared transparent. The desired compound was extracted with EtOAc (5×20mL), washed with brine, then dried over MgSO₄. The resulting red solution was concentrated to a dark oil via rotary evaporation. Upon the addition of MeOH (6 mL) and sonication of the oil, the desired product precipitates out as a tan powder. The product was collected by vacuum filtration. (354 mg, 40% yield). ¹H NMR (400MHz, CDCl₃): δ 16.79 (s, 1H, enolic-H), 16.69 (s, 1H, enolic-H), 7.71 (s, 1H, Ar-H), 7.51 (dd, J=18.6, 8.0 Hz, 2H, Ar-H), 7.31 (dd, J=22.2, 8 Hz, 4H, Ar-H), 1.97 (s, 6H, Me-H), 1.92 (s, 6H, Me-H). ¹³C {¹H} NMR: δ 191.0 (s, 2C, CO), 149.5 (s, Ar-C), 137.8 (s, Ar-C), 137.3 (s, Ar-C), 136.1 (s, Ar-C), 135.3 (s, Ar-C), 135.1 (s, Ar-C), 132.4
(s, Ar-C), 131.6 (s, Ar-C), 128.5 (Ar-C), 126.7 (s, 2C, quartenary C), 114.6 (s, Ar-C), 113.1 (s, Ar-C), 24.4 (s, Me-C), 24.3 (s, 2C, Me-C).

4,4′-(2-nitro-[1,1′-biphenyl]-4,4′-diyl)bis(3,5-dimethyl-1H-pyrazole) (5) - 4 (110 mg, 0.27 mmol, 1 eq) was dissolved in ~12 mL EtOH. Hydrazine (33.0 microL, 0.675 mmol, 2.5 eq) was added to the flask. The reaction was heated to reflux and left to react overnight. The EtOH was removed via rotary evaporation. The resulting yellow solid was washed with ether to remove excess hydrazine and allowed to dry to yield the product without further purification. (88.5 mg, 85% yield) ¹H NMR (400MHz, d₆-DMSO): δ 12.44 (br s, 2H), 7.84 (s, 1H), 7.66 (dd, J=21.6, 8.0 Hz, 2H), 7.40 (s, 4H), 2.28 (s, 6H), 2.25 (s, 6H). ¹³C{¹H} NMR (CDCl₃): δ 149.7, 135.2, 134.5, 134.2, 132.8, 132.3, 132.0, 129.3, 128.3, 123.6, 116.6, 115.1, 12.0.

Solvothermal synthesis of Co₄(O)[4,4′-bis(3,5-dimethyl-1H-pyrazol-4-yl)-1,1′-biphenyl]₃ (7) – Dipyrazole 2 (10 mg, 0.03 mmol, 1 eq) was dissolved in DMA (2 mL) with heating. The solution was allowed to cool back to room temp. Co(NO₃)₂·6H₂O (8.4 mg, 1 eq, mmol) was added to the solution of the ligand. The solution was transferred to an oven-dried, acid pretreated tube (9 in in length, 1 cm in diameter). The solution was degassed by freeze pump thawing 3-4 times and then sealed under vacuum using a torch. The reaction vessel was heated from room temperature to 130 °C over the course of 18 h and then held for 5 days, resulting in blue, cubic, X-ray quality crystals of MOF 7.

Solvothermal synthesis of Co₄(O)[4,4′-(2-nitro-[1,1′-biphenyl]-4,4′-diyl)bis(3,5-dimethyl-1H-pyrazolate)]₃ (8) – Dipyrazole 6 (10 mg, 0.03 mmol, 1 eq) and Co(NO₃)₂·6H₂O (10 mg, 0.03 mmol, 1 eq) were dissolved in DMA (2 mL) in a 1 dram vial, seal with a white Teflon cap.
The reaction vial was placed in an oven at 120 °C for 4 days to afford dark blue powders of MOF 8.

**Solvothermal synthesis of Zn[4,4′-bis(3,5-dimethyl-1H-pyrazol-4-yl)-1,1′-biphenyl]₃ (9)** – Dipyrazole 2 (10 mg, 0.03 mmol, 1 eq) was heated into DMF (2 mL) in a 1 dram vial. The solution was allowed to cool to room temp. Zn(NO₃)₂·6H₂O (35 mg, 0.12 mmol, 4 eq) was added to the solution of the ligand. 1M HCl (0.01 mL) was added to the mixture. The solution was transferred to an oven-dried, acid pretreated tube (9 in in length, 1 cm in diameter). The solution was degassed by freeze pump thawing 3-4 times and then sealed under vacuum using a torch. The reaction vessel was heated from room temperature to 130 °C over the course of 18 h and then held for 5 days, affording a white powder of MOF 9.
Supplemental NMR data

S1 $^1$H NMR (d$_6$-DMSO) of 1.
$^{13}$C NMR (CDCl$_3$) of 1.
S3 $^1$H NMR (d$_6$-DMSO) of 2.
$^{13}$C NMR (d$_6$-DMSO) of 2.
$^{1}$H NMR (d$_6$-DMSO) of 5.
$^1$H NMR (CDCl$_3$) of 5.
$^1$H NMR ($d_6$-DMSO) of 6.
$^{13}$C NMR (d$_6$-DMSO) of 6.
CHAPTER 3

Mixed-linker UiO-67
3.1 Objective

MOFs from the UiO family are characterized by the presence of \([\text{Zr}_6\text{O}_6(\text{OH})_6(\text{carboxylate})_{12}]\) SBUs. Unlike the pyrazolate MOFs, formation of the Zr SBUs is facilitated by acid modulators such as acetic acid or benzoic acid. Sonication of ZrCl\(_4\) and the acid modulator is thought to result in the preformation of these hexanuclear clusters. During MOF synthesis, ligand exchange occurs in solution to form the MOF. These MOFs are stable in a variety of solvents, including water, and are stable to air for extended periods of time.\(^4\)\(^-\)\(^6\)\(^,\)\(^2\(^2\)\) The inherent thermal and chemical stability of these frameworks make them good candidates as supports for heterogeneous catalysis.

The goal of this project was to synthesize a mixed-linker UiO-67 MOF with varying ratios of amine-tagged linkers. After MOF assembly, the material would be reacted with a phosphinoaldehyde to introduce a strong, σ-donating chelate into the framework. This ligand could then chelate catalytically active transition metal species.

3.2 Mixed-linker MOF synthesis

\[\text{H}_2\text{BPDC-NH}_2\] was synthesized according to literature procedures as shown in scheme 9.\(^1\(^2\)\(^1\) Mixed-linker UiO-67 (14) was synthesized by reaction of a 0.2:0.8:1 mol ratio of
13: H$_2$BPDC:ZrCl$_4$ in DMF with the intention of synthesizing a framework where 1/5 linkers is [13]$^\text{2-}$, according to literature precedent (Scheme 10).$^{21}$ No acid modulator was used in the synthesis of 14. The PXRD of the as-synthesized MOF 14 shows that the mixed-linker MOF is an isoreticular analogue of UiO-67. (Figure 18).

Scheme 10. (i) ZrCl$_4$, DMF, 80 °C for 12 h, then 100 °C for 24 h.
After confirming the presence of the desired MOF phase by PXRD, the percent incorporation of amine-functionalized linkers was determined. Literature precedent has suggested that linker composition can be determined by solution state NMR analysis of digested MOFs. Typically, digestions are carried out with strong acids such as TFA, D$_2$SO$_4$, or HF. These hydrolyze the metal ligand bonds, breaking apart the framework and making the MOF components soluble in deuterated solvents, such as D$_2$O and d$_6$-DMSO. Analysis of $^1$H NMR spectra of MOF 14 digested with D$_2$SO$_4$ revealed decomposition of the amine linker and the percent incorporation of amine linkers in the framework could not be determined (Figure 19). However, digestion of the MOF with CsF showed more conclusive results (Figure 20). $^1$H NMR

**Figure 18.** Simulated PXRD pattern of UiO-67 (red) verses as synthesized UiO-67 mixed-linker MOF (blue) and after MeOH exchange (green).
analysis of the digested sample shows about 8% incorporation of the amine linker by integration of the relevant peaks of [BPDC]$^{2-}$ and [13]$^{2-}$.

Figure 19. $^1$H NMR spectrum of a sample of a D$_2$SO$_4$ digested MOF 14.

Figure 20. $^1$H NMR spectrum of a sample of a CsF digested MOF 14.
Magic angle spinning $^{13}$C NMR (MAS NMR) has also been used to determine the ratio of organic linkers in mixed-linker MOFs. Given that solid-state state NMR does not require digestion, it is expected to give a more accurate percent incorporation. Solution state NMR requires exposing the material to harsh reagents which can lead to linker decomposition. Additionally, solubility is not a problem in solid state NMR. Analysis of a $^{13}$C MAS NMR spectra of MOF 14 gave similar results as the solution state NMR experiment, showing 10-12 % (+/- 2 %) of linkers in the framework are [13]$^{2-}$ and 88-90 % are BPDC$^{2-}$ (Figure 21).

![13C MAS NMR spectrum of mixed-linker MOF 14.](image)

**Figure 21.** $^{13}$C MAS NMR spectrum of mixed-linker MOF 14.

Although a 0.2:0.8 mol ratio of 13:BPDC was included in the MOF reaction, the resulting framework contains a 0.1:0.9 of [13]$^{2-}$:[BPDC]$^{2-}$, about half of the desired ratio. Literature shows that it is uncommon for organic linkers containing pendant amine groups to not incorporate fully
into mixed-linker frameworks. Mixed-linker MOF-5, made with varying linker ratios of functionalized 1,4-benzenedicarboxylate ([BDC$_2^-$]) linkers consistently show less incorporation.$^{31}$ However, the mixed-linker UiO-67 and UiO-66 MOFs reported in the literature shows retention of the initial mol ratios from synthesis in the resulting framework.$^4$ It is not well understood at this point why these inconsistencies relating to incorporation of amine-functionalized linkers exists.

### 3.3 Preliminary PSM studies

Diphosphonium salt 5 was synthesized according to literature precedent (Scheme 11).$^{32}$ Following deprotonation with potassium hydride, diphenylphosphide was reacted with 2-bromo-1,1-dimethoxyethane. After quenching with HBr, the air-stable diphosphonium salt (15) was obtained. Compound 15 shows two $^{31}$P NMR resonances at 17.7 and 13.0 ppm in about a 3:4 ratio.

![Scheme 11](image)

**Scheme 11.** (i) KH, THF, rt, then 2-bromo-1,1-dimethoxyethane -78 °C, 30 min, then 1.17 M HBr, 40 °C o/night (ii) KO'Bu, THF, rt.

Compound 15 has been used in the template synthesis of Fe(II) complexes. The putative phosphinoaldehyde 16 is furnished upon reaction with two equivalents of potassium tert-butoxide in THF. (Scheme 11) The $^{31}$P NMR spectrum of the product shows one resonance at
-24.0 ppm. If left standing at ambient conditions, the initially observed species decomposes to complex mixture of products.

Reaction of 16 with aminobiphenyl 12 at 40 °C resulted in formation of one major product as determined by the appearance of a major $^{31}$P NMR resonance at -14.3 ppm and a small signal at -19.4 ppm (Scheme 12). Evaporation of the solvent followed by redissolving in de$_6$-benzene results in decomposition as indicated by a much higher signal to noise ratio in the $^{31}$P NMR spectra. Additionally, analysis of the $^1$H NMR spectra showed that more than 80 % of the contents were starting material aminobiphenyl 12 and no characteristic signals for aldehyde protons were observed. Water, formed from the condensation, does not form an azeotrope with THF and cannot be removed via azeotropic distillation. Thus, upon removal of the solvent, it’s hypothesized that an increase in the concentration of the products resulted in an equilibrium more favored to the reactants.

Scheme 12. (i) THF, 40 °C.

Given the instability of the aldehyde 16, another approach was explored in order to generate imine 17 successfully. After generating the aldehyde and confirming its presence by $^{31}$P NMR spectroscopy, one equivalent of (tht)AuCl (tht = tetrahydrothiophene) was added to the
reaction, as shown in Scheme 13. This resulted in a shift of the major $^{31}$P NMR signal from -14.0 to 16.3 ppm and was attributed to the coordination of phosphine 16 to a AuCl fragment (18).

Scheme 13. (i) (tht)AuCl, THF, rt, 10 min.

The reaction mixture was then filtered in air over celite and the solvent was evaporated. The $^{31}$P NMR spectrum of the resulting product dissolved in CDCl$_3$ showed a signal at 16.3 ppm, assigned to the putative aurated aldehyde 18. The $^1$H NMR spectrum showed a singlet at 9.93 ppm, assigned to the aldehyde proton of 18, as well as a doublet at 3.73 ppm, assigned to the methylene protons of 18. The Au is supposed to effectively stabilize 16 from decomposition. With future work, it’s possible that reaction of this aldehyde-gold chelate with the methyl ester ligand would result in condensation of the amine.

3.4 Summary

We synthesized a mixed-linker UiO-67 MOF (14) containing amine-functionalized linkers. MOF 14 was characterized by PXRD, $^1$H NMR analysis of digested MOF samples, and $^{13}$C MAS NMR analysis. Amine-functionalized linkers do not always fully incorporate into MOF frameworks, and work is underway to optimize reaction conditions that preserve the desired mol ratio of linkers. We generated phosphinoaldehyde 16, characterized by analysis of $^{31}$P NMR spectra, which could be stabilized with coordination to Au (18). Compound 18 was isolated and characterized by analysis of $^{31}$P NMR spectra and $^1$H NMR spectra. Given the short lifetime of 16, work will be done to optimize reaction conditions that favor the condensation product 17.
over decomposition of the substrate. It is possible that chelation of metals, such as Au, Pd, or Pt, could stabilize 16 long enough to react completely with linker 12.
3.5 Experimental

General Considerations

4,4’-dimethylester-2-nitro-biphenyl\textsuperscript{21}, 4,4’-dimethylester-2-amino-biphenyl\textsuperscript{21}, 4,4’-dicarboxylic acid-2-amino-biphenyl\textsuperscript{21}, diphosphonium salt\textsuperscript{32-33}, and mixed-linker MOF\textsuperscript{21} were synthesized according to literature procedures. Starting materials were purchased from Sigma Aldrich, Alfa Aesar, or Fisher Scientific and used as received. DMF, ethanol, methanol, and tetrahydrofuran were used as received unless otherwise noted. Air-sensitive compounds were handled using standard Schlenk and glovebox techniques.

Instrumental Methods

NMR spectra were recorded at ambient temperature on a Varian Inova 400 MHz instrument. Chemical shifts are reported in $\delta$ (ppm). All $^1$H spectra are referenced against residual proton signals in solvent. All $^{13}$C\{H\} spectra are referenced against carbon signals in solvent. All $^{31}$P\{H\} spectra are referenced against phosphoric acid (H$_3$PO$_4$). Powder X-ray diffraction patterns were collected on a Rigaku MiniFlex 600. The $2\theta$ angle was varied from 3 to 45 degrees at a rate of 5 °/min. Dry samples were loaded onto a glass slide open to air. IR spectra were recorded on a Varian 640-IR spectrometer controlled by Resolutions Pro Software. Solid-State NMR experiments were performed on a Bruker (Billerica, MA) DSX-400 spectrometer at a resonance frequency of 400 MHz for $^1$H and 100 MHz for $^{13}$C, using magic-angle spinning (MAS) probe in double-resonance mode. Samples were packed into 4 mm rotors with Kel-F 22 $\mu$L inserts. Experiments were carried out at a spinning frequency of 14 kHz. $^{13}$C 90° pulse-lengths were 4.2 $\mu$s. $^{13}$C spectra were external referenced to the carbonyl of 1-13C Gly ($\beta$ crystal form) at 176.49 ppm on the neat TMS scale.

Generation of 2-(diphenylphosphanyl)acetaldehyde (16) – Diphosphonium salt 15 (50 mg,
0.08 mmol, 1 eq) was suspended in THF. KOtBu (18 mg, 0.16 mmol, 2 eq) was dissolved in THF. The KOtBu solution was added to the diphosphonium salt solution dropwise with stirring at room temperature. $^{31}$P (400 MHz, THF): $\delta$ -24.1.

**Imine condensation** (17) – After generation of 16 in THF, 12 (43 mg 0.16 mmol, 2 eq) was added to the vial. The reaction was heated at 40 °C overnight, yielding one major product by $^{31}$P NMR with a minor side product. $^{31}$P (400 MHz, THF): $\delta$ -14.3, -19.4 (minor).

**Aurated 2-(diphenylphosphanyl)acetaldehyde** (18) – After generation of aldehyde 16, THTAuCl (49 mg, 0.16 mmol, 2 eq) was added to the vial at room temperature. The reaction mixture was filtered over Celite in air and concentrated via rotary evaporation to afford the gold complex. $^1$H (400MHz, CDCl$_3$): $\delta$ 9.93 (s, 1H, aldehyde), 7.69-7.50 (m, 10H, Ar-H), 3.73 (d, $J$ = 6.4 Hz, 2H, CH$_2$). $^{31}$P{H}: $\delta$ 16.3 (major), 13.9 (minor).
References Cited


