TITLE:

Experimental Approaches for the Synthesis of Low-Valent Metal-Organic Frameworks from Multitopic Phosphine Linkers

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SUMMARY:

Here we describe a protocol for the synthesis of Low-Valent Metal-Organic Frameworks (LVMOFs) from low-valent metals and multitopic phosphine linkers under air-free conditions. The resulting materials have potential applications as heterogeneous catalyst mimics of low-valent metal-based homogeneous catalysts.

ABSTRACT:

Metal-Organic Frameworks (MOFs) are the subject of intense research focus due to their potential applications in gas storage and separation, biomedicine, energy, and catalysis. Recently, low-valent MOFs (LVMOFs) have been explored for their potential use as heterogeneous catalysts, and multitopic phosphine linkers have been shown as a useful building block for the formation of LVMOFs. However, the synthesis of LVMOFs using phosphine linkers requires conditions that are distinct from the majority of the MOF synthetic literature, including the exclusion of air and water and the use of unconventional modulators and solvents, making it somewhat more challenging to access these materials. This work serves as a general tutorial for the synthesis of LVMOFs with phosphine linkers, including information on: 1) judicious choice of metal precursor, modulator, and solvent; 2) experimental procedures, air-free techniques, and required equipment; 3) proper storage and handling of the resultant LVMOFs; and 4) useful characterization methods for these materials. The intention of this report is to lower the barrier and make more accessible this new subfield of MOF research and facilitate advancements toward novel catalytic materials.

INTRODUCTION:

Metal-Organic Frameworks, or MOFs, are a class of crystalline, porous materials[1]. MOFs are constructed from metal ions or metal ion cluster nodes, often referred to as secondary building units (SBUs), and multitopic organic linkers to give two- and three-dimensional network structures[2]. Over the past three decades, MOFs have been studied extensively due to their potential applications in gas storage[3] and separation[4], biomedicine[5], and catalysis[6]. The overwhelming majority of MOFs reported in the literature are composed of high oxidation state metal nodes and hard, anionic donor linkers, such as carboxylates[2]. However, many homogeneous catalysts utilize soft, low-valent metals in combination with soft donor ligands, such as phosphines[7]. Therefore, expanding the scope of MOFs that contain low-valent metals increases the range of catalytic transformations to which MOFs can be applied.

Established strategies for the incorporation of low-valent metals into MOFs using embedded soft donor sites are limited in scope and reduce the free pore volume of the parent MOF structure[6,8-10]. An alternative approach is to use low-valent metals directly as nodes or SBUs in combination with multitopic soft donor ligands as linkers to construct the MOF. This strategy not only provides a high loading of low-valent metal sites in the MOF but may also reduce or prevent metal leaching into solution as a result of the stability of the framework structure[11]. For example, Figueroa and co-workers used multitopic isocyanide ligands as soft donor linkers and Cu(I)[12] or Ni(0)[13] as low-valent metal nodes to produce two- and three-dimensional MOFs. Similarly, Pederson and co-workers have synthesized MOFs containing zero-valent group 6 metal nodes using pyrazine as a linker[14]. More recently, our laboratory has reported tetratopic phosphine ligands as linkers for the construction of MOFs containing Pd(0) or Pt(0) nodes (**Figure 1**)[15]. These MOFs are particularly interesting due to the prevalance of phosphine-ligated low-valent metal complexes in homogeneous catalysis[7]. Nevertheless, Low-Valent MOFs (LVMOFs) as a general class of materials are relatively underexplored in the MOF literature, yet have promising potential applications in heterogeneous catalysis for reactions such as azide-alkyne coupling[16], Suzuki-Miyaura coupling[17,18], hydrogenation[17], and others[11].

[Place **Figure 1** here]

While the differences in the nature of the linkers and nodes of LVMOFs may give them unique properties compared to conventional MOF materials, these differences also introduce synthetic challenges. For example, many of the metal precursors and linkers that are commonly used in the MOF literature can be used in air[2]. In contrast, the successful synthesis of phosphine-based LVMOFs requires the exclusion of both air and water[15]. Similarly, the types of modulators used to promote crystallinity and the solvents used in the synthesis of phosphine-based LVMOFs are unusual compared to those used in most of the MOF literature[15]. As a result, the synthesis of these materials requires equipment and experimental techniques that even experienced MOF chemists may be less familiar with. Therefore, in an effort to minimize the impact of these obstacles, a step-by-step method for the synthesis of this new class of materials is provided. The protocol outlined here covers all aspects of the synthesis of phosphine-based LVMOFs, including the overall experimental procedure, air-free techniques, required equipment, proper storage and handling of LVMOFs, and characterization methods. Judicious choice of metal precursor, modulator, and solvent are also discussed. Enabling entry of new researchers to this field will help accelerate the discovery of novel LVMOFs and related materials for applications in catalysis.

PROTOCOL:

1. Setting up the Schlenk line

1.1. Ensure all taps are closed, then secure the cold trap to the Schlenk line using an O-ring (size 229 in this case, though size may vary depending on specific Schlenk line used) and clamp.

1.2. Turn on the vacuum pump (gas-ballast closed), then open the taps of the Schlenk line such that the whole apparatus is open to vacuum.

NOTE: DO NOT open any taps to the hoses or any other taps that are open to the air; the apparatus should be a closed system under dynamic vacuum.

1.3. Wait at least 5 min while the atmosphere of the Schlenk line is evacuated.

NOTE: Some Schlenk lines may be fitted with a barometer to determine the lowest pressure the apparatus will reach under dynamic vacuum. If that pressure has been reached before 5 min have passed, proceed to the next step.

1.4. Cool the cold trap of the Schlenk line by placing a dewar flask filled with liquid nitrogen around it. Use a towel to cover the top of the dewar flask and slow the evaporation of the liquid nitrogen during the experiment.

CAUTION: Contact with liquid nitrogen can cause severe damage to the skin and eyes and should only be handled by those trained to use it safely. Wear skin and eye protection.

NOTE: Often it is easier and safer to first place the empty dewar flask around the cold trap and then use a second dewar to fill the trap dewar flask with liquid nitrogen.

1.5. Open the bubbler to a light flow (approximately 3 bubbles/s) of inert gas ($N_{2(g)}$ or $Ar_{(g)}$).

2. Measuring out the solid reagents

2.1. Measure the tetrakis(triphenylphosphine)palladium(0) and triphenylphosphine modulator into the reaction flask.

2.1.1. Roll a piece of weighing paper into a cone to use as a solid-addition funnel and place it in the tap opening of the 10 mL flask. Ensure the bottom of the cone is inserted far enough that it extends past the hose attachment.

NOTE: Using an empty NMR tube or a similarly small tubular object to roll the weighing paper over is helpful to attain the small diameter required to fit in the tap opening.

2.1.2. Weigh by differences the tetrakis(triphenylphosphine)palladium(0) (0.084 g, 0.073 mmol, 1 equiv.) to the 10 mL flask.

CAUTION: Tetrakis(triphenylphosphine)palladium(0) is harmful to the body, especially if swallowed, and may ignite if finely dispersed in the air. Avoid dust formation, all forms of contact, and wear personal protective equipment.

NOTE: The flask and weighing paper cone can be gently tapped to ensure all the solid is transferred into the bottom of the flask.

2.1.3. Repeat step 2.1.2 with triphenylphosphine (1.23 g, 4.67 mmol, 64 equiv.).

CAUTION: Triphenylphosphine is harmful to the body and central nervous system. Avoid all forms of contact and wear personal protective equipment, including chemical-resistant gloves.

2.1.4. Dispose of the weighing paper cone and screw the poly(tetrafluoroethylene) PTFE tap onto the 10 mL flask.

2.2. Measure the tetratopic phosphine linker into a separate 10 mL flask.

2.2.1. Repeat step 2.1.1 with a second 10 mL flask.

2.2.2. Using the second 10 mL flask, repeat step 2.1.2 with the tetratopic phosphine linker **Sn1** (0.085 g, 0.073 mmol, 1 equiv.).

CAUTION: The hazardous properties of **Sn1** are unknown. As it is a Sn(IV) compound and a tertiary phosphine, assume it is acutely toxic and avoid all forms of contact. Wear personal protective equipment, including chemical-resistant gloves.

2.2.3. Repeat step 2.1.4 with the second 10 mL flask.

3. Putting the reagents under inert atmosphere

3.1. Connect a hose (black rubber vacuum tubing, 3/16" inner diameter × 3/16" wall) from the Schlenk line to each of the 10 mL flasks.

3.2. Open the PTFE tap just enough that the vessel is open to the hose.

NOTE: If the tap is too wide open, the solids may be pulled into the hose during evacuation.

3.3. Open both 10 mL flasks to vacuum. Wait for 5 min.

3.4. Close the tap on each 10 mL flask, then close each hose to vacuum. Switch the hoses to inert gas, then slowly open the tap on each 10 mL flask to backfill with inert gas.

NOTE: When switching from vacuum to inert gas, ensure the bubble flow of inert gas is high enough to prevent oil from being pulled into the Schlenk line but low enough not to disturb the solids in the flask.

3.5. Repeat steps 3.3-3.4 two more times for a total of three cycles.

4. Adding solvent to the reagents under inert atmosphere

4.1. Under a positive pressure of inert gas sufficient to prevent air from entering the flask, remove the PTFE tap and replace it with a septum for each 10 mL flask.

4.2. Add toluene and methylene chloride to the palladium and phosphine mixture.

4.2.1. Use a syringe and needle to transfer 1.5 mL of dry and deoxygenated toluene into the flask containing the tetrakis(triphenylphosphine)palladium(0) and triphenylphosphine.

CAUTION: Toluene is both toxic and flammable. Avoid all forms of contact, keep away from heat sources, work in the fume hood, and wear personal protective equipment.

NOTE: Solvents can be dried by passing them through an activated aluminum column under inert gas and deoxygenated by sparging them with inert gas for 30 min.

NOTE: Be sure to purge the syringe and needle with inert gas three times before drawing solution.

4.2.2. Repeat step 4.2.1 with 1.5 mL of dry and deoxygenated methylene chloride.

CAUTION: Methylene chloride is toxic and carcinogenic. Avoid all forms of contact, work in the fume hood, and wear personal protective equipment.

4.2.5. Swirl the flask until all the solids have dissolved (approximately 30 s).

4.3. Add methylene chloride to the tetratopic phosphine linker.

4.3.1. Use a syringe and needle to transfer 3.0 mL of dry and deoxygenated toluene into the flask containing the tetratopic phosphine linker **Sn1**.

4.3.2. Swirl the flask until all the solid has dissolved (approximately 30 s).

5. Adding the linker to the palladium and phosphine mixture

5.1. Use a syringe and needle to transfer the entire **Sn1** linker solution into the flask containing the tetrakis(triphenylphosphine)palladium(0) and triphenylphosphine.

5.2. Swirl the solution for 30 s to thoroughly mix it, then replace the septum with the PTFE tap under positive pressure of inert gas sufficient to prevent air from entering the flask and seal the flask.

5.3. Sonicate (40 kHz) the reaction solution for an additional 30 s.

6. Heating the reaction

6.1. Place the sealed flask into a pre-heated oil bath at 60 °C and leave it for 24 h without agitating it.

7. Isolating the MOF product

7.1. Remove the flask from the oil bath and allow it to cool to room temperature.

CAUTION: When handling hot glassware and/or surfaces, be sure to wear heat-resistant gloves.

7.2. Setup a vacuum filtration apparatus using a small Buchner funnel and filter paper (8 µm pore size).

7.3. Remove the PTFE tap from the flask, then use a pipette to transfer the total volume of the suspension to the filter.

NOTE: A light flow of inert gas over the top of the filter can help to avoid decomposition of the oxygen-sensitive MOF product.

7.4. Rinse the solid with 2 mL of deoxygenated 3:1 methylene chloride/toluene solution. Repeat this step two more times and allow the solid to dry on the filter paper for 3 min.

7.5. Scrape the solid into a pre-weighed vial, then weigh the vial to obtain the yield of **Sn1-Pd**.

NOTE: Store the LVMOF material under inert gas or dynamic vacuum in order to avoid decomposition in the presence of oxygen in the air.

8. Characterization of the MOF product by Powder X-Ray Diffraction (PXRD)

8.1. Transfer approximately 20–30 mg of the crystalline solid to a silicon PXRD sample holder.

NOTE: While **Sn1-Pd** is sufficiently stable in air for characterization by PXRD, more air-sensitive LVMOF materials can be transferred to an inert atmosphere glovebox and loaded into a sealable capillary PXRD sample holder.

8.2. Place the sample holder in the diffractometer and close the door to the instrument.

8.3. Collect the PXRD pattern from 4 to 40 2θ (scan speed of 0.5 s/step, step size of 0.0204° 2θ) and compare the data to the simulated powder pattern of **Sn1-Pd**.

REPRESENTATIVE RESULTS:

The successful synthesis of **Sn1-Pd** produces a bright yellow, crystalline solid. The Pd(0) MOF products using analogous tetratopic phosphine linkers are also yellow. The most effective way to determine if the reaction was successful is to collect the PXRD pattern and evaluate the crystallinity of the sample. For example, **Figure 2** shows the PXRD pattern of crystalline **Sn1-Pd**. The key features to verify that the sample is crystalline are that the reflection peaks are relatively sharp, and the baseline is relatively flat. Peak broadening is often indicative of amorphous material. To illustrate, **Figure 3** shows the PXRD pattern of a sample of **Sn1-Pd** in which no triphenylphosphine modulator was used in the synthetic procedure. In this case, the diagnostic reflection signals are noticeably broad compared to the pristine sample that used 64 equiv. of triphenylphosphine modulator in the synthesis. This broadening effect is also observed upon decomposition in the presence of oxygen, especially after more than 72 h have passed. Therefore, it is critical that the samples are stored under inert gas or under dynamic vacuum to prevent decomposition and degradation of the crystallinity. If the crystal structure of the desired LVMOF product or an analogous structure is known, a simulated PXRD pattern can be generated for comparison to the experimental powder pattern. If the two PXRD patterns match well, then the quality of the LVMOF sample should be satisfactory (**Figure 2**). It should be noted that even though the experimental LVMOF PXRD pattern may not perfectly match the simulated PXRD pattern for an analogous LVMOF, if the most prominent reflections at low angle are conserved, then this provides strong evidence that the newly-synthesized LVMOF is isostructural to the LVMOF from which the simulated PXRD pattern was generated.

FIGURE AND TABLE LEGENDS:

Figure 1: Synthesis of LVMOFs using phosphine linkers. Sikma and Cohen[15] reported the synthesis of three-dimensional LVMOFs **E1-M** using tetratopic phosphine ligands **E1** as linkers, Pd(0) and Pt(0) as nodes, and triphenylphosphine as a modulator. The central atom **E** can be Si or Sn.

Figure 2: PXRD pattern of pristine Sn1-Pd. The PXRD pattern obtained for a pristine sample of **Sn1-Pd** is shown in blue. This sample was prepared using 64 equiv. of triphenylphosphine modulator to achieve a crystalline material. Below the experimental PXRD pattern in black is the simulated PXRD pattern of **Si1-Pd** obtained from the crystal structure[15].

Figure 3: PXRD pattern of amorphous Sn1-Pd. The PXRD pattern obtained for an amorphous sample of **Sn1-Pd** is shown. This sample was prepared without any triphenylphosphine modulator, resulting in an amorphous or poorly crystalline material.

DISCUSSION:

There are several critical steps in the protocol that must be followed in order to achieve the desired phosphine-based LVMOF product with sufficient crystallinity. The first is that the metal precursor and modulator mixture (in this case, tetrakis(triphenylphosphine)palladium(0) and triphenylphosphine, respectively) must be dissolved independently of the multitopic phosphine linker (in this case, **Sn1**). This is to avoid the rapid and irreversible formation of amorphous coordination polymers, which occurs when the effective concentration of the modulator relative to the linker is too low or there is no modulator present at all[15]. Relatedly, all reagents should be fully dissolved and homogeneous before mixing such that the effective concentration of the reagents relative to one another matches the stoichiometry of the reaction. Another key step is ensuring that no oxygen is present within the reaction flask (or solvent) before mixing and heating the reagents. Not only is the Pd(0) precursor sensitive to oxygen, but the phosphine modulator and phosphine linker are both susceptible to oxidation to the corresponding phosphine oxide in the presence of oxygen, especially when heated. Any of these decomposition events will negatively impact the yield and/or crystallinity of the desired LVMOF product[15]. Similarly, the filtration to isolate the MOF product should be carried out quickly in order to limit O_2 exposure.

If all the steps are followed and a negative result is obtained (no precipitate is observed or the solid formed is amorphous), several parameters may be adjusted. Too few equiv. of modulator may result in poorly crystalline material, but too many equiv. may prevent formation of the MOF altogether. Thus, the equiv. of modulator can be varied to improve yield and crystallinity. Pairing metal precursors and solvent identities and/or ratios that produce a homogeneous solution prior to reaction with the linker is another important consideration. The effects of changing other parameters can be less intuitive, but the reaction temperature, concentration, reaction scale, and stoichiometry of the metal and linker can all influence the yield and crystallinity as well. This represents a limitation of the current method, as deviations in the identity of any of the reagents to target a new material often require re-optimization of all the aforementioned parameters[15]. However, the empirical nature of their synthesis is a common feature among MOFs in general[19].

Despite its limitations, this method is significant as there is currently no other known method to synthesize crystalline, three-dimensional LVMOFs using multitopic phosphine linkers[15]. Indeed, it is our aim that our laboratory and others can use this method as a starting point to guide the exploration of this rare class of materials and access LVMOFs with varied topology and diverse low-valent metal nodes. This will aid the MOF, catalysis, inorganic, and organometallic chemistry communities in the development of new materials with applications in heterogeneous catalysis.

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DISCLOSURES:

The authors have nothing to disclose.

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