

N-Heterocyclic Carbene-Like Catalysis by a Metal–Organic Framework Material

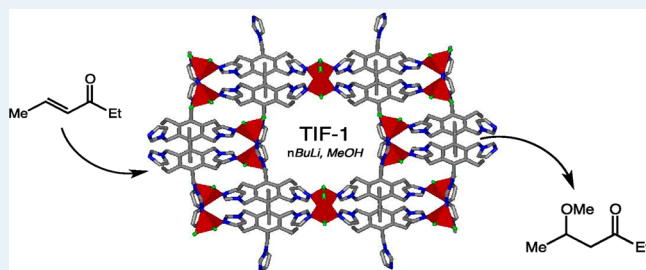
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S Supporting Information

ABSTRACT: Metal imidazolates, an important class of constructs in metal–organic framework chemistry, are shown here to be precursors to N-heterocyclic carbene-like catalysts. By using *n*-butyl lithium to deprotonate tripodal imidazolate framework-1 (TIF-1), N-heterocyclic carbene (NHC) sites can be exposed. These sites are found to be remarkably competent as Brønsted-base-type NHC catalysts. An α,β -unsaturated ketone was converted to the corresponding benzyl ether with benzyl alcohol at a faster rate and in higher yield than with a traditional homogeneous NHC catalyst (1,3-bis-(2,4,6-trimethylphenyl)imidazole), despite lower overall loading. Varying the size of the alcohol in the conjugate addition reaction yielded no change in reaction rate, even when the size of the alcohol exceeded the diameter of the MOF pores, suggesting that catalysis occurs exclusively on the surface of the MOF crystals, as opposed to within the framework pores.

KEYWORDS: N-heterocyclic carbenes, metal organic frameworks, conjugate addition, ethers



Metal–organic frameworks (MOFs) are porous crystalline materials composed of organic linkers and metal nodes.¹ MOFs typically feature large internal surface areas, extensive nanoscale porosity, and crystallographically well-defined cavities, making them attractive for a variety of potential applications including (but not limited to) gas storage and separations,^{2–4} sensing,^{5,6} and catalysis.⁷ Many MOFs for catalysis are constructed by incorporating an existing, powerful, homogeneous catalyst into a linker or, less commonly, a node. Examples of catalytic struts include functionalized metal-porphyrins,^{8,9} metallosalens,^{10–12} and Ti-BINOLate complexes.^{13,14}

N-Heterocyclic carbenes (NHCs) are yet another class of catalyst that would be appealing to feature in MOFs. These powerful homogeneous catalysts are highly effective for a valuable range of addition, rearrangement, and group-transfer reactions entailing controlled carbon–carbon, carbon–nitrogen, and carbon–oxygen bond formation or deletion.^{15–17} Incorporating NHCs into a MOF would (1) make reactions heterogeneous, enabling easy product/catalyst separation; (2) potentially add an extra dimension of substrate size-selectivity due to well-defined pore sizes; and (3) allow multiple catalytic sites to be created in close proximity that generally cannot be used simultaneously in solution (such as NHCs and Lewis acidic metal catalysts), thereby facilitating new patterns of catalytic reactivity.

Although multiple attempts have been made to create NHCs within MOFs,^{10,18–20} thus far, none has succeeded. The causes of failure include inaccessibility of framework-encapsulated carbene-precursor sites, MOF degradation (presumably via competitive coordination) following addition of bases required

for deprotonation of heterocyclic carbon atoms, and unwanted recruitment of metal ions at the intended carbene sites during syntheses of MOFs.

As implied by the modes of failure, previous attempts to create NHCs within MOFs have focused on incorporation of carbene precursors in the form of aryl- or alkylimidazolium-containing struts (see Figure 1). We reasoned that an

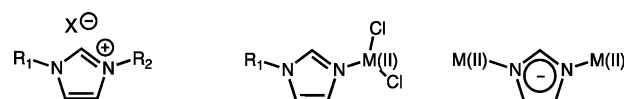


Figure 1. From left to right: an alkyl–alkyl imidazolium cation; an imidazole substituted with 1 alkyl group and 1 metal; and finally, an imidazolate (anion) substituted with two metal cations. (Note that each M(II) in the structure at right is coordinated to three additional imidazolate ions when the structure constitutes part of an overall neutral metal–organic framework.)

alternative to imidazolium species as carbene precursors would be metal cation-coordinated imidazoles or imidazolates (Figure 1). Nitrogen-coordinated metal cations would exert a strong electron-withdrawing effect upon the heterocycle, rendering it susceptible to proton loss and carbene formation. To our knowledge, metal imidazolates have not previously been viewed as potential precursors of NHC-like catalysts.

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Herein, we describe our success in converting sites on Willans' tripodal imidazolate framework-1 (TIF-1)²¹ to carbene-like species through deprotonation of coordinated imidazoles and subsequent successful catalysis of the conjugate addition of alcohols to activated alkenes. The heterogeneous catalyst is formed without evidence for degradation of the MOF.

TIF-1 is a MOF composed of a neutral, benzene-supported linker, B, featuring three imidazole substituents as coordinating groups. Each imidazole coordinates to a cobalt ion in oxidation state II to form, ultimately, two catenated two-dimensional sheets. The catenation of the sheets creates accessible void spaces (one-dimensional channels initially filled with solvent). Taking into account van der Waals radii, the pore (channel) diameter at its smallest measures 8.5 Å (Figure 2). Because

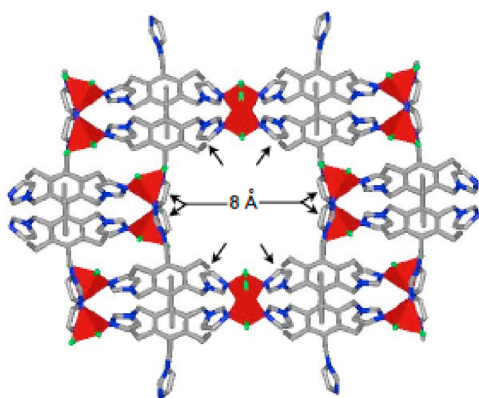
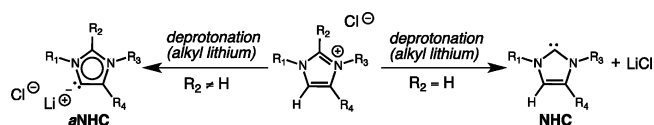


Figure 2. A depiction of TIF-1. Red prisms represent the tetrahedral cobalt nodes; chloride ions are in green. Two catenated 2D sheets form the 8 Å pore, and the potential sites for a NHC formation are indicated with arrows.

each Co(II) also coordinates two chlorides, the overall framework is neutral. Thus, in contrast to molecular imidazolium species, charge-compensating counterions are absent. TIF-1 was appealing to us as an NHC precursor because of its porosity and its remarkable stability. For example, it has been shown to retain crystallinity after heating under vacuum at 200 °C for two days.²¹

Additionally notable for TIF-1 is that the C4/C5 sites of the imidazoles, rather than C2 sites, protrude into the pores. (See Figure 2.) Indeed, a space-filling model of TIF-1 (see the Supporting Information) reveals the C2 carbon to be completely inaccessible to atoms or molecules entering the pores. NHCs are traditionally formed at C2 carbons because they are significantly more acidic than their C4/C5 counterparts. However, under special circumstances, NHCs can be deprotonated at C4 or C5, forming abnormal, or, *a*NHCs (often also describable as mesoionic carbenes). Abnormal NHCs are significantly more basic, and often less stable, than normal NHCs. *a*NHCs are challenging to synthesize, in part because of a propensity for rearrangement.²² Consequently, until recently, only a few examples existed, with most being *a*NHC metal complexes.^{23,24} The first example of a free *a*NHC was isolated by Aldeco-Perez in 2009 and formed by functionalizing all sites of the heterocycle, with the exception of C5 (Scheme 1), thereby eliminating the possibility of deprotonating any other site.^{25,26} We initially hypothesized that by blocking C2 not with a functional group but sterically within

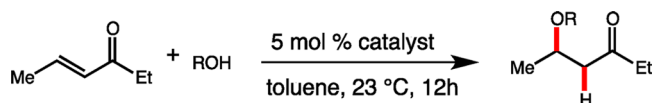
Scheme 1. Formation of Free NHCs versus Free *a*NHCs



a rigid framework, we would create *a*NHCs within the pores of TIF-1 (however, see discussion below).

To determine whether deprotonated TIF-1 behaves catalytically as an NHC, we examined the recently explored NHC-catalyzed addition of alcohols to α,β -unsaturated ketones (Scheme 2). Although the Lewis basicity of NHCs is well-

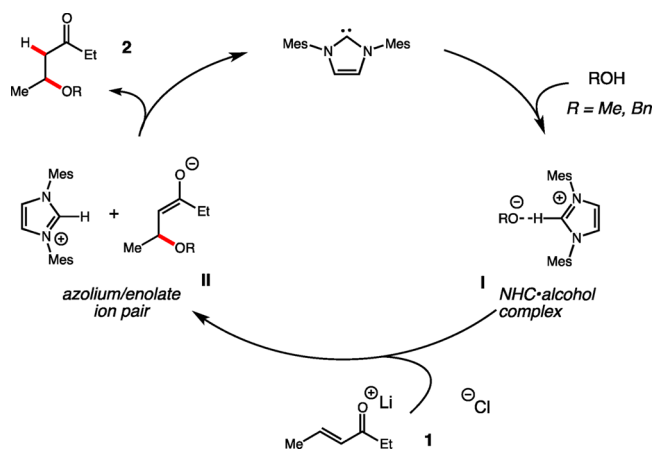
Scheme 2. Conjugate Addition of Alcohol



known, one of us (K.A.S.) has recently drawn attention to the ability of NHCs additionally to act as Brønsted base catalysts.¹⁷ In that work, we used the catalyst IMes·HCl (A; IMes = 1,3-bis-(2,4,6-trimethylphenyl)imidazol-2-ylidene) to catalyze the addition of a wide scope of primary and secondary alcohols to a variety of activated alkenes.

The proposed mechanism (Scheme 3) of the previously studied reaction involves the formation of an NHC-alcohol

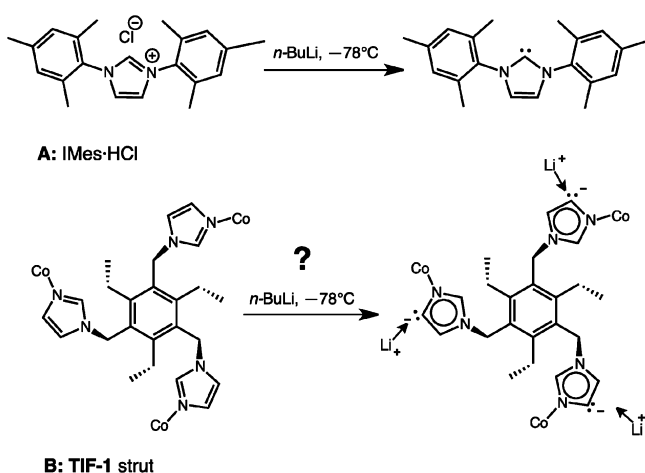
Scheme 3. Proposed Mechanism with IMes



complex (I) as a key intermediate. The lithium ion remaining from initial deprotonation of the azolium by *n*-BuLi can then activate the ketone (I), leading to the 1,4-addition of the alcohol to the conjugate acceptor. This step generates an imidazolium ion and the corresponding enolate (II). The proposed mechanism is supported by the observation of an increased yield of the conjugate addition product when 1 equiv of lithium chloride is included as a cocatalyst.

In parallel with its application to TIF-1, we repeated the procedure used by Phillips et al. to deprotonate the homogeneous NHC-precursor, IMes·HCl using 5 mol % *n*-BuLi. Despite identical carbene formation strategies (Scheme 4;²⁷ only a fraction of the TIF-1 coordination polymer is shown), it is noteworthy that the heterogeneous NHC features a net anionic charge, as opposed to the net neutral charge carried by the homogeneous NHC; accordingly, we expected

Scheme 4. Observed (A) or Initially Proposed (B) Carbene Formation from NHC (or NHC-like) Precursors



the lithium ion to be more closely associated with the NHC formed in TIF-1. (To ensure that the substrate would fit within the pores of TIF-1, we chose to focus initially on the alkene (*E*)-hex-4-ene-3-one.)

For the conjugate addition of alcohols to (*E*)-hex-4-ene-3-one to form the corresponding ethers, we observed for IMes-HCl 77% and 72% conversion with methanol and benzyl alcohol, respectively. For TIF-1, the extents of conversion were 65% and 83%. Plots in Figure 3 show the time of the benzyl alcohol addition to the alkene via the two catalysts.

Addition of Benzyl Alcohol to (*E*)-hex-4-ene-3-one

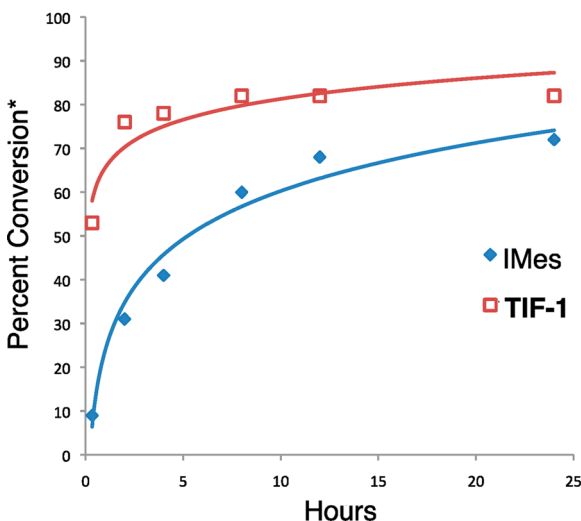


Figure 3. Addition of benzyl alcohol to (*E*)-hex-4-ene-3-one using TIF-1 and IMes-HCl as NHC precursors over 24 h. Percent conversions were calculated using gas chromatography software. See the Supporting Information for logarithmic fit equations.

Control reactions demonstrated that catalysis can be attributed to modified TIF-1 (Table 1). We repeated the procedure for the benzyl alcohol addition with 5 mol % each of exclusively *n*-BuLi; exclusively TIF-1; a cobalt byproduct of TIF-1;²⁸ cobalt metal; and finally, no additive at all, observing 5% percent conversion or less in each of these cases. In addition, powder X-ray diffraction of TIF-1 before and after

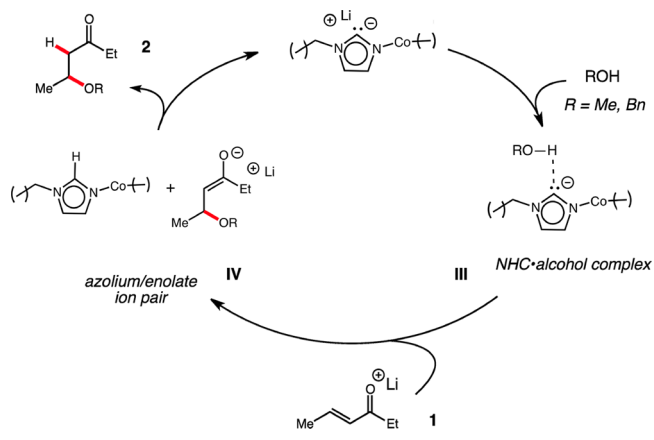
Table 1. Control Reactions

control additive	% conversion (12 h)
<i>n</i> -BuLi only	5
TIF-1 only	2
cobalt TIF-1 byproduct	<1
cobalt metal	<1
no additives	<1

catalysis indicated retention of crystallinity. (See the Supporting Information.)

We propose that catalysis by TIF-1 proceeds via a pathway (Scheme 5) similar to that followed by IMes-HCl. While the

Scheme 5. Proposed Mechanism for Catalysis of Conjugate Addition Reaction by lithiated TIF-1



yields for the homogeneous and heterogeneous reactions are similar, TIF-1 clearly is the more potent catalyst, with its reactions reaching completion roughly an order of magnitude more quickly than those catalyzed by IMes (see Figure 3). We speculatively attribute the higher potency to the anticipated electrostatic association (and, therefore, proximity) of the cocatalytic lithium cation with the active site of deprotonated TIF-1.

Competition reactions involving equal molar amounts of benzyl alcohol and methanol were conducted to probe whether catalysis occurs primarily on the surface of the MOF or within the pores. If catalysis were, in fact, occurring to a significant extent within pores, we might well expect the methyl ether product to be formed preferentially over the benzyl ether, since the latter should be formed only with considerable steric difficulty and perhaps only near the surface termini of the pores. Instead, no significant differences in reactivity were noted, and we infer that catalysis occurs chiefly on the surface of the MOF.

As a further test of the notion that catalysis is occurring only on the surface of the MOF, we compared results for catalytic addition of methanol to (*E*)-4-hex-ene-3-one using TIF-1 that had been ground using a magnetic stir bar before being converted to the NHC and using a sample that was not subjected to crystallite fragmentation. Substantially faster addition was observed with the ground sample (see the Supporting Information), which is consistent with catalysis mainly by sites formed on the external surface of the MOF.

The absence of catalytic behavior that can clearly be ascribed to sites within pores could be a consequence of the lithium source used. In solution, *n*-BuLi is present mainly as a hexamer,²⁹ the diameter of which exceeds that of TIF-1's pores. If hexamer dissociation is negligible, few catalytic sites will be created within the pore. Alternatively, it may be that the few sites that are formed are comparatively ineffective as catalysts. As noted above, these interior sites would necessarily be formed at C4. By analogy with homogeneous NHCs, the pK_a of TIF-1 C4 may well be too high for its conjugate base to function effectively as a catalyst. If so, then even on the exterior of the MOF crystallites, the active catalytic sites would chiefly be deprotonated C2 atoms.³⁰ The catalytic form of TIF-1 would then be better described as NHC-like, rather than *a*NHC-like. The structure in Scheme 5 (rather than Scheme 4) represents, therefore, our best opinion of the nature of the MOF catalytic site.

An additional consequence of catalysis occurring primarily on the external surface of TIF-1 is that the amount of catalyst driving the reaction is significantly less than we initially anticipated. A rough estimate, based on typical TIF-1 crystallite sizes, is that only about 1 in 20 000 imidazole groups is present on the surface (see the Supporting Information) and, therefore, involved in catalysis. Thus, the activity of TIF-1 on a "per-accessible-site" basis appears to be a few orders of magnitude greater than for the solution-phase catalyst, IMes-HCl. Finally, despite IMes-HCl's slightly outperforming TIF-1 in the case of the methanol addition, it is remarkable that TIF-1 achieves conversion levels within the same order of magnitude as IMes-HCl, given that only a tiny fraction of the imidazole units of TIF-1 appear to be accessible to reactants. Improved performance presumably could be engendered by replacing TIF-1 with a MOF featuring large enough channels to enable interior sites to be recruited as active catalysts.

In conclusion, we have presented the first examples of MOF-based NHC-like catalysis, in addition to what we believe is the first example of a metal imidazole as a precursor to an NHC-like catalyst. Further studies will explore different techniques for forming the NHC precursors, utilizing MOFs with larger pores and apertures. These extensions may allow for catalysis within the pores of the MOF as well as permit a wider selection of substrates to be utilized. In addition, as suggested by Figure 1 (right-hand side), evaluation of MOFs based on metal imidazolate, as opposed to metal imidazole, coordination would also clearly be of interest. Indeed, we have already obtained preliminary results showing catalysis by this type of material. We hope to report shortly on details of the study.

■ ASSOCIATED CONTENT

■ Supporting Information

Detailed experimental procedures and references to NMR, MS, XRD data. This information is available free of charge via the Internet at <http://pubs.acs.org>.

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Author Contributions

Experiments were performed by M.B.L. in consultation with the other authors. The manuscript was written through contribu-

tions of all the authors. All authors have given approval to the final version of the manuscript.

Notes

The authors declare no competing financial interest.

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- (27) For simplicity, Scheme 4 shows TIF-1 deprotonation only at C4. As discussed further below, this may well occur also, or instead, at C2.

(28) In manipulating crude TIF-1, we realized it had magnetic properties. We were able to trace the magnetism to the formation of cobalt-based nanoparticles. We subsequently found that these could be readily formed by following the synthesis procedure for TIF-1, but with the organic strut omitted.

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(30) We attempted to quench TIF-1 with D₂O, trapping the carbene, after converting it to the NHC. Unfortunately, we were unable to see any significant difference in the integration of any of the imidazole proton peaks from NMRs of as synthesized TIF-1 and TIF-1 after exposure to *n*-BuLi. The negligible difference supports the hypothesis that only a small number of sites (i.e., those on the MOF external surface) are converted to NHCs. See the Supporting Information for additional details.