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Cerium(IV) vs Zirconium(IV) Based Metal−Organic Frameworks for Detoxification of a Nerve Agent

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Supporting Information

Various materials and methods for the destruction and deactivation of toxic chemicals, such as chemical warfare agents (CWAs), have been investigated for over 1 century.[1,2] Organophosphate nerve agents, a subclass of CWAs, are volatile liquids that are designed to interfere with the human nervous system by shutting down the activity of acetylcholinesterase.[3,4] This results in an accumulation of the neurotransmitter, acetylcholine, and ultimately leads to death by asphyxiation.[5] The selective, hydrolytic cleavage of the P—F bond of organophosphate nerve agents has been shown to be effective for chemical neutralization of these agents.[6] P—F bond cleavage with cationic Lewis acids is particularly promising as phosphate ester hydrolysis can be accelerated by polarizing the P═O bond.[7] In addition, metal ions can form metal coordinated hydroxyl groups by lowering the pK_a for water from their inner hydration sphere.[7] In turn, the ligated hydroxide may (in some cases) serve as the attacking nucleophile for P—F bond disruption.[8] Therefore, bimetallic complexes may show even further enhancement in hydrolysis rates compared to mononuclear counterparts as they may allow both of these steps to happen in close proximity.[9]

Metal−organic frameworks (MOFs) have shown great potential as heterogeneous catalysts due to their tunable textural (i.e., porosity, pore size etc.)[10,11] and chemical (i.e., functional groups, reactivity etc.)[12] properties. In particular, zirconium-based MOFs have gained a great deal of attention as potential heterogeneous catalysts due to their exceptionally high thermal, chemical and mechanical stability.[13,14] We recently demonstrated that Zr_6-cluster-containing MOFs in the UiO family[15,16] as well as NU-1000[17] and MOF-808[18] have unprecedented hydrolysis rates toward organophosphate based nerve agents. We attributed this unusual activity to the Zr—OH—Zr-containing nodes which potentially mimics two-metal-ion catalysis in enzymes where M—OH—M serves as the active site (e.g., phosphotriesterase).[15,19] We discovered that altering the pore size,[20] particle size,[21] chemical functionality[22] and Zr-site accessibility[23] in a series of Zr_6-MOFs can favorably affect the rate of catalytic hydrolysis of dimethyl 4-nitrophenyl phosphate (DMNP), a nerve-agent simulant. Additionally, the rate of hydrolysis observed using a dehydrated version of NU-1000, where ligated water and hydroxide were removed with thermal treatment, was much faster than that of as-synthesized NU-1000.[17] In light of these findings, it is of interest to study MOFs containing different metal ions that can provide similar connectivity to that of the Zr_6 cluster but different ligand exchange rates and/or Lewis acidity while maintaining a similar oxidation state. Although there is no direct comparison of ligand exchange rates on Zr(IV) versus Ce(IV), it has previously been reported that Ce(IV) complexes show superior rates of phosphonate ester bond cleavage compared to Zr(IV) analogues in homogeneous form.[7,24−26] The unprecedented activity of Ce(IV) has been attributed to the role of the Ce(IV) 4f orbitals that can mix with the orbitals of the P═O bond to form hybrid orbitals. This gives rise to a penta-coordinate intermediate that is susceptible to nucleophilic attack.[27] Although this is very promising, Ce(IV) ions tend to form polymeric metal−hydroxo precipitates at pH > 4, which limits the potential of homogeneous Ce(IV) catalysts.[28] Recently, Stock and co-workers reported a Ce(IV) based UiO-66 analogue referred to as Ce-BDC (Figure 1).[29] Because Ce(IV) ions are stabilized in a $[Ce_6O_4(OH)_4]^{12+}$ node, Ce-BDC should not suffer from metal-hydroxo precipitation. We postulated that Ce-BDC would therefore show enhanced hydrolysis rates for DMNP compared to Zr-BDC (UiO-66) given that Ce(IV) shows superior activity to Zr(IV) under homogeneous conditions.

Ce-BDC was synthesized according to a published procedure[29] with slight modifications (see Supporting Information). N_2 isotherms collected at 77 K revealed that Ce-BDC has a BET surface area of 1250 $m^2\ g^{-1}$, which is in line with literature report and comparable to UiO-66 (Figure S3). For UiO type MOFs, surface areas can be related to defect densities,[30] a finding that is relevant here because defects (sites exposed on nodes due to missing linkers) are known to be the active sites for catalysis of hydrolysis reactions. Potentiometric pH titrations offer a more direct way of assaying defect densities in MOFs.[31] Experiments of this kind show that Ce-BDC and UiO-66 (HCl synthesis) have similar densities of defect sites (Figure S7 and Table S1). DRIFTS spectra revealed that the sharp peak at 3674 cm^{-1} corresponding to the hydroxyl groups on the Zr_6 node of UiO-66 is shifted to 3646 cm^{-1} in

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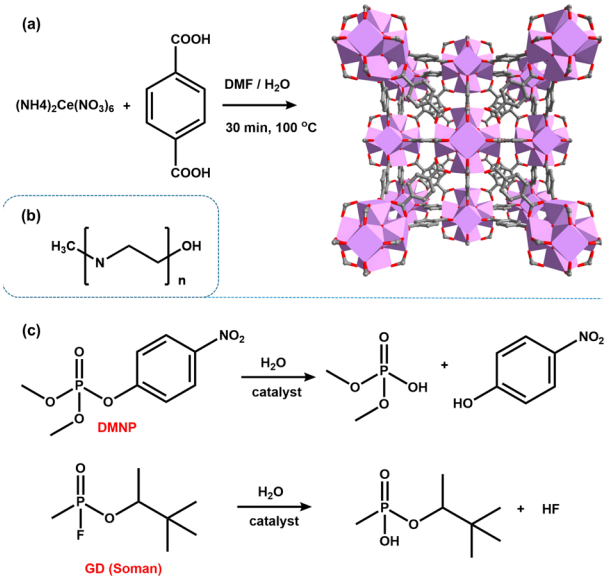

Figure 1. Chemical structures of Ce-BDC (a), linear-polyethylenimine (PEI) (b), and hydrolysis reaction of phosphonate-based nerve agents (*O*-pinacolyl methylphosphonofluoridate, GD and a simulant (dimethyl 4-nitrophenyl phosphonate, DMNP) (c). Carbon (gray), oxygen (red) and cerium (purple).

Ce-BDC, which suggests weaker O−H bonds in the case of Ce_6 node. (Figure S5).

Given the toxicity of organophosphate based nerve agents, we first investigated the catalytic activity of Ce-BDC using the less toxic simulant, DMNP. In general, 3 mg (1.5 μmol, 6 mol % catalyst loading based on Ce_6 cluster) of Ce-BDC was added to a 1 mL aqueous solution, buffered at pH 10 with 0.45 M *N*-ethylmorpholine. To this solution was added 4 μL of DMNP (25 μmol), and the resulting mixture was agitated for 15 s before being transferred to an NMR tube. The ^{31}P NMR spectrum of the mixture was collected every minute for 60 min and conversion was tracked by integrating the peaks associated with DMNP versus the dimethyl phosphate product obtained from cleavage of the P−O bond (Figure 1).

Conversion profiles for both Ce-BDC and UiO-66 are shown in Figure 2. Initial rate calculations reveal that Ce-BDC substantially reduces the DMNP half-life, from 19 to 8 min. It is worth noting that particle size plays a significant role in hydrolysis rates, especially for UiO-66 type MOFs.[21,23] The Ce-BDC used in this example consists of larger particles compared to UiO-66 (Figure S6). Therefore, it is expected that the actual difference in hydrolysis rate might be even more drastic if the particle size could be easily decreased.

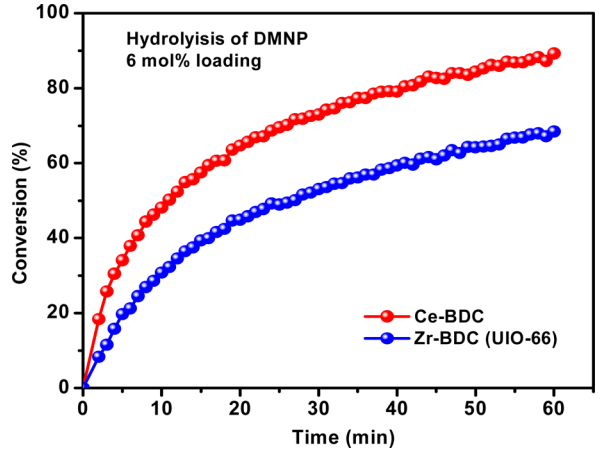

Figure 2. Hydrolysis profiles of DMNP with Ce-BDC (red circle) and UiO-66 (blue circle).

After observation of the fast rate of DMNP hydrolysis using Ce-BDC, the next step was to test Ce-BDC as a catalyst for the hydrolysis of the actual CWA, soman (*O*-pinacolyl methylphosphonofluoridate, also known as GD) (Figure 3). The half-life for the degradation of GD using Ce-BDC was observed to be 3 min whereas UiO-66 showed ~4 min half-life under the same conditions.[20] It is important to note that DMNP is hydrolyzed at the P−O bond whereas GD is hydrolyzed at the P−F bond, which leads to differences in hydrolysis rate between the simulant and agent.[20,32]

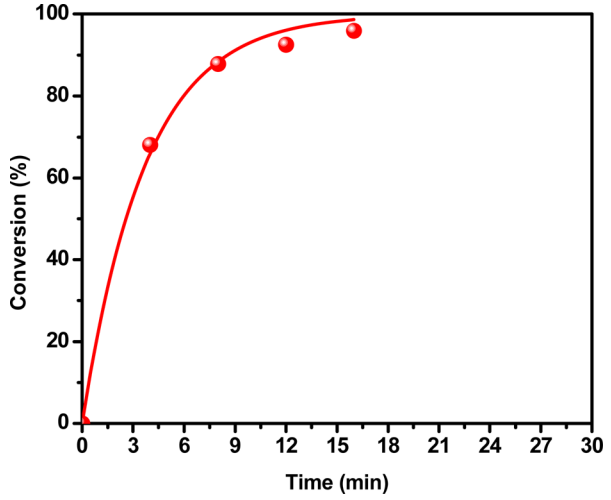

Figure 3. Hydrolysis profiles of GD with Ce-BDC in *N*-ethylmorpholine buffer solution.

Although Ce-BDC presents promising hydrolysis rates for DMNP as well as GD in an *N*-ethylmorpholine buffering solution, the use of liquid buffer must be eliminated for applications such as protective suits and masks.[32] We recently demonstrated that polyethylenimine (PEI), a linear polymer with repeating units composed of amine groups and carbon spacers, can be mixed with a MOF catalyst and employed as a heterogeneous buffer resulting in hydrolysis rates comparable to those found using *N*-ethylmorpholine solutions.[33] With these results in hand, we prepared the PEI/Ce-BDC mixtures with different amounts of PEI to optimize the amine loading (Figure 4 and Figure S8). We previously showed that the hydrolysis reaction with PEI alone in water is negligible.[34] Amazingly, under optimized conditions (Figure S8), a shorter half-life was observed using PEI compared to *N*-ethylmorpholine (4.5 vs 8 min). This highlights the role of primary amines in the hydrolysis mechanism and points to a role for the buffer beyond just controlling the solution hydroxide concentration.

In conclusion, we demonstrated, for the first time, that Ce(IV) based MOFs can be used to achieve fast hydrolysis of a phosphate-ester-based nerve agent, soman, as well as a simulant, DMNP. Hydrolysis is observed to be faster with the Ce(IV) MOF than with previously investigated Zr(IV) analogue (UiO-66). Importantly, Ce-BDC induces even faster hydrolysis rates in a MOF/PEI solid than in an *N*-ethyl-

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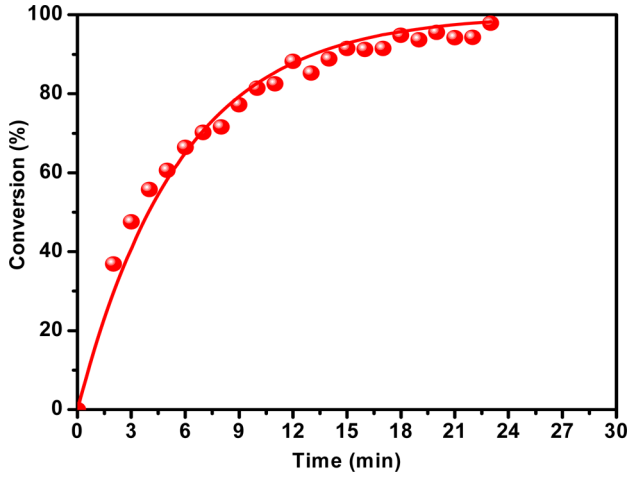

Figure 4. Hydrolysis profiles of DMNP with Ce-BDC in the presence of PEI.

morpholine solution. This observation is especially significant in the context of potential application of these catalysts in protective suits and/or masks. Currently, there is an effort in our laboratories to transfer the knowledge gained from Zr-based systems to Ce-based systems in order to achieve enhanced hydrolysis rates for nerve agents.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.chemmater.6b04835.

Materials and methods, experimental details, N_2 isotherm, DRIFTS spectra, PXRD patterns, SEM images and titration curves for Ce-BDC (PDF)

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Notes

The authors declare no competing financial interest.

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■ ABBREVIATIONS

BDC, benzene-1,4-dicarboxaldehyde; DMF, dimethylformamide; DRIFTS, diffuse reflectance infrared Fourier transform spectroscopy; DMNP, dimethyl 4-nitrophenyl phosphate; MOFs, metal−organic frameworks; NMR, nuclear magnetic resonance; soman also known as GD, *O*-pinacolyl methylphosphonofluoridate; PEI, polyethylenimine

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