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Synthesis of Organic Photodimeric Cage Molecules Based on Cycloaddition via Metal−Ligand Directed Assembly

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Metal−ligand directed assembly has proven successful in the design and synthesis of metal−organic assemblies (e.g., metal−organic frameworks and metal−organic polyhedra),[1] which have emerged as an important class of solid-state materials and have exhibited interesting properties toward their utilization in many applications, from ion exchange to gas storage to separations to catalysis.[2] Recently, we have introduced a method to target rigid and directional single-metal ion based molecular building blocks toward the design and synthesis of metal−organic assemblies (MOAs),[3] including zeolite-like frameworks, a subclass called ZMOFs, that exhibit tunable extra-large cavities which offer potential in (host−guest)−guest sensing.[4] The metal−ligand directed assembly approach also appears highly prospective for positioning olefin ligands[5] within the required distance for [2 + 2] photodimerization (<4.2 Å),[6] an area dominated by the fluid environment in liquid phase,[7] guest interactions (i.e., van der Waals and electrostatic forces) in cavities,[8] and hydrogen-bond (HB)-templated complexes in the solid state.[9]

To date, [2 + 2] photodimerization reactions via metal−ligand directed assembly are scarce and involve only simple linear olefins (i.e., single or chain-type olefins functionalized for metal binding).[5] Likewise, to the best of our knowledge, most HB-templated complexes have been limited to similar simple olefins.[9] Nevertheless, higher dimensional olefins have been photodimerized predominantly in solution, leading to product mixtures with elongated conversion times when compared to solid-state media.[10] On the other hand, directing the assembly of purely functional organic molecules into predetermined positions remains a challenge,[1b,11] and thus their prealignment into the requisite distance for [2 + 2] photodimerization is less evident by direct crystallization.[6]

Our research group, among others, has constructed numerous pyridinedicarboxylate-based MOAs,[3b,12] some where the pyridine moieties overlap antiparallel with a slight offset and are in close proximity (∼3.6 Å), indicating $\pi-\pi$ stacking interactions (**1** in Figure S1). This ligand positioning indicates the potential use of MOAs as platforms toward the synthesis of organic molecules based on cycloaddition via single-crystal-to-single-crystal (SCSC) [2 + 2] photodimerization.[13]

Typically, pyridine-based derivatives show reduced photoreactivities[14] compared to olefins and hydrocarbon aromatics.[15] Therefore, we chose to explore more suitable ligands for such photoreactions, leading us to select the structurally similar, heterocyclic diolefin chelidonic acid (H_2CDO). H_2CDO has two carbon−carbon double bonds within its heterocyclic ring and functional groups available for coordination with metal ions (Figure 1). One can expect dipole−dipole interactions between CDO ligands instead of $\pi-\pi$ stacking of pyridine rings in the crystal and thus similarity in the corresponding crystal structures. In addition, tetraasterane-*like*[16] compounds similar to the photodimeric cage molecule[17] expected from the cycloaddition of CDO ligands have exhibited interesting biological properties (e.g., anti-HIV and anti-cancer activities[18]). However, to the best of our knowledge, there is only one coordination polymer with CDO[19] and a few discrete clusters,[20] none having the proper positioning of the ligands.

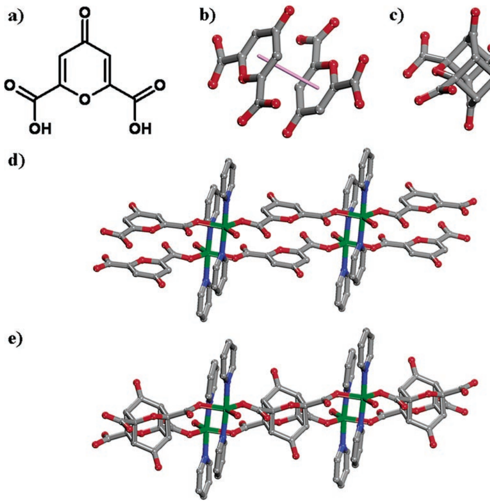

Figure 1. (a) Chelidonic acid, (b) the 3.652 Å centroid···centroid distance (fuschia) between CDO molecules in **2**, (c) the photoproduct, EE1, and (d) neighboring chains of **2** that result in (e) ladders of **3**. H atoms omitted for clarity; Cu = green, C = gray; N = blue; O = red.

Here, we report a new pathway utilizing MOAs as scaffolding agents for organic synthesis, which has allowed the single-crystal-to-single-crystal [2 + 2] photodimerization of higher dimensional olefins, in this case the diolefin chelidonate (CDO), to yield the organic cage dimer, EE1, within the MOA. This MOA then can be dissolved in the presence of strong base to isolate the cage dimer as a sodium salt of the tetrol (hydrated carbonyls) derivative of EE1, heretofore referred to as EE2.

Reaction between H_2CDO and $Cu(NO_3)_3{\cdot}2.5H_2O$ in a DMF, ethanol (EtOH), and pyridine (py) solution yields light blue plate-like crystals characterized and formulated by single-crystal diffraction (SCD) studies as $Cu(CDO)(py)_2(H_2O)$ (**2**). The purity of **2** was confirmed by similarities between simulated and experimental XRPD. In the crystal structure of **2** (Figure 1c), each copper(II) ion assumes a trigonal bipyramidal geometry (MN_2O_3) and is coordinated in the axial positions by the nitrogen atoms of two independent py molecules. The equatorial positions are occupied by the oxygen atom of one water molecule and in a monodentate fashion by the carboxylate oxygen atoms of two CDO ligands. Each CDO ligand coordinates to two individual copper ions to form 1D metal−organic chains along the *b*-axis. Each pair of neighboring chains, related by center of symmetry, are joined by hydrogen bonds (HBs) between coordinated water and the two adjacent carboxylate carbonyl groups to form a well-defined ladder structure (Figure S2a). Dipole−dipole

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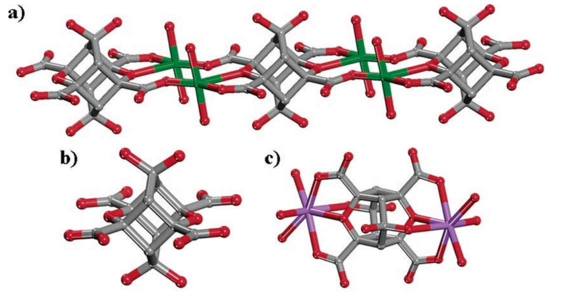

Figure 2. (a) Chains in **4**, (b) EE2, (c) single EE2 disodium salt of **5**. H atoms omitted for clarity; Cu = green, Na = violet, C = gray; N = blue; O = red.

interactions arrange the ladders into pseudo layers parallel to the *bc* plane, while the terminal py ligands are pointed out of such a plane into the interlayer space (Figure S2b). The six-membered heterocyclic rings of the organic components of neighboring metal−organic ladders are arranged antiparallel and completely overlap with interplanar spacing of 3.614 Å, centroid···centroid separation of 3.652 Å, and inter-ring olefin C atom separations of 3.612 and 3.652 Å. Metal−ligand directed arrangement of the organic linkers appears to provide suitable conditions for photodimerization.

Indeed, incubation of a thin layer of **2** for 3 days in a photochemical reactor results in a change of crystal color from light blue to light green. Further analysis reveals the SCSC transformation of **2** to a new structure characterized and formulated by SCD studies as Cu(EE1)(py)$_2$(H$_2$O) (**3**). The purity of **3** was confirmed by similarities between simulated and experimental XRPD, suggesting complete transformation of adjacent pairs of CDO ligands into the cage dimer, EE1. As expected, the unit cell dimensions decrease slightly, resulting in a difference of ∼6% in the volume of the unit cell.[21] The HBs between coordinated water molecules and carboxylate carbonyls are maintained, and the photodimerized ligands unite the ladders, resulting in predicted 2D sheets that are separated by the induced $\pi-\pi$ stacking interactions between interlayer py moieties (Figure S3). To our knowledge, this is the first cage dimerization accomplished utilizing MOAs as directing agents (Figure 1d).

Initial attempts to isolate the new ligand, EE1, utilized strong acid to dissociate the coordination bonds, and potentially precipitate the ligand as the tetracarboxylic acid, H$_4$EE1. The use of nitric acid successfully dissolved the light green crystals of **3**; however, no precipitate formed upon cooling. The resulting solution was then successively heated and cooled to yield a few blue plate-like crystals. Their crystal structure was revealed by SCD studies as Cu$_2$(EE2)(H$_2$O)$_4$·4H$_2$O (**4**). The reaction conditions result in the hydration (oxidation) of each heterocycle ketone of EE1 to the corresponding diol, producing the novel ligand, EE2 (Figure 2b). In the crystal structure of **4**, each copper(II) ion assumes a distorted square pyramidal geometry (MO$_5$) and is coordinated in a monodentate fashion by the carboxylate oxygen atoms of two EE2 ligands in *trans* positions of the basal plane, as well as the oxygen atoms of two water molecules, and the oxygen atom of the heterocyclic ring, which occupies the apex of the distorted pyramid, chelating the metal (Figure 2a). In contrast to **3**, the crystal structure of **4** includes no py molecules, confirming the complete dissolution of **3**. Metal−ligand directed assembly results in ladders along the *c*-axis, and the multiple HBs between neighbors join them into 2D layers parallel to the *ac* plane (Figure S4).

In the presence of NaOH, the light green crystals of **3** also dissolved, and Cu(OH)$_2$ formed almost instantly and was filtered. Upon acidification and cooling of the filtrate, colorless block crystals formed, which SCD studies revealed to be the disodium salt of EE2 (Figure 2c) characterized and formulated as Na$_2$(H$_2$EE2)(H$_2$O)$_6$·2H$_2$O (**5**), proving the successful isolation of the sodium salt of the EE2 photodimer.

Here we have illustrated the utilization of metal−organic assemblies as scaffolding agents for organic synthesis, especially the [2 + 2] photodimerization of higher dimensional olefins. Similar reactions previously have been achieved only via hydrogen bonding of simple pyridine- or, more recently, carboxylate-based olefins and complementary HB donors/acceptors, and have only very recently involved coordination chemistry. Our approach has introduced a novel pathway to organic synthesis, that is, isolation of desirable photodimers, and has proven that higher dimensional cage dimers can be targeted using metal−ligand directed assembly. Work is in progress to expand this approach to molecularly similar higher dimensional olefins, such as chelidamic acid and meconic acid. Recent results also indicate that this approach may be used to target ladderanes.

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Supporting Information Available: XRPD, TGA, and UV/vis data, syntheses, structure figures, and X-ray crystallographic data. This material is available free of charge via the Internet at http://pubs.acs.org.

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(21) Unit cell parameters of **2**: $a = 8.738$ Å, $b = 10.188$ Å, $c = 10.760$ Å, $\alpha = 63.081°$, $\beta = 83.714°$, $\gamma = 76.771°$, $P\bar{1}$, $V = 831.6$ Å^3. For **3**: $a = 8.586$ Å, $b = 9.954$ Å, $c = 10.576$ Å, $\alpha = 62.738°$, $\beta = 87.681°$, $\gamma = 77.070°$, $P\bar{1}$, $V = 781.1$ Å^3.

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