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# Emergent Self-Assembly of a Multicomponent Capsule via Iodine Capture

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 ABSTRACT: Described here is a three-component self-assembly system that displays emergent behavior that differs from that of its constituents. The system comprises an all-hydrocarbon octaaryl
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constituents. The system comprises an all-hydrocarbon octaaryl macrocycle cyclo[8](1,3-(4,6-dimethyl)benzene ( $D_{4d}$ -CDMB-8), corannulene (Cora), and I<sub>2</sub>. No appreciable interaction is seen between any pair of these three-components, either in cyclohexane or under various crystallization conditions. On the other hand, when all three-components are mixed in cyclohexane and allowed to undergo crystallization, a supramolecular iodine-containing capsule, ( $(D_{4d}$ -CDMB-8)<sub>3</sub> $\supset$ (Cora)<sub>2</sub>) $\supset$ I<sub>2</sub>, is obtained. This all-hydrocarbon capsule consists of three  $D_{4d}$ -CDMB-8 and two Cora



subunits and contains a centrally bound I<sub>2</sub> molecule as inferred from single-crystal and powder X-ray diffraction studies as well as solid-state <sup>13</sup>C NMR and Raman spectroscopy. These analyses were complemented by solution-phase <sup>1</sup>H NMR and UV–vis spectroscopic studies. No evidence of I<sub>2</sub> escape from the capsule is seen, even at high temperatures (e.g., up to 418 K). The bound I<sub>2</sub> is likewise protected from reaction with alkali or standard reductants in aqueous solution (e.g., saturated NaOH(aq) or aqueous Na<sub>2</sub>S<sub>2</sub>O<sub>3</sub>). It was also found that a mixed powder containing  $D_{4d}$ -CDMB-8 and Cora in a 3:2 molar ratio could capture saturated I<sub>2</sub> vapor or iodine from aqueous sources (e.g., 1.0 mM I<sub>2</sub> in NaCl (35 wt %) or I<sub>2</sub> + NaI(aq) (1.0 mM each)). The present system displays structural and functional features that go beyond what would be expected on the basis of a simple sum-of-the-components analysis. As such, it illustrates a new approach to creating self-assembled ensembles with emergent features.

## INTRODUCTION

In 1875, George Henry Lewes expressed in philosophical terms the concept of emergence, basically codifying a phenomenon that permeates the social and natural sciences wherein the behavior of a system as a whole cannot be reduced to the sum or difference of its individual components.<sup>1</sup> Often the emergent features are the result of complex, cooperative interactions among the various constituents. For instance, atoms may form small molecules via chemical bonds, which then can undergo polymerization to yield macromolecules (e.g., DNA and proteins) that permit cell construction. Further organization can lead to tissues, organs, and ultimately living entities. In this canonical sequence, multicomponent constructs at each level display emergent behavior in terms of both structure and function. Synthetic self-assembled systems displaying emergent behavior offer a means to understanding the determinants underlying natural, chemical-based emergent systems.

At present, emergent molecular systems based on covalent bonds are reasonably well understood. However, it remains a challenge to create emergent self-assembled systems organized via weak intermolecular interactions.<sup>2</sup> In recent years, several artificial self-assembled systems involving three or more components have been reported. Examples include metal– organic frameworks (MOFs),<sup>3</sup> supramolecular organic frameworks (SOFs),<sup>4</sup> molecular cages,<sup>5</sup> molecular capsules,<sup>6</sup> molecular knots,<sup>7</sup> molecular machines,<sup>8</sup> and so forth.<sup>9</sup> In general, these systems rely on apparent pairwise interactions (e.g., strong binding) between the individual components. However, in principle self-assembly can be achieved in the absence of such direct interactions, thus mimicking the emergent behavior seen in many natural systems.<sup>10</sup> To the best of our knowledge, there are no reports of multicomponent artificial systems that self-assemble in the complete absence of direct component-to-component pairwise interactions. Here we report a self-assembled solid-state supramolecular capsule that displays emergent behavior in that all three constituents are necessary to drive the self-assembly, which occurs in the absence of pairwise interactions (Scheme 1). A noteworthy feature of this system is that all components are uncharged.

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Scheme 1. Schematic Representations of Three-Component Self-Assembly



#### RESULTS AND DISCUSSION

In previous work, we reported that the all-hydrocarbon macrocycle, cyclo[8](1,3-(4,6-dimethyl)benzene ( $D_{4d}$ -CDMB-8), could act as a receptor for fullerenes, perylene, and a series of solvent molecules (e.g., toluene, THF, acetonitrile, nitrobenzene, etc.).<sup>11</sup> These relatively large substrates were found to be bound within the bowl-like cavity of  $D_{4d}$ -CDMB-8 via  $\pi - \pi$  and/or CH- $\pi$  interactions. However, smaller linear molecules (e.g., acetonitrile) were found to thread through the center of the macrocycle, with the resulting bound form being stabilized by possible  $CH-\pi$ interactions. These findings led us to consider that  $D_{4d}$ -CDMB-8 might interact with an appropriately sized curved aromatic compound to form a capsule-like construct capable of capturing small linear molecules. As discussed further below, this design expectation was realized in the case of corannulene (Cora) and I<sub>2</sub>. Little evidence of binding was seen when  $D_{4d}$ -CDMB-8, Cora, or I<sub>2</sub> was allowed to interact with one another in a pairwise fashion in cyclohexane (CYH) in homogeneous solution and under conditions favoring crystallization. In contrast, when all three-components were mixed in CYH and allowed to crystallize, a self-assembled capsule containing an entrapped iodine molecule,  $(((D_{4d}$ -CDMB-8)<sub>3</sub> $\supset$ (Cora)<sub>2</sub>) $\supset$ I<sub>2</sub>), was obtained (Scheme 2). The normal chemical behavior expected for  $\mathrm{I}_2$  was suppressed as a result of being bound within the self-assembled capsule, as evidenced by an inability

to remove it via sublimation at temperatures of up to 418 K and a lack of reactivity when exposed to saturated NaOH(aq) or aqueous Na<sub>2</sub>S<sub>2</sub>O<sub>3</sub> solutions. It was also found that a solid-state mixture of  $D_{4d}$ -CDMB-8 and Cora was able to capture iodine efficiently from I<sub>2</sub> vapor or aqueous sources of I<sub>2</sub>. In contrast, no evidence of interaction was seen for the corresponding solid form of either  $D_{4d}$ -CDMB-8 or Cora. Effective entrapment of iodine thus required full participation of all three constituents, namely,  $D_{4d}$ -CDMB-8, Cora, and I<sub>2</sub>. We believe that the approach reported here provides an attractive strategy for storing small active molecules while illustrating a possible new utility for synthetic emergent systems.

Studies of Possible Interactions in Solution.  $D_{4d}$ -CDMB-8, Cora, and I<sub>2</sub> are all soluble in CYH. This solvent was thus chosen to test the extent of pairwise interactions between these species. In fact, no appreciable changes in the UV-vis or <sup>1</sup>H NMR spectra were seen upon mixing any two components in (deuterated) CYH or in fact all three components at a final concentration of 0.50 or 3.0 mM in each species (cf. Supporting Information Figures S1–S5). We thus infer that any putative interspecies interactions are insufficient to overcome solvation effects.

Studies of Mixtures Containing Two Components under Crystallization Conditions. CYH solutions containing  $D_{4d}$ -CDMB-8 (3.0 mM) and 1 molar equiv of either Cora or I<sub>2</sub> (but not both concurrently) were subject to slow evaporation at room temperature (298 K). Under these conditions, only single crystals of  $[D_{4d}$ -CDMB-8 $\supset$ CYH-(CYH)<sub>4.5</sub>] and [Cora] were obtained. No evidence of iodine in the crystals was seen, leading us to infer that this inherently volatile molecule evaporated off during the crystallization attempts.

In the single crystal  $[D_{4d}$ -CDMB-8 $\supset$ CYH·(CYH)<sub>4.5</sub>], one CYH molecule is located between two neighboring  $D_{4d}$ -CDMB-8 macrocycles. The CYH-to-benzene C-C distances vary from 3.5 to 3.8 Å, leading us to propose that the CYH guest is held in place via CH- $\pi$  interactions (cf. Supporting Information Figure S6). One  $D_{4d}$ -CDMB-8 and one CYH molecule form a repeat unit that presumably favors further 1D packing (Figure 1).



Scheme 2. Schematic Representations of the Self-Assembly of Two- and Three-Component Mixtures Containing  $D_{4d}$ -CDMB-8, Corannulene (Cora), and/or  $I_2$  in Cyclohexane (CYH) or in the Solid State



**Figure 1.** Extended 1D packing arrangement,  $(D_{4d}$ -CDMB-8>CYH)<sub>n</sub>, seen in the solid state for single crystals of  $[D_{4d}$ -CDMB-8>CYH·(CYH)<sub>4.5</sub>].

Single-Crystal Structure of the lodine Complex Obtained upon Self-Assembly of  $D_{4d}$ -CDMB-8, Cora, and I<sub>2</sub>. A mixture of  $D_{4d}$ -CDMB-8, Cora, and I<sub>2</sub> (each at a concentration of 3.0 mM) in CYH was subject to slow evaporation at room temperature (298 K) over the course of 2 days. X-ray diffraction analysis revealed a supramolecular iodine capsule, ([((( $D_{4d}$ -CDMB-8)\_3)(Cora)\_2 \cdot CYH))I\_2). SCYH]), comprising three macrocycles, two Cora components, and one iodine molecule. Individual iodine-containing capsule units, (( $D_{4d}$ -CDMB-8)\_3)(Cora)\_2)I\_2, combine to form as an infinite structure with CYH molecules playing a possible stabilizing role (Figure 2e–g).

Two kinds of limiting geometric arrangements involving the macrocycle and **Cora** are seen within each capsule unit. These are referred to as bowl bottom binding (Figure 2a) and bowl edge binding (Figure 2b), respectively. In the bowl bottom binding mode, the mean distance between the carbon atoms on the **Cora** edge and the benzene centroids of the  $D_{4d}$ -**CDMB-8** macrocycle is ca. 3.4 Å. In the bowl edge binding mode, the mean distance between the carbon atoms on the

**Cora** edge and the benzene centroids of the  $D_{4d}$ -**CDMB-8** macrocycle is ca. 3.5 Å. These distances may reflect the presence of stabilizing  $\pi - \pi$  donor-acceptor and attractive CH- $\pi$  interactions, respectively. The iodine molecule is centered within the capsule and threads through the central  $D_{4d}$ -**CDMB-8** macrocycle. No obvious interactions between the iodine molecule and the surrounding macrocycle were inferred on the basis of the large I-C separations (all >4.4 Å; see Figure 2c). The iodine molecule also inserts into two capping **Cora** subunits within the overall capsule structure. The distance between the iodine atoms and the center of the closest **Cora** centroid (i.e., bowl bottom) is ca. 3.6 Å (Figure 2d). While not a proof, such a separation may reflect a stabilizing I··· $\pi$  halogen bonding interaction.

Gratifyingly, the crystallization procedure leading to  $[(((D_{4d}\text{-CDMB-8})_3)(\text{Cora})_2 \cdot \text{CYH}) \supset I_2) \cdot \text{5CYH}]$  could be run easily on a gram scale. Of note is the fact that the powder X-ray diffraction (PXRD) spectrum of the gram-scale sample proved to be in good agreement with the PXRD pattern simulated on the basis of the single-crystal data (cf. Supporting Information Figure S12).

**Spectral Studies of the Self-Assembly Process in CYH.** To obtain further insights into the three-component selfassembly of  $D_{4d}$ -CDMB-8 with Cora and I<sub>2</sub>, solution-phase UV-vis spectroscopic analyses were carried out in CYH under conditions mimicking those used to obtain single crystals. Specifically, CYH solutions containing one or two components of  $D_{4d}$ -CDMB-8, Cora, and I<sub>2</sub> (10.0 mM in each) were set in small airtight vials on the bench and held at 298 K for 60 h. Crystals, as colorless prisms, were observed in the case of the various  $D_{4d}$ -CDMB-8-containing vials. A decrease in the UVvis absorbance intensity was seen in the resulting supernatants. Note that the supernatant was diluted by a factor of 100 prior



**Figure 2.** Single-crystal X-ray structures showing various interactions among  $D_{4d}$ -**CDMB-8**, **Cora**, I<sub>2</sub>, and CYH seen within the extended solid-state structure,  $[(((D_{4d}$ -**CDMB-8**)\_3 $\supset$ (**Cora**)\_2 $\cdot$ CYH) $\supset$ I<sub>2</sub>)·5CYH]<sub>n</sub>. (a and b) Bowl bottom and bowl edge spatial arrangements of the  $D_{4d}$ -**CDMB-8** and **Cora** portions of the overall capsule. (c) View showing the threading of I<sub>2</sub> through the central  $D_{4d}$ -**CDMB-8** macrocycle. (d) View showing the insertion of I<sub>2</sub> into the capping **Cora**. (e) Basic iodine-containing capsule unit  $(D_{4d}$ -**CDMB-8**)\_3 $\supset$ (**Cora**)\_2) $\supset$ I<sub>2</sub>. (f and g) Side and top views of the extended 1D linear structure produced via self-assembly of individual capsules  $((D_{4d}$ -**CDMB-8**)\_3 $\supset$ (**Cora**)\_2) $\supset$ I<sub>2</sub> and CYH. Some CYH molecules and hydrogen atoms have been omitted for clarity.

to spectral analysis (cf. Supporting Information Figures S16 and S17).

Single crystals analogous to those used for the X-ray diffraction analyses were also subject to solution-phase <sup>1</sup>H NMR spectroscopic analysis after dissolution in benzene- $d_6$  (cf. Supporting Information Figure S13). It was concluded that in all cases the crystals consisted of  $[D_{4d}$ -CDMB-8 $\supset$ CYH·  $(CYH)_{45}$ , the composition of which was ca. 50%  $D_{4d}$ -**CDMB-8** on a per molar basis. No evidence of either  $D_{4d}$ -CDMB-8·Cora or  $D_{4d}$ -CDMB-8·I<sub>2</sub> complex formation was observed. Moreover, no solid material or discernible change in the UV-vis spectral features was seen in the solutions containing only Cora, only  $I_{2}$ , or a 1:1 mixture of the two species (cf. Supporting Information Figure S17). In contrast, brown crystals were produced upon stirring a CYH solution of  $D_{4d}$ -CDMB-8, Cora, and I<sub>2</sub> (each at 10.0 mM) at 298 K for 60 h. UV-vis spectral studies of the CYH solution revealed an absorbance decrease over the 250 to 620 nm spectral region. On the basis of the decrease in the  $I_2$  absorbance at 520 nm, the Cora absorbance at 320 nm, and the superimposed absorbance of D<sub>4d</sub>-CDMB-8, Cora, and I<sub>2</sub> at 268 nm, the molar percentages of  $D_{4d}$ -CDMB-8, Cora, and  $I_2$  in the solid material were calculated to be 68, 42, and 18%, respectively (cf. Supporting Information). These values agree with the 3:2:1 ratio seen in single crystals of  $[(((D_{4d}-CDMB-8)_3))(Cora)_2)$ CYH)⊃I<sub>2</sub>)·5CYH]. Moreover, UV-vis and <sup>1</sup>H NMR spectroscopic studies were carried out by dissolving the single crystals in CYH or benzene- $d_6$ . In aggregate, these studies allowed us to confirm the identities and ratios of the components within the crystals (cf. Supporting Information Figures S14 and S15). Considered in conjunction with both the single-crystal and powder X-ray diffraction analyses, these findings provide support for the conclusion that only the supramolecular iodine capsule ([((( $D_{4d}$ -CDMB-8)<sub>3</sub> $\supset$ (Cora)<sub>2</sub>·CYH) $\supset$ I<sub>2</sub>)·5CYH]) is produced under these crystallization conditions.

Thermodynamic and Kinetic Analyses of Self-Assembly under Conditions of Crystallization. Timedependent UV-vis spectroscopic studies were carried out to compare the crystallization of  $D_{4d}$ -CDMB-8 and the iodine capsule  $((D_{4d}\text{-}CDMB-8)_3 \supset (Cora)_2) \supset I_2$ , respectively, in CYH. In solutions containing either  $D_{4d}$ -CDMB-8 or a mixture of  $D_{4d}$ -CDMB-8 and  $I_2$  (1:1 by concentration), essentially complete crystallization of a D<sub>4d</sub>-CDMB-8-containing species occurred within 5 h. However, a corresponding solution containing  $D_{4d}$ -CDMB-8 and Cora (1:1 by concentration) required nearly 10 h to achieve an equal level of crystallization (cf. Figure 3a, Supporting Information Figure S18d). On this basis, we conclude that even if little direct evidence of interaction between D4d-CDMB-8 and Cora was observed in CYH, the presence of Cora has some impact on the kinetics of *D*<sub>4d</sub>-CDMB-8 crystallization.

In contrast to what was seen for  $D_{4d}$ -CDMB-8, alone or in conjunction with **Cora**, self-assembly leading to crystallization of the iodine capsule complex,  $((D_{4d}$ -CDMB-8)<sub>3</sub> $\supset$ (**Cora**)<sub>2</sub>) $\supset$ I<sub>2</sub>, proved quite slow. Specifically, nearcomplete crystallization of the three-component capsule from a 1:1:1 (concentration basis) solution of  $D_{4d}$ -CDMB-8, **Cora**, and I<sub>2</sub> is seen only after 30 h (cf. Figure 3b, Supporting Information Figure S18). The composition of the resulting crystalline form was found to match what would be expected on the basis of the single-crystal X-ray diffraction analyses discussed above.



**Figure 3.** Time-dependent crystallization studies of  $D_{4d}$ -**CDMB-8** and  $((D_{4d}$ -**CDMB-8**)<sub>3</sub> $\supset$ (**Cora**)<sub>2</sub>) $\supset$ I<sub>2</sub> in CYH monitored by UV-vis spectroscopy. (a) Plot of the percentage of  $D_{4d}$ -**CDMB-8** present in crystalline form starting from CYH solutions of  $D_{4d}$ -**CDMB-8** (10.0 mM) either (i) pure, (ii) containing 1 molar equiv of **Cora**, or (iii) containing 1 molar equiv of **Cora** and I<sub>2</sub>. (b) Plot of the ratio of each component in the crystalline material obtained from a CYH solution containing  $D_{4d}$ -**CDMB-8**, **Cora**, and I<sub>2</sub> (10.0 mM in each) as a function of time. The ratios observed correspond to those seen in  $((D_{4d}$ -**CDMB-8**)<sub>3</sub> $\supset$ (**Cora**)<sub>2</sub>) $\supset$ I<sub>2</sub>. See the text for details.

Assuming that the products of crystallization are under thermodynamic control allowed an analysis of the relative energetics for the formation of  $[D_{4d}$ -CDMB-8 $\supset$ CYH·  $(CYH)_{4.5}$ ] and  $[(((D_{4d}-CDMB-8)_3 \supset (Cora)_2 \cdot CYH) \supset I_2) \cdot$ 5CYH] to be carried out. According to the standard equilibrium (eq 1) and using the percentage of the total material crystallized to deduce the free concentration of  $D_{4d}$ -CDMB-8 (Figure 3a), it proved possible to approximate the equilibrium constant  $(K_{SI}^{\Theta})$  and Gibbs free energy  $(\Delta G_{1_{(298 \text{ K})}}^{\Theta})$ corresponding to the formation of  $[D_{4d}$ -CDMB-8 $\supset$ CYH $\cdot$  $(CYH)_{4.5}$ ] as  $1.9 \times 10^2$  and -13 kcal·M<sup>-1</sup>, respectively. A similar analysis using the relative percentages of each component (i.e.,  $D_{4d}$ -CDMB-8, Cora, and  $I_2$ ) in the  $[(((D_{4d}\text{-CDMB-8})_3 \supset (\text{Cora})_2 \cdot \text{CYH}) \supset I_2) \cdot \text{5CYH}]$  product (Figure 3b) and the equilibrium expression in eq 2 gave  $K_{S2}^{\Theta}$ = 5.5 × 10<sup>4</sup> and  $\Delta G_{2(298 \text{ K})}^{\Theta}$  = -27 kcal·M<sup>-1</sup> for the formation of  $[(((D_{4d}\text{-CDMB-8})_3 \supset (\text{Cora})_2 \cdot \text{CYH}) \supset I_2) \cdot 5\text{CYH}]$ . We thus conclude that the emergent behavior that leads to the formation of  $[(((D_{4d}-CDMB-8)_3 \supset (Cora)_2 \cdot CYH) \supset I_2) \cdot$ 5CYH] is energetically favorable. A comparison of the  $(\Delta G_{2(298 \text{ K})}^{\Theta})$  values also provides support for the observation that under crystallization conditions where all three components are present  $[(((D_{4d}-CDMB-8)_3 \supset (Cora)_2 \cdot CYH) \supset I_2) \cdot$ 5CYH] is formed in preference to  $[D_{4d}$ -CDMB-8 $\supset$ CYH $\cdot$  $(CYH)_{4.5}$ ].

$$[\mathbf{D}_{4d}\text{-}\mathbf{CDMB}\text{-}\mathbf{8}] \stackrel{K_{S1}^{\theta}}{\longrightarrow} [D_{4d}\text{-}\mathbf{CDMB}\text{-}\mathbf{8}]\downarrow$$
(1)  
$$[\mathbf{D}_{4d}\text{-}\mathbf{CDMB}\text{-}\mathbf{8}] + \frac{2}{3}[\mathbf{Cora}] + \frac{1}{3}[\mathbf{I}_{2}]$$

$$\underset{\longleftarrow}{\overset{K_{S_2}^{\theta}}{\longleftarrow}} \frac{1}{3} [(\boldsymbol{D}_{4d} \text{-} \mathbf{CDMB} \text{-} \mathbf{8})_3 \supset 2\mathbf{Cora} \cdot \mathbf{I}_2] \downarrow$$
(2)

$$K_{S1}^{\theta} = 1.9 \times 10^{2}; \ \Delta G_{1(298\text{K})}^{\theta} = -13 \text{ kcal} \cdot \text{M}^{-1}$$
$$K_{S2}^{\theta} = 5.5 \times 10^{4}; \ \Delta G_{2(298\text{K})}^{\theta} = -27 \text{ kcal} \cdot \text{M}^{-1}$$

**Theoretical Calculations.** Further support for the emergent self-assembly of  $D_{4d}$ -CDMB-8, Cora, and I<sub>2</sub> came from theoretical calculations. On the basis of the single-crystal structure reported in this study, the lowest energies in vacuum for  $D_{4d}$ -CDMB-8, Cora, or I<sub>2</sub> and their pairwise and three-component capsule complexes were calculated via molecular mechanics (MM+) using the force field in the HyperChem 7.5 program<sup>12</sup> or by semiempirical methods (PM7) using the MOPAC software.<sup>13</sup> The resulting binding energies ( $\Delta E$ ) are given in Table 1. These values correspond to the enthalpy

Table 1. Optimized Geometries<sup>*a*</sup> of Possible Complexes among  $D_{4d}$ -CDMB-8, Cora, and I<sub>2</sub> and Their Corresponding Minimized Binding Energies ( $\Delta E$ ) as Calculated in Vacuum



"The structures shown were optimized under vacuum conditions by molecular mechanics (MM+) using the force field in Hyperchem 7.5 or by semiempirical methods (PM7) using the MOPAC software.

changes from the individual components to the indicated complexes. It was found that the three-component complex,  $((D_{4d}\text{-}CDMB\text{-}8)_3 \supset (Cora)_2) \supset I_2$ , has a much lower binding energy than the other hypothetical complexes shown in Table 1.

Solid-State <sup>13</sup>C NMR and Raman Spectroscopic Studies. Solid-state <sup>13</sup>C NMR and Raman spectroscopic studies were carried out in an effort to determine the nature of the interactions, if any, among the three-components that make up the iodine-containing capsule,  $[(((D_{4d}-CDMB-$ 

8)<sub>3</sub> $\supset$ (Cora)<sub>2</sub>·CYH) $\supset$ I<sub>2</sub>)·5CYH]. With this goal in mind, the solid-state <sup>13</sup>C NMR spectra of the crystalline I<sub>2</sub>-containing capsule were compared with that of pure  $D_{4d}$ -CDMB-8 and Cora (Figure 4a). In [((( $D_{4d}$ -CDMB-8)<sub>3</sub> $\supset$ (Cora)<sub>2</sub>·



**Figure 4.** (a) Solid <sup>13</sup>C NMR (100 MHz) spectra of the crystalline I<sub>2</sub>containing capsule,  $[(((D_{4d}-CDMB-8)_3 \supset (Cora)_2 \cdot CYH) \supset I_2) \cdot 5CYH]$ (a<sub>1</sub>), pure  $D_{4d}$ -CDMB-8 (a<sub>2</sub>), and pure Cora (a<sub>3</sub>). (b) Partial Raman spectra of I<sub>2</sub> (b<sub>1</sub>) in CYH (3.0 M), solid I<sub>2</sub> (b<sub>2</sub>), and I<sub>2</sub> in the I<sub>2</sub> capsule (b<sub>3</sub>).

CYH) $\supset$ I<sub>2</sub>)·5CYH], an upfield shift change of about -2.3 ppm is seen for the signal corresponding to the C(1) carbons on **Cora**, while a change in peak shape was noted for the signals corresponding to the carbons on  $D_{4d}$ -**CDMB-8**. These changes are considered to reflect the shielding effect of the benzene rings in  $D_{4d}$ -**CDMB-8** on the C(1) carbon atoms of **Cora** as well as the changes in the chemical environment of  $D_{4d}$ -**CDMB-8** that arise upon capsule formation.

Next, the Raman spectrum of  $I_2$  in crystalline  $[(((D_{4d}-CDMB-8)_3)(Cora)_2 \cdot CYH)] > I_2) \cdot 5CYH]$  was recorded and compared to that for solid  $I_2$  and iodine dissolved in CYH (3.0 M) (Figure 4b). Peaks at 182 and 190 cm<sup>-1</sup> are seen in the Raman spectrum of solid iodine and are ascribed to the inphase and out-of-phase stretching vibrational modes of two different  $I_2$  molecules present in the unit cell.<sup>14</sup> In contrast, a peak at 212 cm<sup>-1</sup> is seen in the Raman spectrum of the  $I_2$ containing capsule,  $[(((D_{4d}-CDMB-8)_3)(Cora)_2 \cdot CYH))]_2) \cdot$ 5CYH]. This value coincides with a peak ascribed to a stretching vibration seen in the Raman spectrum of  $I_2$  recorded in CYH. The observation of an isolated  $I_2$  stretching vibration is unusual for a solid  $I_2$  form and likely reflects the capsuleenforced absence of  $I_2-I_2$  interactions that characterize crystalline  $I_2$ .

Stability of the lodine-Containing Capsule. In the supramolecular I<sub>2</sub>-containing capsule, [(( $(D_{4d}$ -CDMB-8)<sub>3</sub> $\supset$ (Cora)<sub>2</sub>·CYH) $\supset$ I<sub>2</sub>)·5CYH], I<sub>2</sub> is surrounded by what might be viewed as being an all-hydrocarbon shell. Efforts were thus made to determine if this local environment served to stabilize the bound I2. As an initial check, single crystals of  $[(((D_{4d}\text{-CDMB-8})_3 \supset (\text{Cora})_2 \cdot CYH) \supset I_2) \cdot 5CYH]$  were kept open to the air (298 K) for 1 year. Separately, they were heated at 378 K for 2 h. In neither case was a visible change in the color of the crystals seen. Moreover, the crystalline nature of the samples was maintained as inferred from single-crystal X-ray diffraction analyses. The crystals used in these studies were also dissolved in CYH or benzene- $d_6$  and used in UV-vis and <sup>1</sup>H NMR spectroscopic studies, respectively. This allowed the composition and relative stoichiometry of the components to be further confirmed. Crystallinity was also maintained when a sample of the I2-containing capsule was heated at 418 K for 2 h, as inferred from follow-up X-ray diffraction analyses; however, in this case, small amounts of I<sub>2</sub> (ca. 5%) and CYH (ca. 10%) are lost on the basis of UV-vis and <sup>1</sup>H NMR spectroscopic analyses of solutions of the samples dissolved in CYH or benzene- $d_{6}$ , although little visible change in the sample color was observed. When the capsule crystals were held at 418 K for 36 h, roughly 20% of the initial I<sub>2</sub> was still retained (cf. Figure 5a, Supporting Information Figures S20 and S21).



Figure 5. (a) Photographs of single crystals of the I<sub>2</sub>-containing capsule,  $[(((D_{4d}-CDMB-8)_3)(Cora)_2 \cdot CYH)]_2) \cdot SCYH]$ , as prepared after exposure to air for 1 year at 298 K and upon heating to 378 or 418 K for 2 h. (b) TGA plot recorded when single crystals of  $[(((D_{4d}-CDMB-8)_3)(Cora)_2 \cdot CYH)]_2) \cdot SCYH]$  are heated under a nitrogen atmosphere (10 °C/min). (c) Photographs of single crystals of  $[(((D_{4d}-CDMB-8)_3)(Cora)_2 \cdot CYH)]_2) \cdot SCYH]$  treated with aqueous solutions of saturated NaOH (c<sub>1</sub>) or Na<sub>2</sub>S<sub>2</sub>O<sub>3</sub> (c<sub>2</sub>) for 1 week or with toluene (c<sub>3</sub>) or CH<sub>2</sub>Cl<sub>2</sub> (c<sub>4</sub>) for 5 min (3.0 mg/mL).

A TGA analysis of  $[(((D_{4d}-CDMB-8)_3))(Cora)_2)$ .  $CYH) \supset I_2) \cdot 5CYH$  (Figure 5b) revealed that the first appreciable mass loss occurs between 155 and 225 °C, an event we ascribe to the loss of CYH and I2. Further mass loss is seen between 225-300 °C and 425-550 °C. These latter processes are considered to reflect loss of Cora and the decomposition of D<sub>4d</sub>-CDMB-8, respectively. These stepwise mass losses match well what would be expected on the basis of the composition of crystalline  $[(((D_{4d}-CDMB-8)_3))(Cora)_2)]$  $CYH) \supset I_2) \cdot 5CYH$  (i.e.,  $D_{4d}$ -CDMB-8 = 66.5%, Cora = 13.3%,  $I_2 = 6.8\%$ , and CYH = 13.4% by weight). With the exception of  $I_2$  constrained within single-walled carbon nanotubes ( $I_2 @$ SWNTs),<sup>15</sup> we are unaware of any other I<sub>2</sub>-containing materials where the bound I<sub>2</sub> is retained appreciably at temperatures above 100 °C.<sup>16</sup> On this basis, we conclude that I<sub>2</sub> within the capsule,  $[(((D_{4d}-CDMB-8)_3) \subset (Cora)_2)]$ CYH) $\supset$ I<sub>2</sub>)·5CYH], is stabilized to an appreciable degree.

Further evidence of I<sub>2</sub> stabilization carne from studies where single crystals of the capsule  $[(((D_{4d}\text{-CDMB-8})_3)(\text{Cora})_2, CYH)) ]_2) \cdot 5CYH]$  were placed in saturated aqueous solutions of either NaOH or Na<sub>2</sub>S<sub>2</sub>O<sub>3</sub> and allowed to sit for 1 week. In neither case was evidence of reaction seen. We thus conclude that the all-hydrocarbon shell that surrounds the I<sub>2</sub> within the  $[(((D_{4d}\text{-CDMB-8})_3)(\text{Cora})_2, CYH)] ]_2) \cdot 5CYH]$  capsule serves to protect the entrapped iodine from the external environment. On the other hand, it is to be noted that single crystals of  $[(((D_{4d}\text{-CDMB-8})_3)(\text{Cora})_2, CYH)] ]_2) \cdot 5CYH]$ could be broken up quickly (typically within 5 min) upon treatment with organic solvents such as toluene or  $CH_2Cl_2$ (Figure 5c). Note that a number of other common apolar organic solvents were also effective at promoting disassociation (cf. Supporting Information Figure S22).

Emergent Self-Assembly under Conditions of Solid-State Mixing. The self-assembly of  $(D_{4d}$ -CDMB- $(\mathbf{S})_3 \supset (\mathbf{Cora})_2 \supset I_2$  via crystallization from CYH led us to hypothesize that self-assembly and iodine capture might be achievable by other means. As an initial test of this postulate, a powder mixture obtained by grinding D<sub>4d</sub>-CDMB-8 with Cora (3:2 molar ratio, 30 mg; powder I) was placed in a vial containing  $I_2$  vapor (assumed to be saturated in air at 298 K). Over the course of several hours, the mixture corresponding to powder I changed from white to brown (Figure 6a). The presumed time-dependent uptake of I<sub>2</sub> was followed by gravimetric analysis (Figure 6d). It was found that after 10 h the weight of the mixed solid, referred to as powder II, had increased by ca. 20%. This weight increase corresponds to the uptake of nearly 0.8 molar equiv of  $I_2$  (relative to  $D_{4d}$ -CDMB-8).

Further evidence of I<sub>2</sub> uptake came from dissolving powder II in CYH and recording the UV-vis spectrum (cf. Supporting Information Figure S24). The Raman spectrum of powder II was then recorded. Two I<sub>2</sub> signals at ca. 180 and 210 cm<sup>-1</sup> were seen (Figure 6f). These signals were assigned to stretching vibrations of loosely adhered and encapsulated I<sub>2</sub> species, respectively, leading us to suggest that there are two kinds of I<sub>2</sub> within powder II, namely, I<sub>2</sub> held in place by simple physical absorption and that entrapped within the ( $D_{4d}$ -CDMB-8)<sub>3</sub> $\supset$ (Cora)<sub>2</sub> core. Support for this conclusion comes from the finding that when analogous experiments were carried out with either  $D_{4d}$ -CDMB-8 or Cora alone (both in solid powder form) no obvious color or weight change was seen (Figure 6c,d).



**Figure 6.** I<sub>2</sub> capture and emergent self-assembly of iodine-containing solid forms from an initial solid mixture of  $D_{4d}$ -CDMB-8 and Cora (3:2 molar ratio). (a) Photographs corresponding to the presumed I<sub>2</sub> capture by a mixed powder containing  $D_{4d}$ -CDMB-8 and Cora as well as the loss of I<sub>2</sub> seen upon letting the product sit open to the air or by treatment with CYH. (b) Schematic representation of the change in structure that is thought to accompany the conversion of powder I to powder V. (c) Photographs of powders of pure  $D_{4d}$ -CDMB-8 and Cora before and after exposure to I<sub>2</sub> vapor. (d) Time-dependent capture of I<sub>2</sub> by  $D_{4d}$ -CDMB-8, Cora, and a solid-state mixture of these two hydrocarbons (powder I) as determined by means of gravimetric analysis. (e) Stability studies of powders II and IV in air (298 K) as monitored by gravimetric or UV–vis spectroscopic analyses. (f) Raman spectra of powders I, II, IV, and V.

In contrast to the high stability seen for the crystalline iodine capsule  $[(((D_{4d}$ -CDMB-8)\_3)(Cora)\_2)(CYH)]\_2)(CYH), powder II was found to release bound I2 easily. For instance, the exposure of powder II to air for 30 h caused the brown color to fade to white (giving powder III) with a nearly complete loss of I<sub>2</sub> being observed (as judged from a gravimetric analysis). This finding inspired us to explore the stability of the powder forms in the presence of CYH. To this end, powder II was exposed to CYH vapor (assumed to be saturated in air at 298 K) for 5 min. This yielded powder IV, which retained the brown color of powder II. Over time, the brown color faded to pink, giving powder V (Figure 6a), with no more color changes being observed over the course of 30 h. Quantification of the UV-vis spectrum of powder V dissolved in CYH revealed the presence of approximately 0.33 molar equiv of  $I_2$  relative to  $D_{4d}$ -CDMB-8. This ratio matches what would be expected for a material that corresponds to  $((D_{4d}$ -

**CDMB-8**)<sub>3</sub> $\supset$ (**Cora**)<sub>2</sub>) $\supset$ I<sub>2</sub> (Figure 6e). Moreover, Raman spectroscopic analyses revealed that on passing from powder **IV** to powder **V** the signal assigned to the loosely associated I<sub>2</sub> all but disappears while the feature ascribed to the bound I<sub>2</sub> remained intact (Figure 6f). Holding powder **V** at 378 K for 2 h and then at 418 K for 2 h prior to subjecting it to UV–vis analysis as above revealed that 0.1 molar equiv of I<sub>2</sub> is retained in the solid form. In fact, even holding the powder at 418 K for 24 h and then at 448 K for 3 h failed to remove all of the presumably tightly encapsulated I<sub>2</sub> molecules (cf. Supporting Information Figure S27).

Further PXRD and <sup>1</sup>H NMR spectroscopic analyses of these powders served to confirm that powders **I–III** are amorphous and contain little or no entrapped CYH. In contrast, powders **IV** and **V** proved to be microcrystalline and have structures similar to that of crystalline  $[(((D_{4d}-CDMB-8)_3))(Cora)_2)$ · CYH) $\supset I_2)$ ·SCYH], albeit with different numbers of molar equivalents of CYH within the lattice as inferred from <sup>1</sup>H NMR spectroscopic studies of samples dissolved in benzene- $d_6$  (cf. Supporting Information Figure S25). Furthermore, the conversion among powders I, II, and IV could be achieved in recurring fashion at least three times (cf. Supporting Information Figure S28). On this basis, we conclude that it is possible to access the multicomponent capsule,  $((D_{4d}-CDMB-8)_3\supset(Cora)_2)\supset I_2$ , by routes other than direct crystallization from CYH. This inference is fully consistent with the suggestion that this emergent system constitutes a thermodynamic minimum for mixtures of macrocycle  $D_{4d}^-CDMB-8$ , Cora, and I<sub>2</sub>.

lodine Capture from Aqueous Source Phases. The same solid-state 3:2 molar mixture of  $D_{4d}$ -CDMB-8 and Cora used in the above studies (powder I) also proved capable of capturing I<sub>2</sub> from aqueous source phases. For instance, when 9.0 mg of powder I was added to 1.5 mL of a solution of I<sub>2</sub> in 35 wt % NaCl (ca. 1.0 mM in NaCl, which simulates the salt concentration of seawater) or a 1:1 aqueous mixture of I<sub>2</sub> and NaI (each at 1.0 mM) and then subjected to shaking for 2 min, the color of the powder changed from white to pink (cf. Supporting Information Video). Concurrently, the color of the solutions changed from orange to colorless. UV–vis spectroscopic analyses revealed that almost all of the I<sub>2</sub> was captured from the aqueous source phases.

When the mixture (powder I) was replaced by either  $D_{4d}$ -CDMB-8 or Cora, no evidence of iodine uptake was seen, even after strong shaking followed by stirring for 24 h. It is important to appreciate that neither  $D_{4d}$ -CDMB-8 nor Cora is soluble in the aqueous medium used in these studies, and no evidence of water was found in any of the solid forms, including the pink powder obtained when the 3:2 mixture of  $D_{4d}$ -CDMB-8 and Cora (powder I) was placed in contact with aqueous I<sub>2</sub>. On this basis, we conclude that I<sub>2</sub> capture occurs in the solid state (Figure 7).

#### CONCLUSIONS

Presented here is an unusual example of a multicomponent artificial emergent self-assembly system. Specifically, a threecomponent capsule was obtained by allowing D<sub>4d</sub>-CDMB-8, Cora, and I<sub>2</sub> to crystallize from CYH. The I<sub>2</sub> constrained within the resulting capsule is "protected" by what is effectively an all-hydrocarbon  $(D_{4d}$ -CDMB-8)<sub>3</sub> $\supset$ (Cora)<sub>2</sub> shell. Iodine capture was also seen when a mixed solid, consisting of a 3:2 molar ratio of  $D_{4d}$ -CDMB-8 and Cora, was treated with  $I_2$ vapor or an aqueous iodine source. No such uptake was seen for either  $D_{4d}$ -CDMB-8 or Cora alone. The I<sub>2</sub> bound within the present self-assembled capsule is stabilized by the surrounding all-hydrocarbon environment. For instance, no appreciable reaction is seen upon exposure to base (i.e., NaOH(aq)) or reducing agents (e.g., Na<sub>2</sub>S<sub>2</sub>O<sub>3</sub>); nor are significant quantities of I<sub>2</sub> lost when subjected to heating at elevated temperature. Thus in terms of both structure and function, the self-assembled capsule system we report here differs dramatically from what would be expected on the basis of simple sum-of-the-parts considerations. As such, we believe that it provides a paradigm for the construction of new emergent multicomponent supramolecular structures that could be used inter alia for the capture and storage of small high-energy molecules or the stabilization of reactive intermediates. Consistent with this latter supposition, we have found in preliminary work that the combination of  $D_{4d}$ -**CDMB-8** and **Cora** can also capture  $Br_2$  to form a species in



Figure 7.  $I_2$  capture from aqueous source phases using a 3:2 molar mixture of solid  $D_{4d}$ -CDMB-8 and Cora (powder I). (a) Schematic representation of the presumed structural changes that occur when powder I is exposed to an aqueous  $I_2$  source. (b) Photographs of Cora ( $b_1$  or  $b_5$ ),  $D_{4d}$ -CDMB-8 ( $b_2$  or  $b_6$ ), and their solid mixture (powder I) after ( $b_4$  or  $b_8$ ) or before ( $b_3$  or  $b_7$ ) treatment with a saturated aqueous solution of  $I_2$  in 35 wt % NaCl(aq) (1.0 mM) or an aqueous mixture of  $I_2$  and NaI (1.0 mM in each). (c) UV–vis spectra of the solutions shown in b.

which the inherent reactivity of bromine is attenuated, as inferred from studies between the solid form and styrene vapor (cf. Supporting Information Figures S29 and S30). Studies of this and other emergent systems involving all-hydrocarbon building blocks are ongoing in our laboratories and will be reported in due course.

#### ASSOCIATED CONTENT

#### **Supporting Information**

Supporting Information is provided that includes experimental details, UV-vis and NMR spectroscopic analysis, computational calculations and single crystal X-ray structures with CCDC Nos. 1860000 and 2041554 which contain the supplementary crystallographic data for this paper. These materials are available free of charge via the Internet at . The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/jacs.0c11838.

General considerations, solution-phase studies, singlecrystal X-ray structural studies, self-assembly studies, theoretical calculations, thermostability studies of crystals, emergent self-assembly in the solid state, and Br<sub>2</sub> capture from water (PDF) Change in powder color (AVI) Structure  $[D_{4d}$ -CDMB-8 $\supset$ CYH·(CYH)<sub>4.5</sub>] (CIF) Structure  $[(((D_{4d}$ -CDMB-8)\_3 $\supset$ (Cora)<sub>2</sub>·CYH) $\supset$ I<sub>2</sub>)· SCYH] (CIF)

Optimized geometries by MM+ (ZIP)

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#### Notes

The authors declare no competing financial interest.

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