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Supramolecular $Ga_4L_6^{12-}$ Cage Photosensitizes 1,3-Rearrangement of Encapsulated Guest via Photoinduced Electron Transfer

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Supporting Information

ABSTRACT: The $K_{12}Ga_4L_6$ supramolecular cage is photoactive and enables an unprecedented photoreaction not observed in bulk solution. $Ga_4L_6^{12-}$ cages photosensitize the 1,3-rearrangement of encapsulated cinnamylammonium cation guests from the linear isomer to the higher energy branched isomer when irradiated with UVA light. The rearrangement requires light and guest encapsulation to occur. The $Ga_4L_6^{12-}$ cage-mediated reaction mechanism was investigated by UV/vis absorption, fluorescence, ultrafast transient absorption, and electrochemical experiments. The results support a photoinduced electron transfer mechanism for the 1,3-rearrangement, in which the $Ga_4L_6^{12-}$ cage absorbs photons and transfers an electron to the encapsulated cinnamylammonium ion, which undergoes C−N bond cleavage, followed by back electron transfer to the cage and recombination of the guest fragments to form the higher energy isomer.

Photosynthesis inspires the development of systems capable of absorbing photons, transferring the harvested energy, and storing it in chemical bonds.[1] Artificial photosynthetic systems pair light-harvesting molecules, commonly porphyrins,[2] with energy acceptors such as quinones,[3] carbon nanotubes,[4] and fullerenes[5] to investigate the intricacies of energy transfer. Less explored are photosensitizing supramolecular nanovessels (cyclodextrins,[6] cavitands,[7] tubular hosts[8]) that transfer absorbed light energy to encapsulated guest acceptors and, in rare cases, elicit chemical transformations. For example, Fujita and co-workers reported a cationic palladium $M_6L_4^{12+}$ supramolecular assembly that participates in the photooxidation of alkanes.[9] In contrast to a polycationic photoreactive cage, a polyanionic photosensitizing cage would have significantly different photophysical properties and would preferentially react with a different class of substrates. For this reason, we investigated the water-soluble, highly anionic, gallium $M_4L_6^{12-}$ supramolecular assemblies[10] that have polyaromatic bridging ligands as potential photosensitizing agents. We hypothesized that the redox-active catecholate ligands could be photoexcited and donate excited-state energy to encapsulated guest molecules to induce chemical reactivity (Figure 1). Herein, we report that $Ga_4L_6^{12-}$ (L = diaminonaphthalene biscatecholamide) **1** photosensitizes an unprecedented allylic 1,3-photorearrangement[11] of encapsulated 1-cinnamylalkylammonium ions **2** to form the thermodynamically disfavored 3-substituted ammonium ion **3**. Chemical and photophysical studies implicate a photoinduced electron transfer (PET) mechanism for this process.

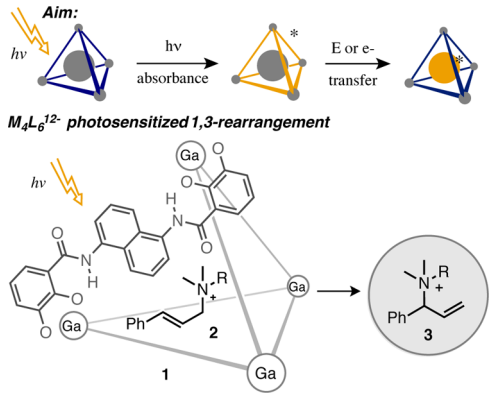
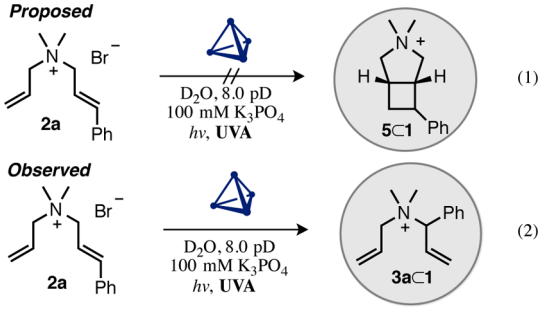


Figure 1. $K_{12}Ga_4L_6$ host **1** photosensitizes an allylic 1,3-rearrangement of encapsulated cinnamylammonium guests.

We envisioned that cationic allyldimethylcinnamylammonium ion **2a** would be strongly encapsulated[12] within **1**, and **1** could photosensitize the [2+2] cyclization of **2a** to form a bicyclic cyclobutane product (**5**, eq 1) with UVA light,



the triplet-photosensitized process that occurs in the absence of **1**.[13] Addition of **2a** (4.0 μmol, 6 mM) to a K_3PO_4-buffered (pD 8.0) aqueous solution of **1** (4.2 μmol) provides encapsulation complex **2a⊂1** (⊂ denotes encapsulation) determined by ^1H NMR spectroscopy (see SI).[14] Subsequent UVA irradiation of

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2a⊂1 (14 h, 35 °C) provides not the expected encapsulated cyclobutane complex **5⊂1** but instead a new product, assigned by ^{1}H NMR as encapsulated **3a**, resulting from allylic 1,3-rearrangement of the cinnamyl functional group (eq 2). Independent synthesis of an authentic sample of **3a** and subsequent formation of encapsulation complex **3a⊂1** confirmed that the product resulting from UVA irradiation was rearrangement product **3a**, 4 kcal/mol higher in energy than linear isomer **2a** based on DFT calculations.

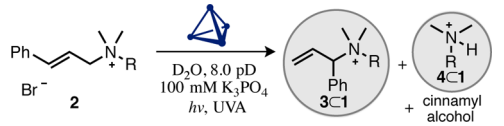
The photorearrangement can be extended to other encapsulated cinnamylammonium ions, although competitive cleavage to amines **4** is observed in some cases (see Table 1; vide infra). In the case of trimethylammonium substrate **2b**, broad resonances in the ^{1}H NMR spectrum of **2b⊂1** indicate that **2b** is in rapid equilibrium[15] between the internal encapsulation complex **2b⊂1** and an external association complex.[16] Due to evidence for rapid guest exchange, it was important to assess whether the observed 1,3-rearrangement occurred in bulk solution or within the confines of **1**'s cavity. UVA irradiation of **2b** (without **1**) in K_3PO_4-buffered D_2O solution (pD 8.0, 14 h, 30 °C) provided only starting material. However, increasing the time of irradiation to 32 h showed 9% conversion of the *trans*-**2b** isomer to *cis*-**2b**. In contrast, in the presence of **1** and UVA light, **2b** reacts completely after 14 h to form rearrangement product **3b**, trimethylamine **4b**, and cinnamyl alcohol.[17] Further evidence that formation of the 1,3-rearrangement product requires encapsulation is provided by a NEt_4^+-blocked host experiment.[18] UVA irradiation of a solution of **NEt_4⊂1** and **2b** fails to provide rearrangement product **3b** after 12 h. A similar result is observed in an attempted catalytic reaction, in which 1 equiv of **2b** and 20 mol % of **1** provide only 20 mol % of rearrangement product **3b**, suggesting that **3b⊂1** prevents catalyst turnover.

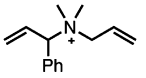
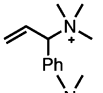
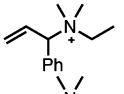
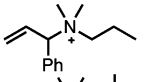
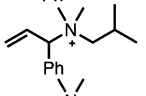
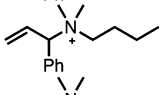
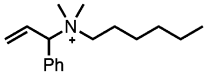
Heating **2b⊂1** at 50 °C for 12 h in the absence of light fails to provide rearrangement product **3b** or trimethylamine **4b** and cinnamyl alcohol, and only encapsulated starting material **2b⊂1** is observed via ^{1}H NMR. These experiments provide evidence that both UVA light and encapsulation in the cavity of **1** are necessary for the formation of products **3b** and **4b**. Formation of products **3b** and **4b** cannot be attributed to background thermal reactions that occur outside the confines of the supramolecular assembly.

Having established that the rearrangement is a photoinduced process mediated by assembly **1**, we carried out a further exploration of the factors that influence the rearrangement: cleavage ratio.[19] We found that *N*-alkyl substitution affects the ratio of rearrangement product **3** to tertiary amine **4** (Table 1). All substrates that undergo the rearrangement have an internal binding affinity of $\log(K_{int}) > 2$, as determined by competition studies with NMe_4^+.[14] *N*-Ethyl **2c**, *N*-propyl **2d**, and *N*-allyl **2a** are optimal substrates for the rearrangement; in these cases, **3** is formed in good yields, and tertiary amine side product is not observed by ^{1}H NMR. Substrates that are weakly encapsulated, such as *N*-hexyl substrate **2g** with $\log(K_{int}) < 2$, do not form the rearrangement product **3g**, and only encapsulated tertiary amine **4g** is observed. These results suggest that weak binding of the substrate correlates with weak binding of the fragments formed upon photoreaction (see mechanistic discussion below).

To test whether the trialkylamine products **4** were the result of a decomposition pathway of rearrangement product **3**, encapsulated rearrangement product **3b⊂1** was irradiated with UVA, but no decomposition was seen after 12 h of irradiation.

Table 1. Yields of Products Formed in the 1,3-Rearrangement of Variously Substituted Cinnamylammonium Ions Determined by ^{1}H NMR Integration



Entry	R	Rearrangement Product		3 (%)	4 (%)
1			**3a**	66	0
2	Me		**3b**	28	62
3			**3c**	82	0
4			**3d**	83	0
5			**3e**	40	51
6	*n*-Bu		**3f**	20	47
7	*n*-Hex		**3g**	0	65

This suggests that the tertiary amine **4b** is the result of a photolytic process derived from the cinnamylammonium substrate **2b** as opposed to product **3b** decomposition.

To assess whether **1** was acting simply as a reaction vessel for the photo-rearrangement or also as a photosensitizing agent transferring absorbed energy to encapsulated **2**, we conducted UV/vis absorption studies of **1** and **2b**, respectively. The UV/vis absorption spectrum of **1** in H_2O shows absorption maxima at 224 and 330 nm (Figure 2A). The molar absorptivity (ε) for **1** was determined to be $(7.6 \times 10^4) \pm 0.3\ M^{-1}\ cm^{-1}$ at 330 nm. Importantly, the molar absorption coefficient of **1** is more than 4 orders of magnitude greater than that of **2b** in the portion of the spectrum where the UVA light source emits (315−400 nm). Thus, selective excitation of **1**, and not **2b**, is possible with a UVA light source. Use of a UVA light source in the photoreactions enables the unambiguous determination that **1** is a sensitizing agent in the photo-rearrangement of **2b**. We carried out quantum yield studies of this rearrangement and found that the process occurs with a low quantum yield of $\Phi_{R\text{-}2b} = 0.010 \pm 0.007$. Quantum yields were determined using the Norrish type II cleavage of butyrophenone as an actinometer.[20]

Photosensitization of the encapsulated guest by the supramolecular host could occur by two means: energy transfer or electron transfer. For either Förster energy transfer (FRET) or Dexter energy transfer mechanisms to be operative, overlap of the cinnamylammonium cation **2b** absorption spectrum with the $Ga_4L_6^{12-}$ fluorescence emission spectrum needs to be present.[21] However, an overlay of **2b** absorption and $Ga_4L_6^{12-}$ emission shows no overlap (Figure 2A), which means that a mechanism of exciton energy transfer to **2b** is not operative in this system. This leaves a PET mechanism as the likely mode of photosensitization.

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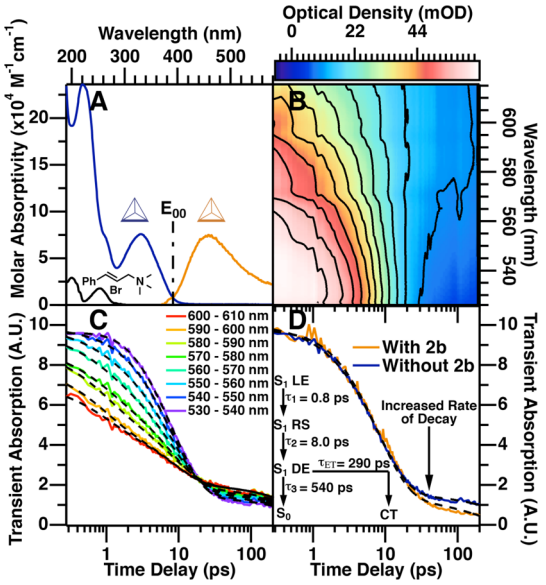


Figure 2. (A) UV/vis absorption spectra of $K_{12}Ga_4L_6$, **1** (blue) and cinnamylammonium **2b** (black) at 4×10^{-6} M in H_2O, 10 mM K_3PO_4, pH 8.0, overlaid with fluorescence emission of **1** (gold). (B) Contour plot of dispersed transient absorption of $K_{12}Ga_4L_6$ in H_2O from 200 fs to 200 ps after 400 nm actinic excitation. (C) Band integral over each 10 nm range in the transient absorption and the global exponential fits to the decay. (D) Comparison of transient absorption decay between 540 and 550 nm with and without **2b**.

Having identified **1** as the photosensitizing agent, we sought to understand the role of the excited state of **1** in activating the rearrangement of **2b** through transient absorption spectroscopy (see SI for details). Upon pulsed excitation with 400 nm light, an excited-state absorption band appears with λ_{max} = 540 nm, as seen in the contour plot of the optical density change with wavelength (Figure 2B) and in the wavelength-separated absorption plot (Figure 2C). The excited-state absorption band corresponds to a transition from the first excited singlet state (S_1) to a higher energy electronic state (S_n). The signals were analyzed in the context of first-order kinetics with three steps identified.

In the first resolvable step, the absorption blue-shifts (τ_1 = 0.8 ± 0.3 ps), corresponding to librational reorientation of the water solvent shell.[22] The next excited-state absorption decay step (τ_2 = 8.0 ± 0.8 ps) likely corresponds to exciton migration over the six ligands of tetrahedron **1**. The highly symmetric tetrahedral structure allows excitons to "hop" between the orbitals of neighboring ligand residues through Förster-type dipole coupling.[23] This interpretation is supported by the depolarized fluorescence emission (see SI for details). In the final step, the excited-state population S_1 relaxes back to the ground electronic state S_0 (τ_3 = 540 ± 40 ps). In comparison with "empty" **1**, encapsulation complex **2b⊂1** shows that interactions with **2b** only weakly perturb the electronic structure of **1**. The greatest difference is apparent in the final relaxation step out of S_1. In the presence of **2b**, the excited-state population decays with a time constant of 190 ± 60 ps, as compared to 540 ± 40 ps in the absence of **2b** (Figure 2D). Thus, we estimate that the excited-state electron transfer occurs with a time constant of 290 ± 150 ps and a quantum yield of Φ_{ET} = 0.65 ± 0.34.

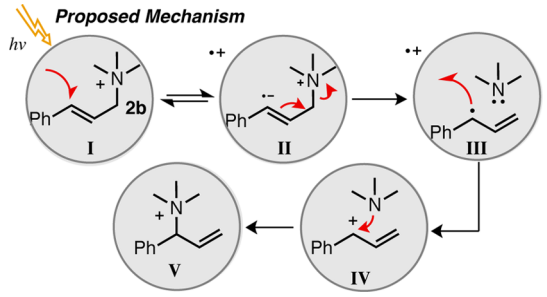
Additional evidence for the PET mechanism is provided by calculation of the Gibbs energy of photoinduced electron transfer (eq 3).[21] Gibbs energy of PET is approximated using the standard reduction potentials of donor **1** (E_D) and acceptor

$$\Delta G^\circ = E^\circ_{D^+/D} - E^\circ_{A/A^-} - E^*_D - C \quad (3)$$

2b (E_A) and the electronic excited-state energy of the donor (E^*_D). Cyclic voltammetry was used to estimate that the E_D of **1** is 0.73 V vs SHE (16.8 kcal/mol), and the E_A of **2b** is estimated at −1.69 V vs SHE (−39.6 kcal/mol, see SI for details).[24] The electronic excitation energy (E^*_D) is estimated from the $E_{0,0}$ transition at 391 nm, found at the intersection of the absorption and emission spectra of **1** (Figure 2), to be 3.17 eV, or 73.1 kcal/mol. The Coulombic term, *C*, for solvent stabilization of opposite charges in H_2O is estimated to be 0.08 kcal/mol.[21] With the above information, we find a negative free energy of −17.2 kcal/mol for the transfer of an electron from excited singlet **1** to the charge-transfer state of **2b⊂1**. The negative free energy value provides support for a PET mechanism.

We propose that photoexcited assembly **2⊂1*** acts as a PET agent in the 1,3-rearrangement mechanism. In this pathway, **1** absorbs incoming light to generate the excited charge-transfer state **2⊂1***, in which an electron has been donated to the encapsulated cinnamylammonium acceptor **2** (**I**, Scheme 1).

Scheme 1. Proposed Mechanism of $K_{12}Ga_4L_6$-Photosensitized 1,3-Shift of Cinnamylammonium Cations



Excited-state electron donation to cation **2** results in heterolytic C−N cleavage (**II**), forming a tertiary amine and a geminal radical ion pair (RIP). In this case, the RIP is the stabilized allyl radical and a ligand-based radical cation moiety incorporated into the multi-anionic cage (**III**). Back electron transfer from either the allyl radical or the tertiary amine to the ligand-based radical cation would form a stabilized allyl cation or tertiary amine radical cation and reestablish the original charge on the ligand (**IV**).[25] The encapsulated tertiary amine recombines with the allyl cation within the cavity to form the 3-substituted allyl product (**V**) or, in some cases, competitively escapes the cavity to give free amine. The cation either attacks one of the bridge ligands or reacts with H_2O to form cinnamyl alcohol.

In summary, we have found that $K_{12}Ga_4L_6$ supramolecular cages act as photosensitizers to transfer energy to encapsulated guest molecules, inducing transformations not observed in bulk solution. Encapsulation of the cinnamylammonium substrates is required for the 1,3-rearrangement to occur. Energy transfer was found to occur by a photoinduced electron transfer mechanism. Photosensitization and 1,3-rearrangement via PET are new modes of action enabled by the cavity of the $Ga_4L_6^{12-}$ cage.

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■ ASSOCIATED CONTENT

Supporting Information

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Experimental details and characterization data (PDF)

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Notes

The authors declare no competing financial interest.

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(24) Irreversible electrochemical cycles are observed after multiple scans for **1**, dependent on scan rate, and after a single scan for **2b**.

(25) We propose that the cinnamyl radical is the source of BET for several reasons. We observe tertiary amine **4**. We observe < 5% product where the cinnamyl has reacted with one cage ligand. We do not observe intramolecular cyclization onto a pendant alkene radical cation trap. [As an example, see: Newcomb, M.; Deeb, T. M. *J. Am. Chem. Soc.* **1987**, *109*, 3163.] We do not observe hemiaminal or aldehyde products that would result from amine radical cation decomposition. [As an example, see: Shono, T.; et al. *J. Am. Chem. Soc.* **1982**, *104*, 5753.] Although we cannot rule out the formation of an amine radical cation, at this time we have not found evidence to support its formation.

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