Received: 13 April 2017 | Revised: 17 May 2017 | Accepted: 18 May 2017

DOI: 10.1002/poc.3728

SPECIAL ISSUE ARTICLE

WILEY Journal of Physical Organic Chemistry

Container Chemistry: Manipulating excited state behavior of organic guests within cavitands that form capsules in water

Pradeepkumar Jagadesan | Shampa R. Samanta | Rajib Choudhury | Vaidhyanathan Ramamurthy

Department of Chemistry, University of Miami, Coral Gables, FL, USA

Correspondence
Vaidhyanathan Ramamurthy, Department of Chemistry, University of Miami, Coral Gables, FL 33146, USA.
Email: murthy1@miami.edu

Funding information
Division of Chemistry, Grant/Award Number: CHE-1411458; National Science Foundation, Grant/Award Number: CHE-1411458

Abstract

Two new cavitands substituted with acid and alcohol groups (tetra-acid tetra-alcohol [TATA] and inverted TATA [iTATA]) bearing the same molecular skeleton as octa acid (OA) have been synthesized and their use as photochemical reaction containers explored. Isothermal calorimetric titration experiments suggest that the inclusion of organic molecules within these cavitands is driven both by favorable ΔH and ΔS and the substituents at the portals have little role to play. Comparison of the 2 new cavitands with the previous results on OA reveals that the presence of benzoate anion at the top periphery is essential for the cavitand to be a triplet sensitizer. Polarity within the water-soluble capsules, resulting from TATA and iTATA, was found to be close to that of ethylacetate and hydrocarbons, similar to that of OA. Photophysical studies with anthracene and camphorthione as guests disclose that the capsules made of 2 molecules of cavitands do not disassemble in the time scale of the excited states of the above guests (S_1 in the case of anthracene and T_1 in the case of camphorthione). Capsules ability to confine guests and the resulting photochemical intermediates has been tested by examining the photochemistry of 1-phenyl-3-*para*-tolyl-2-propanone. The radicals resulting from the Norrish type 1 cleavage of 1-phenyl-3-*para*-tolyl-2-propanone did not escape the cage and gave products, resulting from 100% cage effect. Availability of TATA and iTATA along with already reported similar cavitands expands the list of water-soluble capsule forming cavitands that could be used as molecular containers.

KEYWORDS

cage effect, capsules, excimer, photochemistry, photophysics, water-soluble cavitands

1 | INTRODUCTION

Supramolecular cavitands such as cyclodextrins, calixarenes, and cucurbiturils are important class of molecular architectures that have been investigated, extensively, in the past few decades.[1] Recently, tailor-made deep-cavity cavitands synthesized from basic calixarene and resorcinarene skeletons as well as from inorganic strutures have emerged as promising confining environment wherein organic reactions could be manipulated.[2,1d] Moreover, functionalization of the above deep-cavity cavitands with hydrophilic groups such as –COOH, NH_2, and SO_3H renders them water-soluble allowing entry into green and sustainable chemistry. Hydrophobic nature of the interior of the cavitands enables them to strongly bind water-insoluble organic guests in aqueous media.[3] In this context, we have been exploring a water-soluble (pH = 8.7) deep-cavity cavitand known as octa acid (OA; Figure 1) originally synthesized by Gibb CLD and Gibb BC.[4] The 8 –COOH groups present at the top and bottom

This article is dedicated to Prof. W. Adam, an outstanding scientist, an exceptional human being and a role-model for younger generation

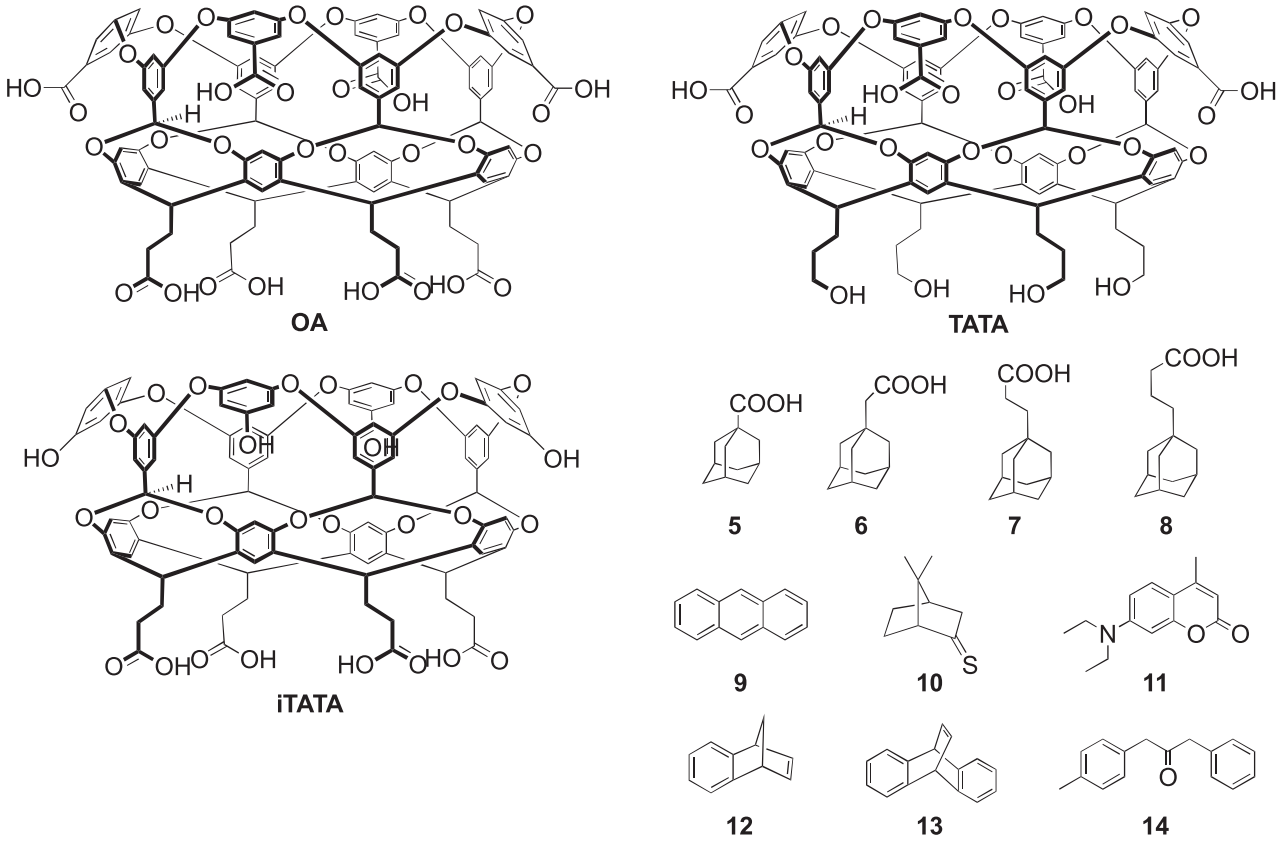


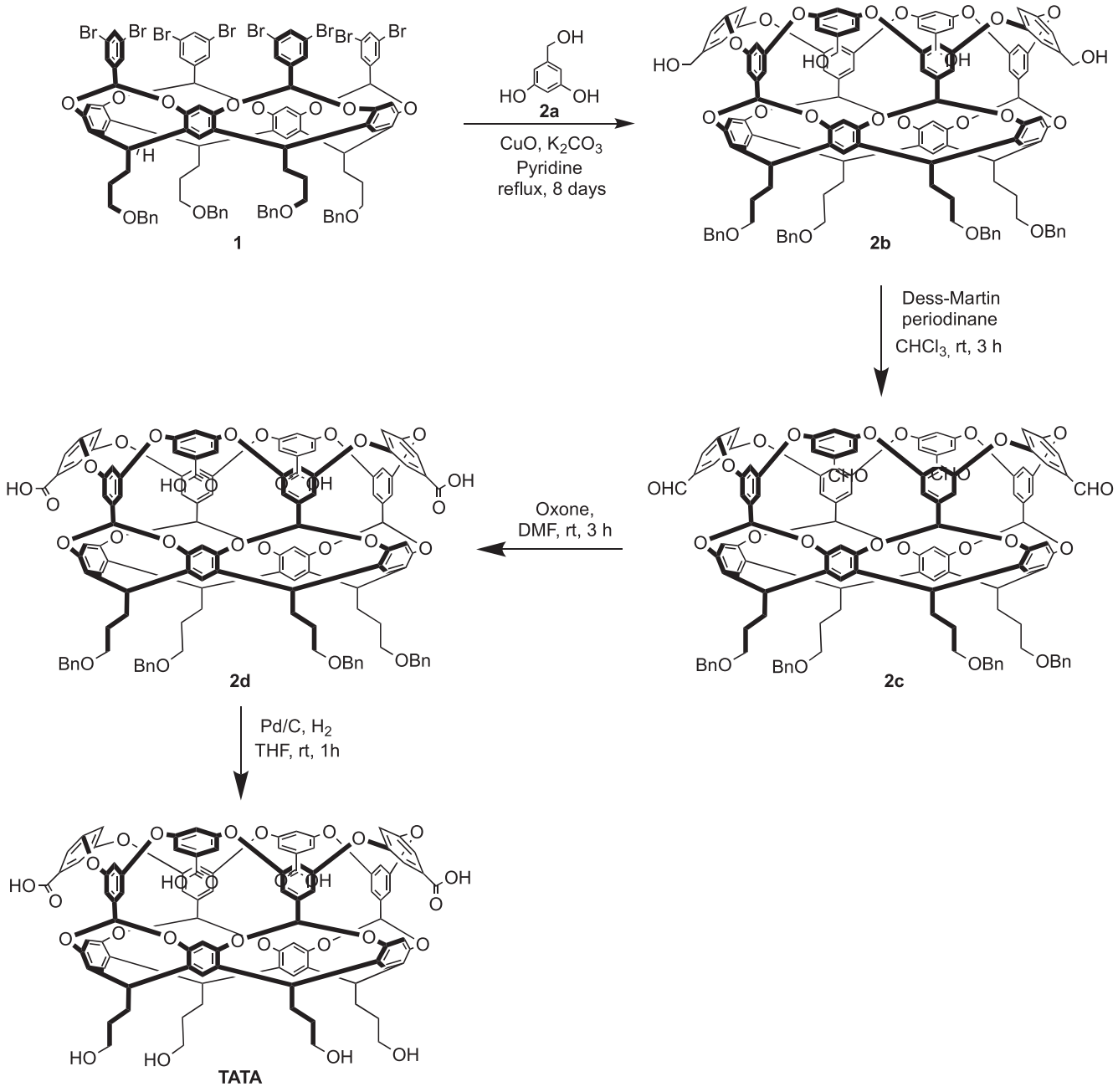
FIGURE 1 Structures of deep-cavity cavitands OA, TATA, iTATA, and guest molecules investigated

portals of the cavitand (total 16 per capsule) facilitate OA to dissolve in water under basic conditions (pH ~ 8.7). Compared to other recently reported cavitands,[1d] OA is unique as it prefers to self-assemble in presence of a guest molecule to form a capsule. During the last decade we have exploited OA capsule to modify and control the excited state chemistry and physics of organic molecules.[5] Prompted by the success with OA we have modified it with amino groups (octaamine, OAm) making it soluble under acidic conditions.[6,7] In addition, to perform studies on silica, gold nanoparticles, and TiO_2 surfaces and on the interlayers of clay and Zr phosphates, we have modified the functional groups on OA.[8]

One of the disadvantages of OA is that it allows it to be used as a reaction medium only under basic aqueous conditions. To expand the utility of this type of cavitand, we have been involved in synthesizing cavitands with OA skeleton but with different functionalities at the periphery. In this article we report the synthesis of 2 new water-soluble deep-cavity cavitands, their complexation properties, and their ability to modulate the photochemical and photophysical properties of the incarcerated guest molecules. Structures of the 2 cavitands that contain 4 COOH and 4 OH groups are provided in Figure 1. These are termed as tetra-acid tetra-alcohol (TATA, benzoic acid units at the top and propanol units at the bottom) and *inverted* tetra-acid tetra-alcohol (iTATA, phenol units at the top and propanoic acid units at the bottom). Synthetic procedures, ^{1}H NMR spectral details, binding constants with various organic guests, and photophysics and photochemistry of select guest molecules within these cavitands are discussed here. We are delighted that TATA and iTATA have nearly the same inner cavity properties as OA and are potentially as useful as OA. Although these also, like OA, are soluble only under basic conditions (sodium hydroxide) in water, they offer an opportunity to test the role of OH instead if COOH on the complexation and excited state properties of the cavitands. Interestingly, replacement of benzoic acid group by phenol at the top portal has eliminated its ability to undergo intersystem crossing upon excitation and thus do not act as triplet sensitizer, a property displayed by OA. Availability of TATA and iTATA along with already reported similar cavitands have expanded the list of water-soluble capsule forming cavitands that could be used as molecular containers. Figure 1 lists the structure of the hosts and the guests investigated in this study.

2 | RESULTS AND DISCUSSION

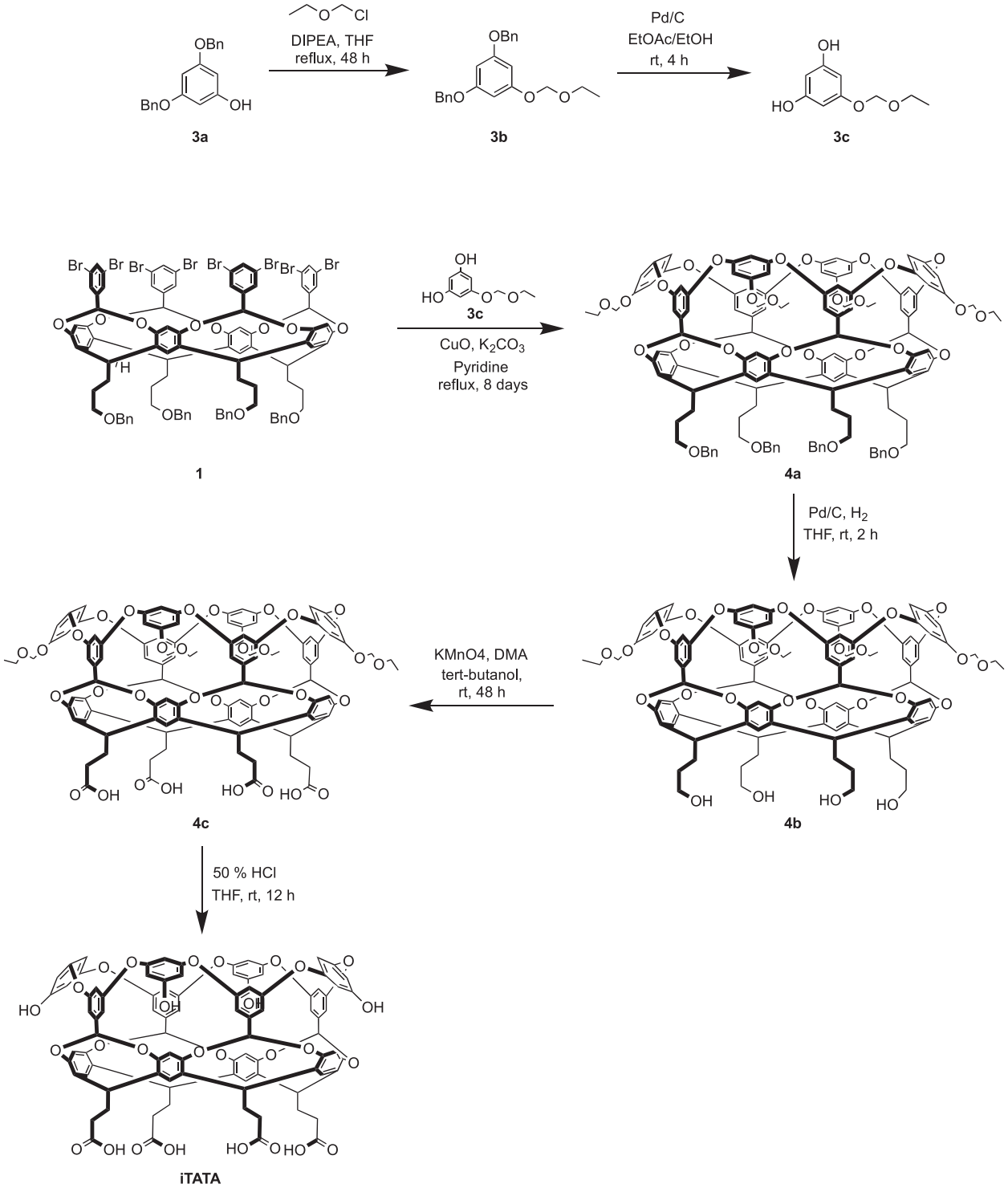
Synthetic scheme adopted to prepare TATA and iTATA are shown in Schemes 1 and 2. Detailed procedure and spectral data are included in Supporting Information. The precursor



SCHEME 1 Schematic representation of synthesis of TATA

1, **2a**, and **3a** were synthesized by following the reported procedures.[9] Oxidation of **2b** to **2d** was performed in 2 steps via Dess-Martin periodinane and oxone-mediated conditions,[10] respectively, to avoid the oxidation of bottom benzyl ether units. Gentle purging of H_2 gas to a solution of **2d** in THF in presence of Pd/C afforded TATA. Compound **3c** was prepared in 45% yield in 2 steps by reacting chloromethyl ethyl ether with **3a** in presence of DIPEA/THF to yield 75% of **3b** followed by the deprotection of benzyl units. The one-pot Ullman coupling reaction of **1** with **3c** in presence of CuO/K_2CO_3 in pyridine gave **4a** in 37% yield. Compound **4a** was selectively deprotected at the bottom part by purging a solution of **4a** in THF with H_2 gas in presence of Pd/C to obtain **4b** in 88% yield, which was further oxidized with $KMnO_4$ to give **4c** in 47% yield. Finally, stirring a solution of **4c** in THF in presence of 50% HCl at room temperature for 12 hours yielded iTATA in 97% yield. The structures of TATA, iTATA, and their precursors were characterized by ^1H, ^{13}C NMR, and ESI-MS (for spectral details and spectra, see Figures S2-S12).

The ^1H NMR spectra of iTATA in DMSO-d_6 and 10mM $NaOD/D_2O$ solution are displayed in Figure 2. On the basis of 2D COSY and NOESY experiments the chemical shifts corresponding to various protons in iTATA were assigned (Figures S8-S11). As seen in Figure 2, in 10mM $NaOD/D_2O$ solution chemical shifts due to H_a and H_d of



SCHEME 2 Schematic representation of synthesis of iTATA

iTATA were upfield shifted compared to that in DMSO-d_6. Such upfield shift of the protons is most likely a result of increased electron density at the top portal because of the delocalization of electrons of phenolate moieties. Moreover, peaks corresponding to the remaining protons on the cavitand wall (H_b, H_c, H_g, and H_h) did not shift significantly. Unlike iTATA discussed above the ^{1}H NMR spectrum of 1mM solution of TATA in 10mM NaOD/D_2O consisted of broad peaks most likely because of aggregation (Figures 2D and S12). Decreasing the concentration from 1mM to 0.1mM improved the resolution of the proton peaks, which is consistent with the above suggestion. However, the spectrum never displayed sharp signals, suggesting that TATA has a tendency to aggregate in water. Attempts to obtain a NOESY or COSY spectra with broad signals were not successful. Nevertheless, similarity in the

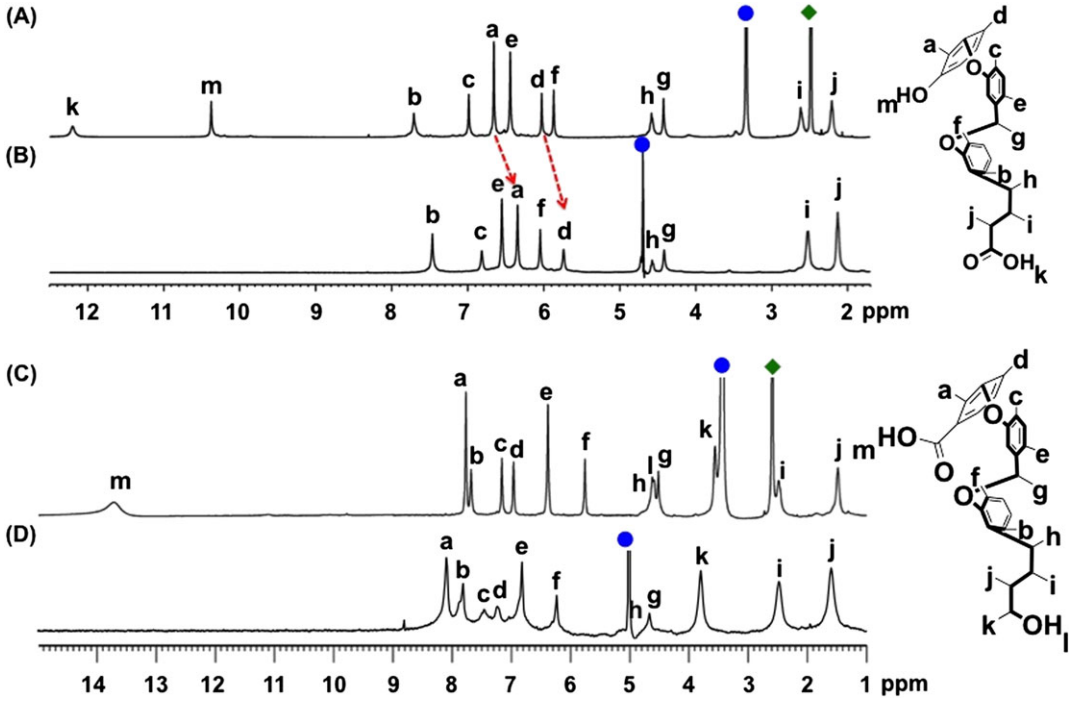


FIGURE 2 The ^{1}H NMR (500 MHz) spectra of iTATA in (A) DMSO-d_6 and (B) 10mM NaOD/D_2O and TATA in (C) DMSO-d_6 and (D) 1mM NaOD/D_2O. ● and ◆ represent residual proton resonances of water and DMSO-d_6, respectively

chemical shifts of TATA in both DMSO-d_6 (Figure S2) and 10mM NaOD/D_2O solution (Figure 3C,D) helped us assign the peaks.

Complexation abilities of iTATA and TATA with guests **5** to **8** were investigated by ^{1}H NMR spectroscopy and isothermal titration calorimetry and with guests **9** to **14** by ^{1}H NMR

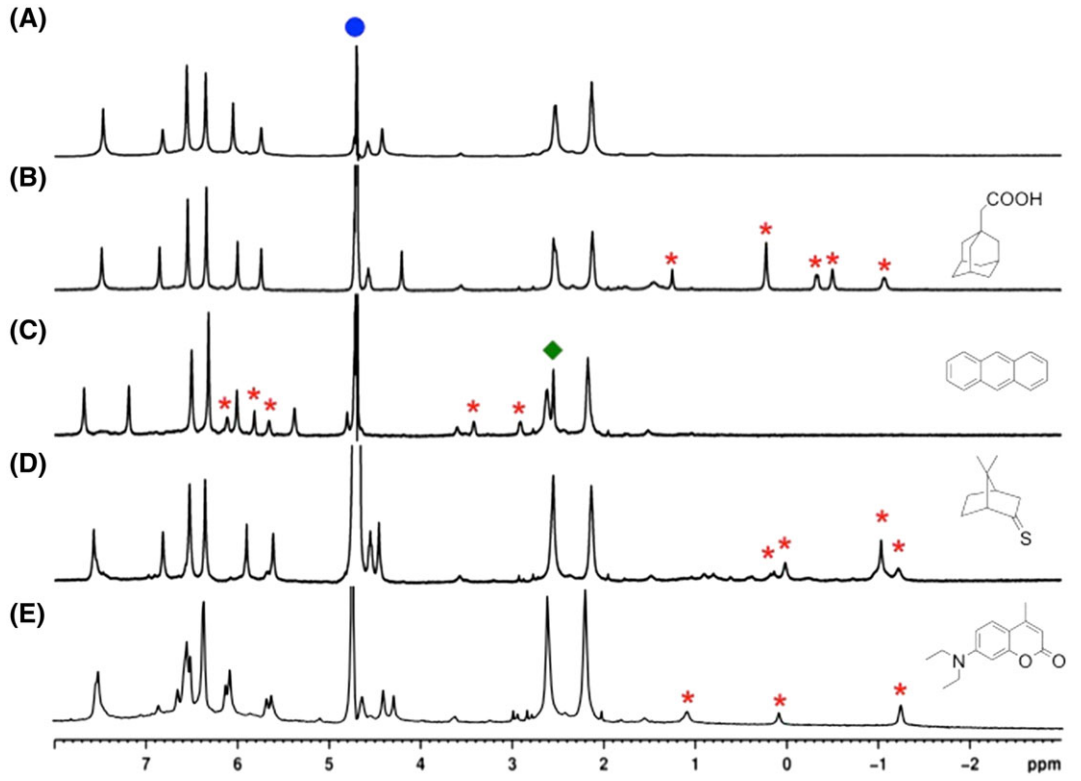


FIGURE 3 The ^{1}H NMR (500 MHz, 10mM NaOD/D_2O) spectra of (A) iTATA, (B) **6**@iTATA, (C) $\mathbf{9}_2$@$iTATA_2$, (D) $\mathbf{10}_2$@$iTATA_2$, and (E) **11**@$iTATA_2$. ✱, ●, and ◆ represent iTATA incarcerated guests proton peaks, residual proton resonances of water, and DMSO-d_6, respectively

spectroscopy. The former group of guests was used to probe the factor(s) that control the binding while the latter was used to explore the use of iTATA and TATA as reaction media. The 1:1 stoichiometric complexes of **6** with iTATA and TATA were prepared by mixing the host and the guest in 1:1 molar ratio in basic aqueous solution. Appearance of large upfield shifted NMR signals (for ^{1}H NMR of **6** see Figures 3B and 4B) of the adamantyl protons of **6** confirmed its inclusion within iTATA and TATA (Figure 3B).[11] The diffusion constants estimated for free iTATA and **6**@iTATA complex were 1.62×10^{-6} and 1.67×10^{-6} cm^2 s^{-1} (Figures S13 and S14), respectively, confirmed the formation of 1:1 complex. A lower diffusion constant value of 1.1×10^{-6} cm^2 s^{-1} (Figure S15) determined for a 0.5mM solution of TATA reflects its aggregation behavior. A rise in the diffusion constant value to 1.58×10^{-6} cm^2 s^{-1} (Figure S16) upon the addition of **6** confirmed the formation of **6**@TATA 1:1 complex. Moreover, the stoichiometry of the complexes obtained from isothermal titration calorimetry (Table 1) supported this conclusion.

The binding constants (K_a) determined for **5**-**8**@iTATA and **5**-**8**@TATA complexes are in the range of 10^6M^{-1}, slightly lower than that obtained for **5** to **8** with OA (Table 1).[3b] The thermodynamic parameter ΔH obtained for OA, iTATA, and TATA were in the similar range. As shown in Table 1, a large negative enthalpy change (ΔH) was associated with the complexation of host with all 4 guest molecules. This suggests that the complexation process is favored by enthalpy. Most likely, van der Walls interaction between the guest and interior walls of the capsule favors the complexation.[12] On the contrary, the overall entropy change (ΔS) associated with the complexation was slightly positive. This unexpected observation suggests that although host-guest complexation would be expected to reduce the translational and rotational degrees of freedom of the interacting partners (host and guest), resulting in a negative change of entropy, the release of large number of cavity confined water molecules to the bulk (desolvation) wins the competition, resulting in an overall entropy gain. On the basis of the calorimetric data we conclude that binding of guests within the hosts' cavity most likely is driven by both enthalpy, arising from strong van der Waals interactions between the guest and internal walls of the cavity and favorable desolvation entropy. The ΔS values are slightly more positive in the case of OA in comparison to TATA and iTATA. Complexation of guests within OA, TATA, and iTATA is both enthalpically and entropically favored. Before complexation both host and guest molecules are solvated, and the solvent molecules around them are highly ordered. During complexation, solvation shells of guest and host undergo reorganization, resulting in freeing some solvent molecules to the bulk. This process leads to an overall entropy gain. Data in Table 1 show that origin of higher binding constants for OA is due to more positive entropy change. We believe OA bearing 8 ionizable acid groups is better solvated than TATA and iTATA. Complexation, resulting in the release of these tightly solvated water molecules, leads to a gain in entropy. Among the 3 hosts OA being better solvated and upon

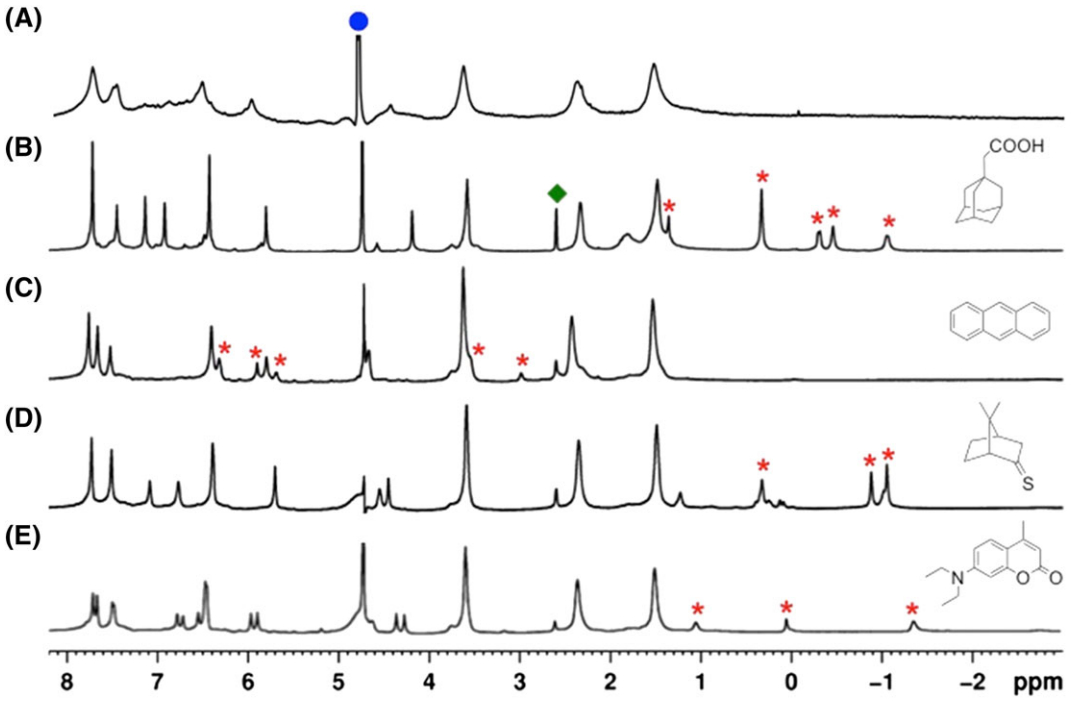


FIGURE 4 The ^{1}H NMR (500 MHz, 10mM NaOD/D_2O) spectra of (A) TATA, (B) **6**@TATA, (C) $\mathbf{9}_2$@$(TATA)_2$, (D) $\mathbf{10}_2$@$TATA_2$, and (E) **11**@$TATA_2$. ✱, •, and ◆ represent TATA incarcerated guests proton peaks, residual proton resonances of water, and DMSO-d_6, respectively

TABLE 1 Binding constant (K_a) and relevant thermodynamic parameters for complexation of guests with OA, TATA, and iTATA at 25°C

Guest	Host	K_a ($\times 10^6 M^{-1}$)[a]	ΔG[b] kcal/mol	ΔH[c] kcal/mol	$T\Delta S$[d] kcal/mol	Stoichiometry
5	OA	2.2 (± 0.1)	−8.7 ± 0.03	−7.6 ± 0.01	1.09 ± 0.04	0.93 ± 0.005
	TATA	0.9 (± 0.02)	−8.2 ± 0.01	−7.4 ± 0.04	0.78 ± 0.05	0.85 ± 0.007
	iTATA	1.3 (± 0.1)	−8.4 ± 0.04	−7.8 ± 0.00	0.58 ± 0.05	0.93 ± 0.02
6	OA	4.0 (± 0.3)	−9.0 ± 0.04	−7.6 ± 0.03	1.43 ± 0.05	0.90 ± 0.0
	TATA	1.1 (± 0.08)	−8.3 ± 0.04	−7.6 ± 0.10	0.70 ± 0.02	0.90 ± 0.005
	iTATA	2.2 (± 0.2)	−8.7 ± 0.07	−7.6 ± 0.05	1.09 ± 0.1	0.92 ± 0.05
7	OA	7.6 (± 0.2)	−9.4 ± 0.02	−8.5 ± 0.05	0.90 ± 0.07	0.91 ± 0.01
	TATA	1.2 (± 0.06)	−8.3 ± 0.03	−7.9 ± 0.20	0.40 ± 0.02	0.91 ± 0.01
	iTATA	2.5 (± 0.05)	−8.8 ± 0.01	−8.7 ± 0.04	0.04 ± 0.004	0.96 ± 0.02
8	OA	9.4 (± 0.05)	−9.6 ± 0.09	−8.7 ± 0.05	0.83 ± 0.04	0.90 ± 0.01
	TATA	1.1 (± 0.04)	−8.3 ± 0.02	−8.0 ± 0.05	0.32 ± 0.04	0.94 ± 0.02
	iTATA	2.3 (± 0.05)	−8.7 ± 0.01	−9.1 ± 0.03	0.40 ± 0.02	1.01 ± 0.005

[a]Mean values measured from at least 3 ITC experiments at 25°C in 10mM NaOH. Standard deviations are given in parentheses.

[b]Gibbs free energy values calculated from K_a values.

[c]Enthalpy values measured by ITC.

[d]Entropic contributions to ΔG calculated from K_a and ΔH values.

complexation, it would be expected to release more number of solvent molecules leading to more favorable entropy gain in comparison to TATA and iTATA. Unlike **5** to **8** that contain hydrophilic head group and hydrophobic body, more hydrophobic guests **9** to **11** without hydrophilic head group formed 1:2 or 2:2 (guest to host) complexes with iTATA and TATA (Figures 3C-E and 4C-E).[11a]

Earlier, on the basis of information inferred from the use of fluorescence probes, we concluded that the interior of OA capsule has a polarity close to that of benzene.[13] To assess whether the change of substituent from COO^- (COOH in basic media) to O^- (OH in basic media) altered the internal polarity, we recorded fluorescence of the polarity probe coumarin-1 (**11**) included within iTATA and TATA. It is known that the emission maximum, fluorescent quantum yield, and lifetime of **11** depend on the polarity of the environment in which it is present.[14] The 1:2 capsular complexes between **11** and iTATA (**11**@$iTATA_2$) and **11** and TATA (**11**@$iTATA_2$) were prepared by mixing a solution of 1mM iTATA or TATA and 0.5mM **11** in 10mM NaOD/D_2O. Appearance of large upfield shifted aliphatic proton peaks of **11** (1 to −1.3 ppm) and asymmetrical splitting pattern of the aromatic proton peaks of iTATA along with the disappearance of signals due to free iTATA ensured the encapsulation of **11** inside iTATA capsule (Figure 3E). Similar spectral observation confirmed the formation of **11**@$TATA_2$ complex (Figure 4E). Fluorescence emission spectrum of **11**@$(iTATA)_2$ showed an intense band (380-520 nm, Figure 5A)

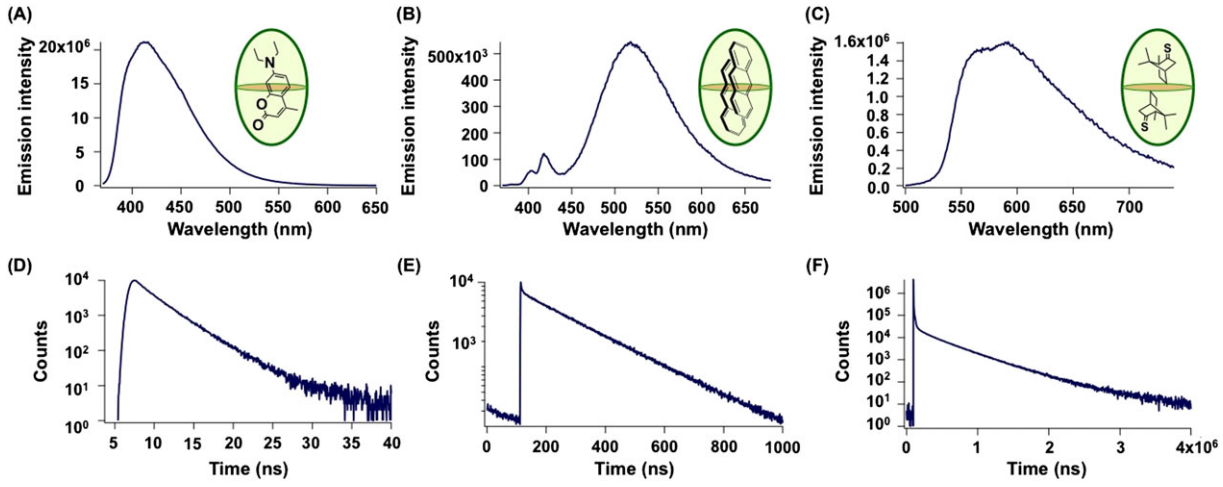


FIGURE 5 Emission spectra of (A) **11**@$(iTATA)_2$, (B) $(\mathbf{9})_2$@$(iTATA)_2$, (C) $(\mathbf{10})_2$@$(iTATA)_2$, and fluorescence lifetime decay spectra of (D) **11**@$(iTATA)_2$, (E) $(\mathbf{9})_2$@$(iTATA)_2$, and (F) $(\mathbf{10})_2$@$(iTATA)_2$. [iTATA] = 50μM in 10mM NaOD/D_2O, [**9**] = 50μM (λ_{ex} = 350 nm), [**10**] = 50μM (λ_{ex} = 254 nm), and [**11**] = 25μM (λ_{ex} = 350 nm)

with a maximum at 413 nm, suggesting the polarity of the iTATA interior is slightly lower than ethylacetate (ethylacetate, 416 nm; cyclohexane, 395 nm; and acetonitrile, 430 nm).[14] Similar to the iTATA complex, **11**@$(TATA)_2$ showed an intense emission (slightly narrower band between 380 and 500 nm and maximum at 413 nm) (Figure 6A). Thus, all 3 hosts, OA, TATA, and iTATA, possess similar internal polarity.

To ascertain the value of iTATA and TATA as reaction vessels, we probed these with a few well-established systems that we have already examined within OA. These included (a) monitoring the emission from anthracene (**9**),[15] (b) recording the phosphorescence from camphorthione (**10**),[16] (c) performing spin-dependent excited state reactions of bicyclic systems **12** and **13**,[17] and (d) measuring the cage effect during the photoreaction of dibenzyl ketone **14**.[18]

Anthracene does not show any excimer emission in solution[19] but can be forced to self-assemble to display excimer emission within the confined capsule of OA.[15] Anthracene that is not water-soluble becomes solubilized in presence of iTATA and TATA. Inclusion of 2 molecules of anthracene within iTATA and TATA capsules was confirmed by the appearance of 5 characteristic[15] upfield shifted ^{1}H signals due to $\mathbf{9}_2$@$iTATA_2$ (Figure 3C). The ^{1}H NMR spectrum resembles very much like that of $\mathbf{9}_2$@OA_2 that already has been established to form a 2:2 complex. Similar spectrum obtained for $\mathbf{9}_2$@$TATA_2$ (Figure 4C) confirmed the inclusion of anthracene within TATA. As shown in Figures 5B and 6B upon excitation of the 2:2 complexes of anthracene and iTATA, and TATA a broad emission band (450-620 nm) was obtained, and the emissive species was found to have a long lifetime (236 ns; Figures 5E and 6E), a value close to that of $\mathbf{9}_2$@OA_2 (263 ns).[15] The spectral region and nature and lifetime of the emission are consistent with its assignment to be from an excimeric state. Thus, iTATA and TATA similar to OA is able to force 2 molecules to associate in the excited state within the capsule and emit rather than dimerize.

Camphorthione (**10**) in spite of having a reasonably high-spin forbidden radiative rate constant is well known not to emit phosphorescence at room temperature in solution. The triplet state is efficiently quenched by oxygen and by the ground-state thione (self-quenching).[20] We believed that given the high radiative rate constant once the 2 quenching processes are suppressed it should be possible to record phosphorescence at room temperature in solution. If that happens camphorthione would be one of a few compounds that show phosphorescence at room temperature in solution. We have established previously that by encapsulating camphorthione within OA capsule the 2 processes that inhibit phosphorescence could be suppressed.[16] Wishing to test whether iTATA and TATA could also favor phosphorescence from camphorthione, we prepared 2:2 complexes of camphorthione with iTATA, and TATA (for ^{1}H NMR, see Figures 3D and 4D).[16,21] The emission spectrum of $\mathbf{10}_2$@$iTATA_2$ and $\mathbf{10}_2$@$TATA_2$ revealed an intense phosphorescence band (Figures 5C and 6C) with a lifetime of 69 and 53 μs, respectively (Figures 5F and 6F). These clearly show that iTATA and TATA capsules do not disassemble in the time scale of the triplet lifetime of camphorthione (~50-70 μs) to permit the diffusion of oxygen within the capsule. The above results relating to the excited state photophysics of anthracene and camphorthione lead us to conclude that irrespective of the functional groups present on the top portal of the deep-cavity cavitand the inherent properties of the capsule in water are similar to that of OA.

We have previously established that OA upon direct excitation can triplet sensitize the photoreactions of included guests such as the bicyclic systems **12** and **13**.[17] This suggested to us that in the excited state the host OA can

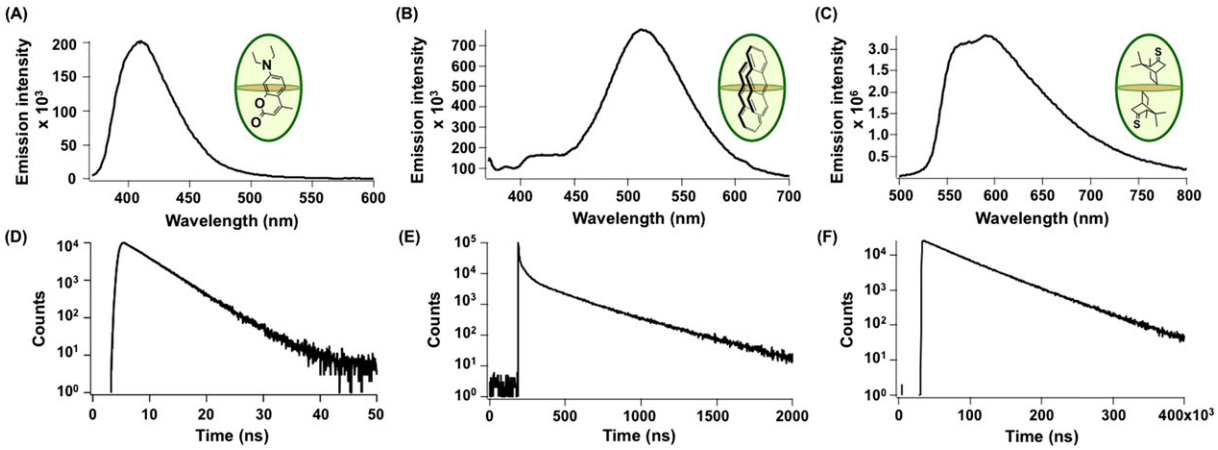
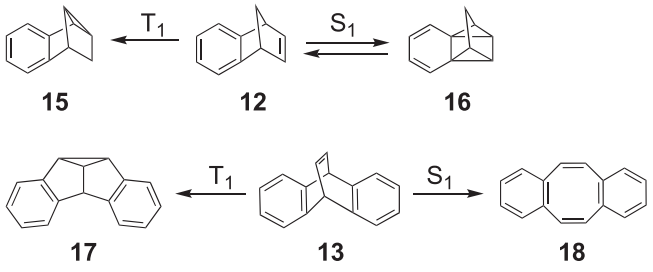


FIGURE 6 Emission spectra of (A) **11**@$(TATA)_2$, (B) $(\mathbf{9})_2$@$(TATA)_2$, (C) $(\mathbf{10})_2$@$(TATA)_2$, and fluorescence lifetime decay spectra of (D) (**11**)@$(TATA)_2$, (E) $(\mathbf{9})_2$@$(TATA)_2$, and (F) $(\mathbf{10})_2$@$(TATA)_2$. [TATA] = 50μM in 10mM NaOD/D_2O, [**9**] = 50μM (λ_{ex} = 350 nm), [**10**] = 50μM (λ_{ex} = 254 nm), and [**11**] = 25μM (λ_{ex} = 350 nm)

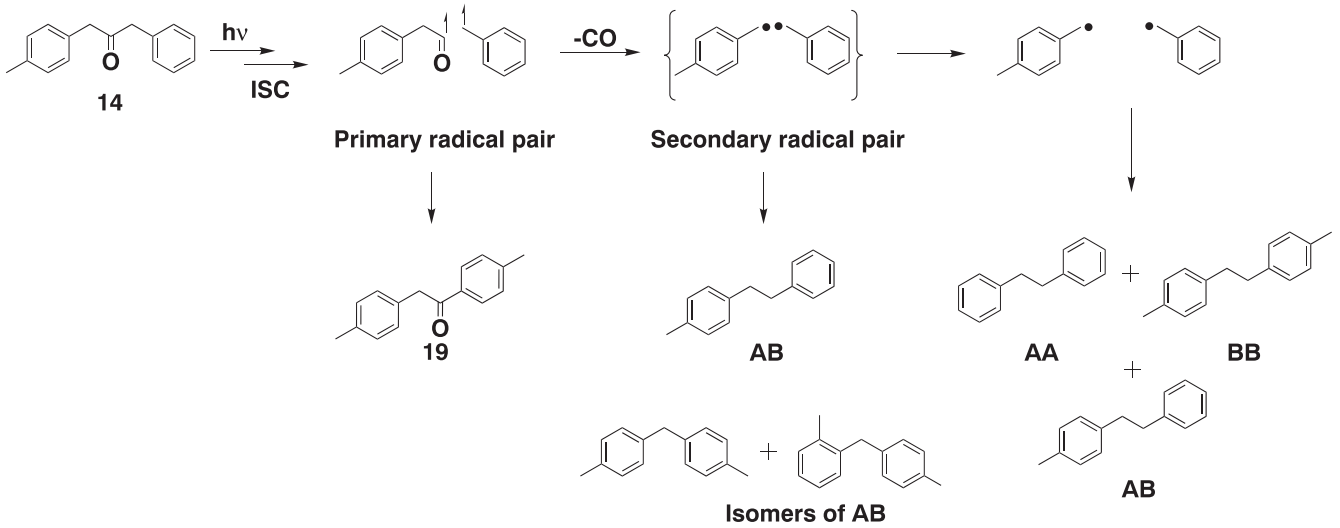
efficiently intersystem cross from S_1 to T_1 and thus participate in the photoreactions of the included guests. Thus, OA unlike cyclodextrins and cucurbiturils is not an inert photochemical reaction container.[22] We speculated that the sensitizer part of OA is in fact the benzoate ion present at the top periphery. The TATA and iTATA provided an opportunity to test this hypothesis. Between the 2, the above speculation suggests that TATA with benzoate ion should act as a triplet sensitizer and iTATA with phenolate ion should not. With this proviso we examined the photochemistry of **12** and **13** included within TATA and iTATA.

It is well known that **12** and **13** give different products from S_1 and T_1. (Scheme 3).[23] When these molecules were included within OA and irradiated in the region where OA absorbs (250-320 nm), only the triplet products were obtained. Encapsulation of guests **12** and **13** within TATA and iTATA resulted in the formation of $\mathbf{12}_2$@iTATA$_2$, $\mathbf{12}_2$@TATA$_2$, **13**@iTATA$_2$, and **13**@TATA$_2$ as confirmed from their ^{1}H NMR spectra (Figures S17-S20). Irradiations were carried with UV-light ($\lambda > 300$ nm) and progress of the reaction monitored by recording ^{1}H NMR spectra (Figures S21-S24), GC, and GC-MS. Conversion of $\mathbf{12}_2$@TATA$_2$ to $\mathbf{15}_2$@(TATA)$_2$ and **13**@(TATA)$_2$ to **17**@(TATA)$_2$ occurred within an hour, similar to the case of OA. On the other hand, irradiation of $\mathbf{12}_2$@iTATA$_2$ and **13**@(iTATA)$_2$ did not yield any products even after a day. This confirmed that for triplet sensitization benzoate moiety is essential. Thus, TATA similar to OA is an active reaction media while iTATA is an inert one. Given that all 3 have similar internal features and complexation abilities we suggest that one should use iTATA if an inert reaction container is desired.



SCHEME 3 Photochemistry of **12** and **13** in solution. Note the reactants **12** and **13** give different products in excited singlet and triplet states

Studies above have established that both TATA and iTATA, similar to OA, form tight capsules and they do not disassemble-assemble in the microsecond time scale. Confinement favored excimer formation in the case of anthracene. Lack of disassembly-assembly in microsecond time scale inhibited quenching by oxygen in the case of camphorthione. The same factors in principle would be expected to influence photoreactions that involve fragmentation of a reactant. In solution the fragments (eg, radicals) resulting from a fragmentation reaction (eg, Norrish type 1 reaction of a ketone) would be free to diffuse and yield products on the basis of statistical recombination of fragments. However, when a reactant molecule confined within a capsule is fragmented, the fragments are likely to yield products different from that in solution. The extent of confinement in various supramolecular assemblies has been measured by using 1-phenyl-3-*para*-tolyl-2-propanone **14** as a photochemical probe.[24] 1-Phenyl-3-*para*-tolyl-2-propanone **14** upon excitation undergoes Norrish type 1 reaction to yield 2 free radicals through primary and secondary radical pairs as illustrated in Scheme 4.[25] In isotropic solution one of the primary radical pair $Ar^{\circ}CH_2CO$ undergoes decarbonylation to give the secondary 4-methylbenzyl and benzyl radical pair. These combine in a statistical ratio to give 1:2:1 mixture of AA, AB, and BB (Scheme 4). However, when the primary and secondary



SCHEME 4 Norrish type 1 reaction of **14**. Note the involvement of primary and secondary radical pairs

TABLE 2 Distribution of photoproducts obtained after photolysis of guest 1-phenyl-3-*para*-tolyl-2-propanone (**14**) within host TATA and iTATA

	Relative distribution of photoproducts		
	19	**AB**	**Isomers of AB**
TATA	48	39	13
iTATA	55	31	14
OA	44	41	15

radical pairs are confined different distribution of products is expected. Depending on the extent of confinement the ratio of AA, AB, and BB changes in favor of AB and even a new rearrangement product **19** results. To examine how well TATA and iTATA in comparison to OA could confine diradical intermediates, we performed the well-known Norrish type 1 reaction of TATA and iTATA included **14**.

The ^{1}H NMR spectra of ketone **14** included within iTATA and TATA (Figure S25 and S26) confirmed the formation of 1:2 complexes. Irradiation of these complexes gave only AB, isomers of AB, and the rearranged starting ketone **19**. Absence of AA and BB suggests that secondary radicals do not escape the capsule. Even more interesting is the fact that the primary radical reorients and couples to form **19** even before it can decarbonylate. Isolation of **19**, AB and rearranged AB and absence of AA and BB confirm that the capsule remains intact during the transformation of reactants and products. Apparently, none of the primary and secondary radical pairs escapes the capsule. Product distribution within the 3 capsules summarized in Table 2 clearly implies that the interior and integrity of TATA and iTATA are similar to that of OA.

3 | EXPERIMENTAL

3.1 | Materials and methods

Guests coumarin-1 (**11**) and adamantane acids (**5**-**8**) (from Sigma-Aldrich/Acros) were used as received. Anthracene (from Sigma-Aldrich/Acros) was recrystallized from ethanol. Camphorthione (**10**),[14] benzonorbornadiene (**12**),[26] dibenzobarrelene(**13**),[27] and 1-phenyl-3-*para*-tolyl-2-propanone (**14**)[28] were synthesized by following the literature procedure. The hosts TATA and iTATA were synthesized by following the Schemes 1 and 2. Detailed procedure and spectral data are provided in Supporting Information.

3.2 | NMR experiments

The 1D, 2D DOSY, COSY, and 2D NOESY NMR studies were performed on a 500-MHz NMR spectrometer at 25°C.

3.3 | Fluorescence and phosphorescence emission experiments

Steady-state luminescence spectra were recorded using an FS920CDT fluorometer (Edinburgh Analytical Instruments). In some experiments the Corning #3-74 filter was placed in the emission light path to eliminate scattered excitation light. Fluorescence lifetimes were measured by time-correlated single photon counting using F920 fluorimeter (Edinburgh Analytical Instruments). Using LED as an excitation light source (centered at 368.6 nm and pulse width 804.5 ps). Phosphorescence lifetimes were measured on an OB920 fluorimeter (Edinburgh Analytical Instruments) using a pulsed microsecond xenon lamp as excitation source and multichannel scaling for data acquisition.

The ^{1}H NMR studies with guests@ TATA and iTATA: 600 μL of a 10mM NaOD/D_2O solution of host TATA and iTATA was taken in an NMR tube and to this 0.25 equivalent increment of guest was added. The ^{1}H NMR experiments were performed after shaking the NMR tube for 5 minutes after each addition. Completion of host-guest complexation was ascertained by monitoring the disappearance of the free host signals upon the addition of guest.

3.4 | Procedure for photolysis and analysis of the photoproducts of 1-phenyl-3-*para*-tolyl-2-propanone (14) within host TATA and iTATA

Stock solution of the guest was prepared in DMSO-d_6. The hosts' solutions (2 mM) were prepared in 10mM NaOD/D_2O. Aliquots of the guest solution were added to the hosts' solution maintaining the host-guest ration 2:1, and the solution was sonicated for 30 minutes. The NMR analysis of the solution showed formation of a 2:1 complex. The solution was then bubbled with nitrogen for 30 minutes and irradiated using a medium pressure Hg lamp. The photoproducts were extracted from the aqueous solution with chloroform and the organic layer was analyzed by GC and GC/MS.

3.5 | Isothermal titration calorimeter study for binding constant (K) and relevant thermodynamic parameters for complexation of adamantane acids with hosts TATA, iTATA, and OA

Isothermal titration calorimeter (ITC) measurements were performed with a nano-ITC instrument purchased from TA instruments in 10mM aqueous solutions of NaOH at 25°C. The instrument was calibrated electrically following the procedure recommended by the manufacturer before each experiment. All the titrations were performed at 25°C while stirring at 350 rpm. Each microcalorimetric titration experiment consisted of 30 successive injections. In each titration,

a constant volume (6 μL/injection) of guest solution was injected into the reaction cell (969 μL) charged with host solution. The concentration of the host and guest solution was determined by weighing required amount of compound and dissolving in deionized water. The concentration of the host solution was 0.1mM to 0.15mM whereas the guest concentration was 1mM to 2mM. The required concentration for the titration was obtained by diluting standard solution of each component. The dilution heat was determined by adding the guest stock solutions into water using the same number of injections and concentrations as in the titrations. The data were analyzed and fitted by the Nanoanalyze software adapted for ITC data analysis. The accuracy of the calculated thermodynamic quantities for all the 1:1 complexations were checked by performing several independent titration runs.

4 | SUMMARY

In conclusion, we have reported the synthesis of 2 new water-soluble deep-cavity cavitands that have the same skeleton as the well investigated OA. The new cavitands TATA and iTATA have benzoate and phenolate ions at the periphery. Replacement of benzoate ion by phenolate ion arrested the intersystem crossing from S_1 to T_1. This observation confirmed that the main triplet senstizer part of OA is the benzoate ion present at the top portals. Thus, while OA and TATA are good triplet sensitizers, iTATA is not. Internal polarity of the 2 new capsules are nonpolar like that of OA. Just like OA, both TATA and iTATA form 2:2, 1:2, and 1:1 complexes with various guests. The capsules formed by TATA and iTATA are stable and do not assemble-disassemble in time scales of photochemical interest. Excited state chemistry and physics of several well-known systems (anthracene, camphorthione, and dibenzylketone) revealed that the new cavitands have properties similar to that of OA. The ITC experimental data have confirmed that the factors that control guest inclusion within OA is not affected by the change of substituents at the periphery. Both ΔH and ΔS favor guest inclusion within OA, TATA, and iTATA. Availability of 2 new cavitands expands the arsenals available to perform highly selective photochemistry and modify the excited state photophysics of organic guest molecules.

ACKNOWLEDGEMENT

V.R. thanks the National Science Foundation (CHE-1411458) for financial support.

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Additional Supporting Information may be found online in the supporting information tab for this article.

How to cite this article: Jagadesan P, Samanta SR, Choudhury R, Ramamurthy V. Container Chemistry: Manipulating excited state behavior of organic guests within cavitands that form capsules in water. *J Phys Org Chem*. 2017;e3728. https://doi.org/10.1002/poc.3728