Xanthene[n]arenes: Exceptionally Large, Bowl-shaped Macrocyclic Building Blocks Suitable for Self-Assembly

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Supporting Information Placeholder

ABSTRACT: A new class of macrocycles denoted as "xanthene[n]arenes" was synthesized. In contrast to most other macrocycles, they feature a rigid bowl-shape, required for the synthesis of cavitands and for the self-assembly to molecular capsules via non-covalent interactions. The derivatization potential of the novel macrocycles was demonstrated on the xanthene[3]arene scaffold. Beside a deep cavitand, a modified macrocycle was synthesized that self-assembles into a hydrogen-bonded tetrameric capsule. Both supramolecular systems display host-guest binding properties, demonstrating the potential of xanthene[n]arenes as a new set of macrocyclic building blocks.

Macrocycles have been a cornerstone in supramolecular chemistry since its beginning, which was marked by the discovery of crown ethers.[1] A wide variety of macrocycles featuring different degrees of rigidity and sizes has been developed and explored intensively ever since.[2] An important subset of these macrocycles is comprised of rigid, bowl-shaped derivatives, which are required for the construction of cavitands[3] and closed host structures like (hemi)carcerands.[2c, 2d, 4] Moreover, the self-assembly of molecular capsules via non-covalent interactions depends on such bowl-shaped macrocycles.[5] These macrocycles mainly comprise phenol-based systems like the calixarene family of compounds (**1**, Figure 1a),[6] including resorcinarene (**2**)/ pyrogallolarene (**3**),[7] and also the cyclotriveratrylene (**4**).[8] Naturally, it was attempted to broaden this subclass of macrocycles by replacing the benzene-based building blocks *via* larger, for instance naphthalene-derived ones. Unfortunately, all attempts have failed to deliver symmetric, bowl-shaped macrocycles as of yet.[9] During the last decade, many new large phenol-based macrocycles, including **5**-**10** (Figure 1b)[10] have been reported.[11] Importantly, in contrast to **1**-**4**, they do not feature a rigid bowl-like structure but a flexible, more parallel orientation of the aromatic rings.

Herein we report the synthesis of new, exceptionally large, rigid, bowl-shaped macrocycles **X-3** and **X-4** (Figure 1c), composed of three or four xanthene units, respectively, and propose the name "xanthene[n]arenes" (**X-n**). We demonstrate that they are well suited for to the construction of deeper cavitands and for the self-assembly to hydrogen bond-based molecular capsules.

The known xanthene **11** can easily be obtained on the decagram scale from acetone and resorcinol in the presence of the Lewis acid $ZnCl_2$ (Scheme 1).[12] In analogy to the calixarene/resorcinarene syntheses, a direct macrocyclization of **11** and different aldehydes under acidic conditions was attempted. However, no traces of xanthene[n]arenes were detected *via* ^{1}H-NMR and ESI-MS analysis. Therefore, we decided to attempt macrocyclization in a head to tail manner from the prefunctionalized monomer **17** equipped with the side chain and the reactive benzylic alcohol moiety. Compound **17** is accessible *via* a simple four-step procedure. After benzyl protection in high yield (92%), the selective mono-formylation was achieved using Vilsmeier-Haack conditions in excellent yield (96%).

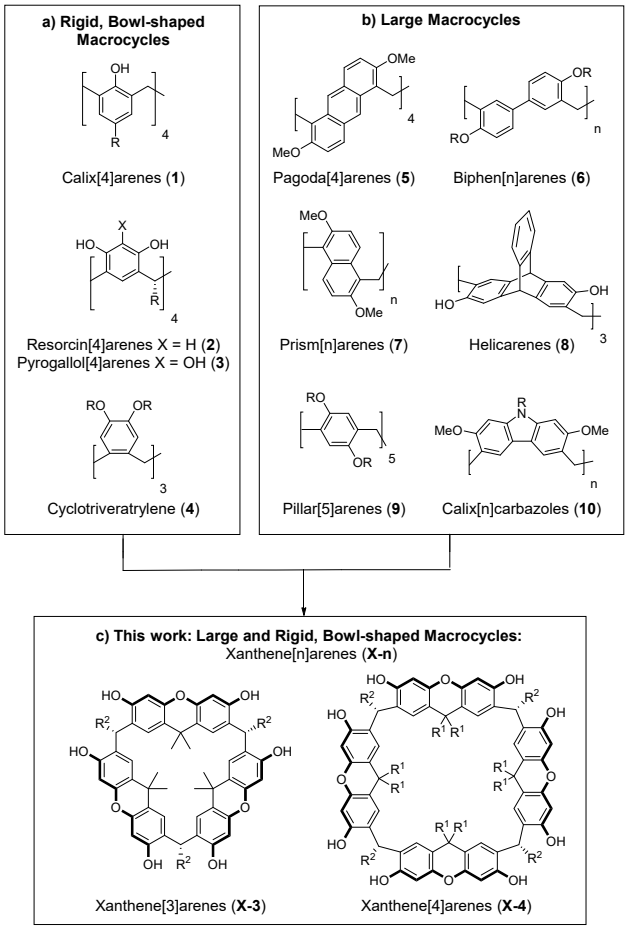
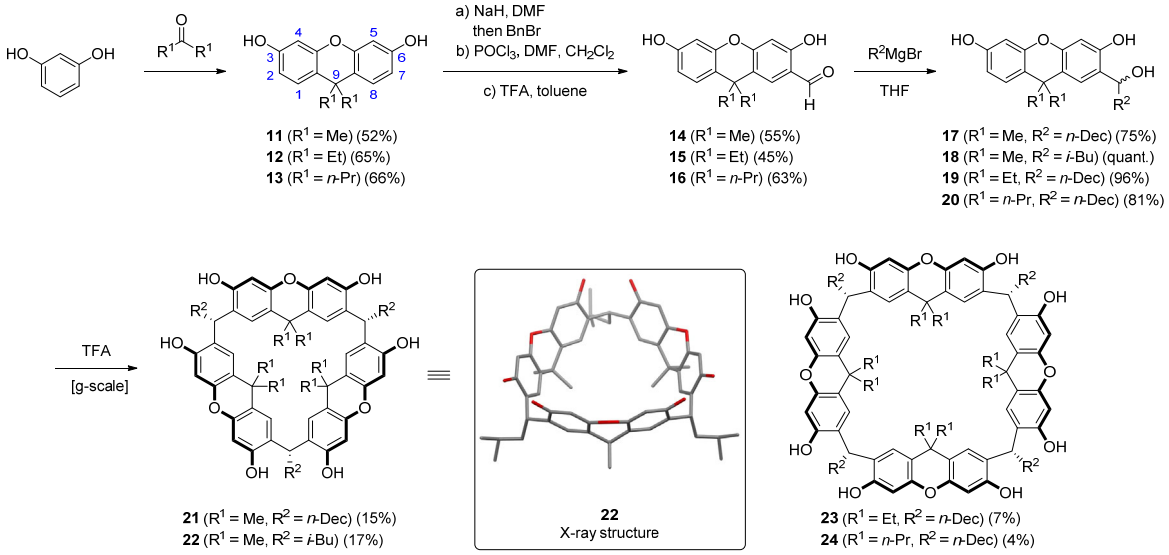


Figure 1. Xanthene[n]arenes extend the narrow field of rigid, bowl shaped macrocycles as its largest representative.

Scheme 1. Synthesis of Xanthene[n]arenes 21 - 24.



Subsequently the benzyl groups were removed using TFA, to deliver aldehyde **14** (62%). Finally, Grignard-addition yielded the desired benzylic alcohol **17** (75%). Extensive screening of cyclization conditions, using different acids, solvents, and concentrations, resulted in very low yields (<5%) of the macrocyclic products in most cases (see SI-chapter 6.1). Gratifyingly, under optimized conditions (25 mM **17**, 1:9 TFA:CH_2Cl_2, 20 h, 0 °C to rt), the xanthene[3]arene **21** was obtained as the major macrocyclic product in 15% isolated yield. The even larger **X-4** was only observed in traces *via* MALDI-MS. Attempts to increase the amount of **X-4** by changing the reaction conditions failed. We speculated that the product distribution might be shifted towards the larger **X-4** by the installation of larger R^1-groups that might prevent **X-3** formation sterically. The ethyl- and *n*-propyl-xanthenes **12** and **13** were obtained in gram scale from resorcinol and the corresponding ketone using hydrochloric acid instead of the zinc chloride utilized for **11**. They were converted to the benzylic alcohols **19** and **20** in good yields utilizing the chemistry developed for **17**. Indeed, utilizing the cyclization conditions optimized for the conversion of **17** to **21**, conversion of **19** and **20** led to the tetrameric **X-4** structures **23** and **24** as the only defined cyclization product, albeit in very low yields (<1%). Although the yield was terrible, the selective formation of **X-4** over **X-3** was promising. Furthermore, it was found that the product **X-4** decomposes during the extended reaction time (20 h). After extensive optimizations, shorter and milder reaction conditions were found (85 mM **19**/**20**, 1:9 TFA:DCE, 90 min, 0 °C) that yielded the **X-4**-derivatives **23** and **24** in at least useful yields of 7% and 4%, respectively.

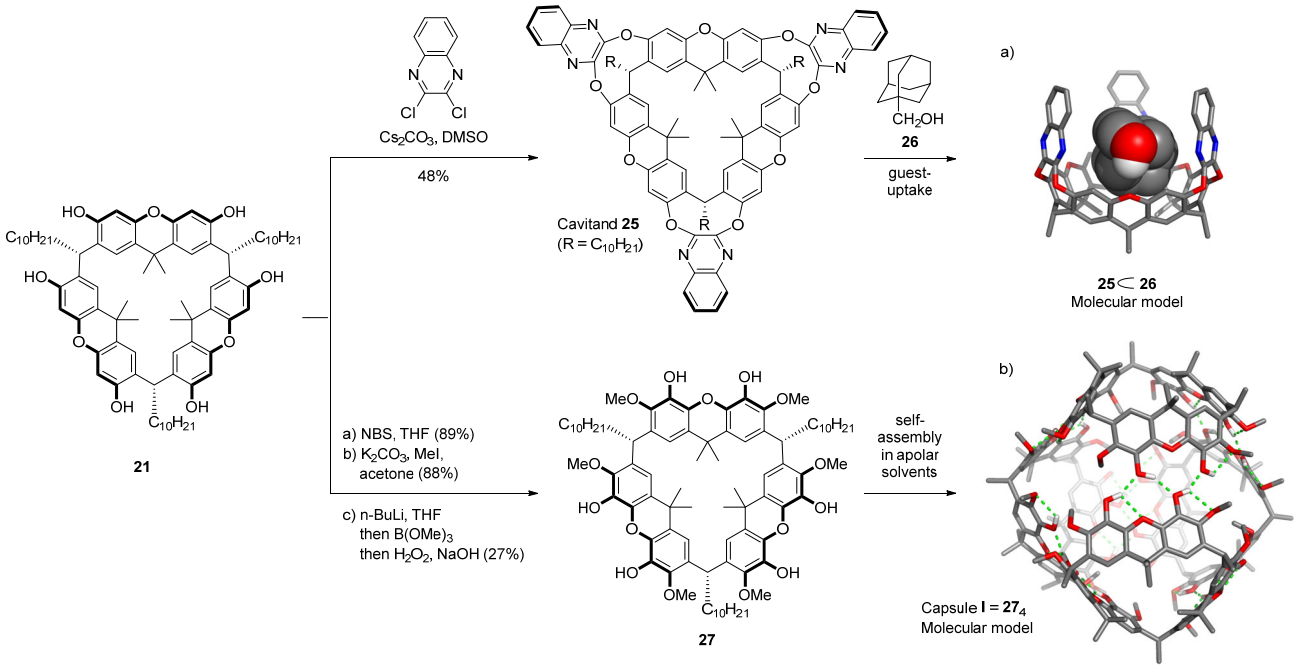
All macrocycles synthesized (**21**, **23** and **24)** were characterized by ^{1}H-, ^{13}C- and 2D-NMR spectroscopy as well as ESI-HRMS measurements. Additionally, the crystalline xanthene[3]arene derivative **22**, featuring *i*-Bu instead of *n*-Dec feet was synthesized *via* alcohol **18**. Single crystals suitable for X-ray crystallography were obtained by slow evaporation of a solution of **22** in THF. The crystal structure analysis of **22** (space group: P4/n) confirms the crown conformation (C_{3v}-symmetry, Scheme 1). While the tetrahedral angles between two adjacent xanthene units remain at 109.4°, interestingly the dihedral angles between the two aromatic units of each xanthene are 16.5°, induced by the strain of the macrocycle.

After having confirmed the structure of the macrocycles, their ability to self-assemble was explored. Surprisingly, in contrast to resorcinarene (**2**) and pyrogallolarene (**3**), neither **X-3** nor **X-4** formed assemblies in apolar solvents such as chloroform or toluene. Therefore, the derivatization of **21** was explored.

Like their smaller resorcinarene (**2**) counterparts, these bowl-shaped macrocycles are an ideal platform for further modifications. For instance, quinoxaline walls[13] were introduced by nucleophilic aromatic substitution, to deliver cavitand **25** in reasonable yield (48%, 88% yield per substitution, Scheme 2). **25** was found to weakly bind adamantanemethanol (**26**) in $CDCl_3$ with a binding constant K_a of 23.9 ± 2.6 M^{-1}.

Derivatization at the upper rim of **X-3** was conducted in analogy to a literature procedure on resorcinarene.[14] After NBS-bromination (89%), and subsequent permethylation (88%), the aryl bromides were converted into phenolic moieties *via* halogen/lithium exchange, followed by quenching with trimethylborate and subsequent oxidation. Product **27** was obtained in good yield considering that six positions were functionalized (27%, 80% yield per functionality). Macrocycle **27** was characterized by ^{1}H-, ^{13}C- and 2D-NMR spectroscopy as well as ESI-HRMS measurements. In apolar solvents such as chloroform and toluene, **27** self-assembles to defined larger structures. Whereas the signals of the ^{1}H-NMR spectra are broad at room temperature, the signals sharpen upon cooling (Figure 2). At 228 K, the phenol signals resonate as sharp peaks at 12.9 and 8.8 ppm, while the signals for the aromatic C-H groups and the methoxy-groups split into two sharp singlets each. DOSY-NMR experiments at 298 K in toluene-d_8 provided a diffusion value of $D = 0.23 \times 10^{-5}$ cm^2s^{-1}. The geometric requirements of the C3-symmetric macrocycle **27** would, in principle, enable the self-assembly to dimeric, tetrameric, and octameric structures. Since the diffusion value of the self-assembled structure is a little bit higher than for the hexameric resorcinarene capsule in the same solvent ($D = 0.17 \times 10^{-5}$ cm^2s^{-1}), a tetrameric assembly is the most likely structure. This conclusion is further supported by guest encapsulation studies (see below). Interestingly, to date, only very few examples of self-assembled tetrameric capsules are known.[15]

Scheme 2. Derivatization of the Xanthene[3]arene scaffold. Molecular models of a) complex 25 ⊂ 26. b) Self-assembly of monomer 27 into tetrameric capsule I.



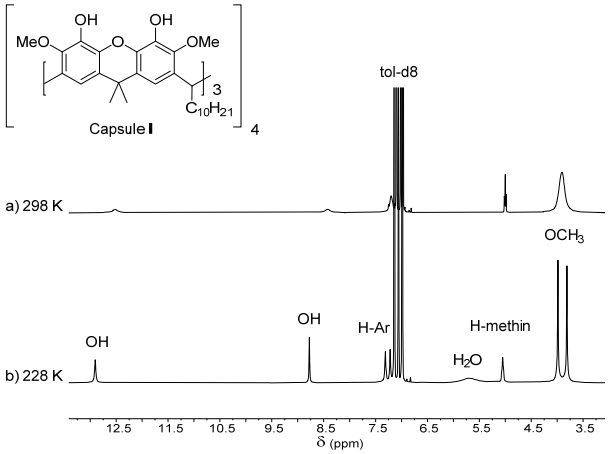


Figure 2. ^{1}H-NMR spectra of capsule **I** in toluene-d_8 (1.25 mM), at a) 298 K, b) 228 K.

Next, the host-guest properties of the assembly were explored. With Et_4NBr as cationic ammonium guest, the formation of a precipitate was observed. The precipitate was filtered, washed, dissolved in acetone-d_6, and analyzed by ^{1}H-NMR measurement. A 2:1 stoichiometry of **27** and Et_4NBr was found, which indicated the precipitation of a dimeric complex (**27**$_2$ ⊂ Et_4NBr). Dimeric assemblies of pyrogallolarene (**3**) containing ammonium species were previously observed to form in solid state[16] and as precipitates from solution.[17] Interestingly, larger ammonium guests (nBu$_4$NBr, nPen$_4$NBr, NBn$_3$(BntBu)Br) did not lead to the formation of host-guest complexes.

Beside ammonium guest, also fullerenes were explored due to their suitable size and spherical shape. Molecular modeling indicated that fullerene-C_{60} would fit into the cavity, while fullerene-C_{70} is slightly too bulky. Indeed, guest uptake of fullerene-C_{70} was not observed, while the uptake of fullerene-C_{60} was confirmed by ^{13}C-NMR. As shown in figure 3, mixing four equivalents of macrocycle **27** with one equivalent of C_{60} resulted in almost complete encapsulation of the fullerene. This not only indicates a high binding affinity, but also further supports the previous evidence for a tetrameric assembly **I** (see SI-chapter 6.2 for further titration data). DOSY-NMR experiments furthermore provided a diffusion value of $D = 0.24 \times 10^{-5}$ cm^{2}s^{-1} for the host-guest complex, confirming the structural stability of assembly **I** upon guest uptake.

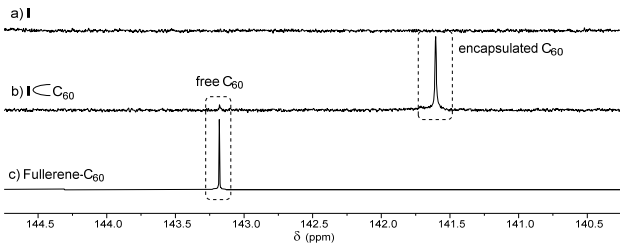


Figure 3. ^{13}C-NMR spectra in toluene-d_8 of a) capsule **I** (1.25 mM), b) capsule **I** and fullerene-C_{60} (both 0.85 mM), c) fullerene-C_{60} (2.50 mM).

In summary, we have developed a novel class of exceptionally large, rigid, bowl-shaped macrocycles denoted xanthene[n]arenes. The selective synthesis of xanthene[3]arenes or xanthene[4]arenes was achieved through modulation of the steric hindrance at the C9-position of the monomer (methyl, ethyl, n-propyl). The macrocycles are amenable to further modifications as demonstrated for **X-3**. Cavitand **25** and macrocycle **27**, which is able to self-assemble to a tetrameric capsule, were synthesized in one and three steps, respectively. Both supramolecular hosts displayed guest binding properties. Macrocycles with an intrinsic curvature are essential for

the construction of closed container molecules like molecular capsules. Only very few suitable building blocks are available as of yet. Importantly, all available macrocycles are rather small with a diameter of approx. 7 Å. In contrast, the developed macrocyles **X-3** and **X-4**, feature a diameter of 9.6 and even 14 Å, respectively. Rigid, bowl-shaped macrocycles of this size are unprecedented. Considering the current interest directed to the synthesis of novel macrocyclic hosts and self-assembling systems, we are convinced that they will serve as valuable platforms for the construction of a wide range of host structures, far beyond the two examples we report in this letter.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI:
Experimental details and NMR spectra of new compounds (PDF)

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Notes

The authors declare no competing financial interests.

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REFERENCES

1. (a) Pedersen, C. J., Cyclic polyethers and their complexes with metal salts. *J. Am. Chem. Soc.* **1967,** *89* (10), 2495-2496; (b) Pedersen, C. J., Cyclic polyethers and their complexes with metal salts. *J. Am. Chem. Soc.* **1967,** *89* (26), 7017-7036.

2. (a) Lehn, J. M., Cryptates: inclusion complexes of macropolycyclic receptor molecules. *Pure Appl. Chem.* **1978,** *50* (9-10), 871; (b) Lehn, J.-M., Supramolecular Chemistry: Receptors, Catalysts, and Carriers. *Science* **1985,** *227* (4689), 849-856; (c) Cram, D. J., The Design of Molecular Hosts, Guests, and Their Complexes (Nobel Lecture). *Angew. Chem. Int. Ed.* **1988,** *27* (8), 1009-1020; (d) Cram, D. J.; Cram, J. M., *Container molecules and their guests*. Royal Society of Chemistry: 1997; (e) D'Souza, V. T.; Lipkowitz, K. B., Cyclodextrins: Introduction. *Chem. Rev.* **1998,** *98* (5), 1741-1742; (f) Crini, G., A history of cyclodextrins. *Chem. Rev.* **2014,** *114* (21), 10940-10975; (g) Assaf, K. I.; Nau, W. M., Cucurbiturils: from synthesis to high-affinity binding and catalysis. *Chem. Soc. Rev.* **2015,** *44* (2), 394-418; (h) Liu, Z.; Nalluri, S. K. M.; Stoddart, J. F., Surveying macrocyclic chemistry: from flexible crown ethers to rigid cyclophanes. *Chem. Soc. Rev.* **2017,** *46* (9), 2459-2478.

3. (a) Cram, D. J., Cavitands: Organic Hosts with Enforced Cavities. *Science* **1983,** *219* (4589), 1177-1183; (b) Biros, S. M.; Rebek, J. J., Structure and binding properties of water-soluble cavitands and capsules. *Chem. Soc. Rev.* **2007,** *36* (1), 93-104.

4. (a) Collet, A., Cyclotriveratrylenes and cryptophanes. *Tetrahedron* **1987,** *43* (24), 5725-5759; (b) Jasat, A.; Sherman, J. C., Carceplexes and Hemicarceplexes. *Chem. Rev.* **1999,** *99* (4), 931-968; (c) Warmuth, R.; Yoon, J., Recent Highlights in Hemicarcerand Chemistry. *Acc. Chem. Res.* **2001,** *34* (2), 95-105; (d) Ajami, D.; Rebek, J., More Chemistry in Small Spaces. *Acc. Chem. Res.* **2013,** *46* (4), 990-999; (e) Yu, Y.; Rebek, J., Reactions of Folded Molecules in Water. *Acc. Chem. Res.* **2018,** *51* (12), 3031-3040.

5. (a) Lawrence, D. S.; Jiang, T.; Levett, M., Self-Assembling Supramolecular Complexes. *Chem. Rev.* **1995,** *95* (6), 2229-2260; (b) Conn, M. M.; Rebek, J., Self-Assembling Capsules. *Chem. Rev.* **1997,** *97* (5), 1647-1668; (c) de Mendoza, J., Self-Assembling Cavities: Present and Future. *Chem. Eur. J.* **1998,** *4* (8), 1373-1377; (d) Jin, P.; Dalgarno, S. J.; Atwood, J. L., Mixed metal-organic nanocapsules. *Coord. Chem. Rev.* **2010,** *254* (15-16), 1760-1768; (e) Kobayashi, K.; Yamanaka, M., Self-assembled capsules based on tetrafunctionalized calix[4]resorcinarene cavitands. *Chem. Soc. Rev.* **2015,** *44* (2), 449-466; (f) Jordan, J. H.; Gibb, B. C., Molecular containers assembled through the hydrophobic effect. *Chem. Soc. Rev.* **2015,** *44* (2), 547-585; (g) Ajami, D.; Liu, L.; Rebek Jr, J., Soft templates in encapsulation complexes. *Chem. Soc. Rev.* **2015,** *44* (2), 490-499.

6. (a) Gutsche, C. D., Calixarenes. *Acc. Chem. Res.* **1983,** *16* (5), 161-170; (b) Gutsche, C. D.; Rogers, J. S.; Stewart, D.; See, K.-A., Calixarenes: paradoxes and paradigms in molecular baskets. *Pure Appl. Chem.* **1990,** *62* (3), 485; (c) Böhmer, V., Calixarenes, Macrocycles with (Almost) Unlimited Possibilities. *Angew. Chem. Int. Ed.* **1995,** *34* (7), 713-745.

7. Timmerman, P.; Verboom, W.; Reinhoudt, D. N., Resorcinarenes. *Tetrahedron* **1996,** *52* (8), 2663-2704.

8. (a) Hardie, M. J., Recent advances in the chemistry of cyclotriveratrylene. *Chem. Soc. Rev.* **2010,** *39* (2), 516-527; (b) Hardie, M. J., Self-assembled Cages and Capsules Using Cyclotriveratrylene-type Scaffolds. *Chem. Lett.* **2016,** *45* (12), 1336-1346.

9. (a) Shorthill, B. J.; Glass, T. E., Naphthalene-Based Calixarenes: Unusual Regiochemistry of a Friedel−Crafts Alkylation. *Org. Lett.* **2001,** *3* (4), 577-579; (b) Georghiou, P. E.; Li, Z.; Ashram, M.; Chowdhury, S.; Mizyed, S.; Tran, A. H.; Al-Saraierh, H.; Miller, D. O., Calixnaphthalenes: Deep, Electron-Rich Naphthalene Ring-Containing Calixarenes. The First Decade. *Synlett* **2005,** *2005* (06), 0879-0891; (c) Shorthill, B. J.; Granucci, R. G.; Powell, D.

R.; Glass, T. E., Synthesis of 3,5- and 3,6-Linked Calix[n]naphthalenes. *J. Org. Chem.* **2002,** *67* (3), 904-909; (d) Yang, L.-P.; Liu, W.-E.; Jiang, W., Naphthol-based macrocyclic receptors. *Tetrahedron Lett.* **2016,** *57* (36), 3978-3985.

10. (a) Ogoshi, T.; Kanai, S.; Fujinami, S.; Yamagishi, T.-a.; Nakamoto, Y., para-Bridged Symmetrical Pillar[5]arenes: Their Lewis Acid Catalyzed Synthesis and Host–Guest Property. *J. Am. Chem. Soc.* **2008,** *130* (15), 5022-5023; (b) Xue, M.; Yang, Y.; Chi, X.; Zhang, Z.; Huang, F., Pillararenes, A New Class of Macrocycles for Supramolecular Chemistry. *Acc. Chem. Res.* **2012,** *45* (8), 1294-1308; (c) Chen, H.; Fan, J.; Hu, X.; Ma, J.; Wang, S.; Li, J.; Yu, Y.; Jia, X.; Li, C., Biphen[n]arenes. *Chem. Sci.* **2015,** *6* (1), 197-202; (d) Yang, P.; Jian, Y.; Zhou, X.; Li, G.; Deng, T.; Shen, H.; Yang, Z.; Tian, Z., Calix[3]carbazole: One-Step Synthesis and Host–Guest Binding. *J. Org. Chem.* **2016,** *81* (7), 2974-2980; (e) Ogoshi, T.; Yamagishi, T.-a.; Nakamoto, Y., Pillar-Shaped Macrocyclic Hosts Pillar[n]arenes: New Key Players for Supramolecular Chemistry. *Chem. Rev.* **2016,** *116* (14), 7937-8002; (f) Zhang, G.-W.; Li, P.-F.; Meng, Z.; Wang, H.-X.; Han, Y.; Chen, C.-F., Triptycene-Based Chiral Macrocyclic Hosts for Highly Enantioselective Recognition of Chiral Guests Containing a Trimethylamino Group. *Angew. Chem. Int. Ed.* **2016,** *55* (17), 5304-5308; (g) Chen, C.-F.; Han, Y., Triptycene-Derived Macrocyclic Arenes: From Calixarenes to Helicarenes. *Acc. Chem. Res.* **2018,** *51* (9), 2093-2106; (h) Della Sala, P.; Del Regno, R.; Talotta, C.; Capobianco, A.; Hickey, N.; Geremia, S.; De Rosa, M.; Spinella, A.; Soriente, A.; Neri, P.; Gaeta, C., Prismarenes: A New Class of Macrocyclic Hosts Obtained by Templation in a Thermodynamically Controlled Synthesis. *J. Am. Chem. Soc.* **2020,** *142* (4), 1752-1756; (i) Han, X.-N.; Han, Y.; Chen, C.-F., Pagoda[4]arene and i-Pagoda[4]arene. *J. Am. Chem. Soc.* **2020,** *142* (18), 8262-8269.

11. (a) Wang, M.-X., Heterocalixaromatics, new generation macrocyclic host molecules in supramolecular chemistry. *ChemComm* **2008,** (38), 4541-4551; (b) Wu, J.-R.; Yang, Y.-W., New opportunities in synthetic macrocyclic arenes. *ChemComm* **2019,** *55* (11), 1533-1543; (c) Jia, F.; He, Z.; Yang, L.-P.; Pan, Z.-S.; Yi, M.; Jiang, R.-W.; Jiang, W., Oxatub[4]arene: a smart macrocyclic receptor with multiple interconvertible cavities. *Chem. Sci.* **2015,** *6* (12), 6731-6738; (d) Yang, W.; Samanta, K.; Wan, X.; Thikekar, T. U.; Chao, Y.; Li, S.; Du, K.; Xu, J.; Gao, Y.; Zuilhof, H.; Sue, A. C.-H., Tiara[5]arenes: Synthesis, Solid-State Conformational Studies, Host–Guest Properties, and Application as Nonporous Adaptive Crystals. *Angew. Chem. Int. Ed.* **2020,** *59* (10), 3994-3999.

12. Hanousek, V., Nebenprodukte der Fluoreszeinschmelze. *Collect. Czechoslov. Chem. Commun.* **1959,** *24*, 1061-1073.

13. Moran, J. R.; Karbach, S.; Cram, D. J., Cavitands: synthetic molecular vessels. *J. Am. Chem. Soc.* **1982,** *104* (21), 5826-5828.

14. Merget, S.; Catti, L.; Piccini, G.; Tiefenbacher, K., Requirements for Terpene Cyclizations inside the Supramolecular Resorcinarene Capsule: Bound Water and Its Protonation Determine the Catalytic Activity. *J. Am. Chem. Soc.* **2020,** *142* (9), 4400-4410.

15. (a) Martín, T.; Obst, U.; Rebek, J., Molecular Assembly and Encapsulation Directed by Hydrogen-Bonding Preferences and the Filling of Space. *Science* **1998,** *281* (5384), 1842-1845; (b) Hof, F.; Nuckolls, C.; Craig, S. L.; Martín, T.; Rebek, J., Emergent Conformational Preferences of a Self-Assembling Small Molecule: Structure and Dynamics in a Tetrameric Capsule. *J. Am. Chem. Soc.* **2000,** *122* (44), 10991-10996; (c) Baillargeon, P.; Dory, Y. L., Rational Design and Gas-Phase Characterization of Molecular Capsules by Self-Assembly of a Symmetric Hexasubstituted Benzene with Seven-Membered Lactams. *J. Am. Chem. Soc.* **2008,** *130* (17), 5640-5641; (d) Suzuki, A.; Akita, M.; Yoshizawa, M., Amphiphilic tribranched scaffolds with polyaromatic panels that wrap perylene stacks displaying unusual emissions. *ChemComm* **2016,** *52* (65), 10024-10027.

16. (a) Shivanyuk, A.; Friese, J. C.; Döring, S.; Rebek, J., Solvent-Stabilized Molecular Capsules. *J. Org. Chem.* **2003,** *68* (17), 6489-6496; (b) Åhman, A.; Luostarinen, M.; Rissanen, K.; Nissinen, M., Complexation of C-methyl pyrogallarene with small quaternary and tertiary alkyl ammonium cations. *New J. Chem.* **2007,** *31* (1), 169-177; (c) Beyeh, N. K.; Rissanen, K., Dimeric Resorcin[4]arene Capsules in the Solid State. *Isr. J. Chem.* **2011,** *51* (7), 769-780.

17. Zhang, Q.; Catti, L.; Kaila, V. R. I.; Tiefenbacher, K., To catalyze or not to catalyze: elucidation of the subtle differences between the hexameric capsules of pyrogallolarene and resorcinarene. *Chem. Sci.* **2017,** *8* (2), 1653-1657.