Organic LETTERS

Letter

pubs.acs.org/OrgLett

Probing the Inner Space of Salt-Bridged Calix[5]arene Capsules

Giovanna Brancatelli,[†] Giuseppe Gattuso,[‡] Silvano Geremia,*[,†] Anna Notti,[‡] Sebastiano Pappalardo,[§] Melchiorre F. Parisi,*[,‡] and Ilenia Pisagatti[‡]

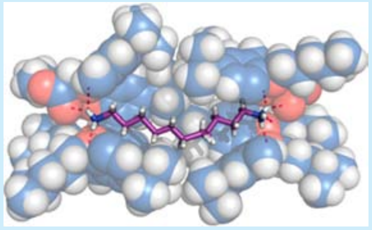
[†]Centro di Eccellenza in Biocristallografia, Dipartimento di Scienze Chimiche e Farmaceutiche, Università di Trieste, via L. Giorgieri 1, 34127 Trieste, Italy

[‡]Dipartimento di Scienze Chimiche, Università di Messina, viale F. Stagno d'Alcontres 31, 98166 Messina, Italy

[§]Dipartimento di Scienze Chimiche, Università di Catania, viale A. Doria 6, 95125 Catania, Italy

S *Supporting Information*

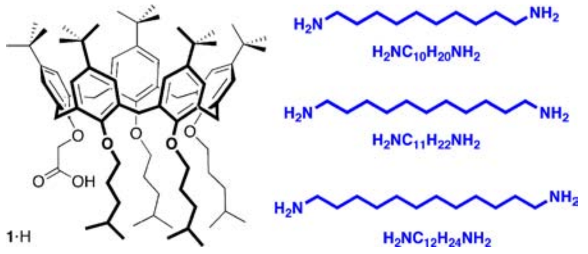
ABSTRACT: A combined DOSY and XRD study indicates that a carboxylcalix[5]arene receptor is able to encapsulate α,ω-diamines of appropriate length by means of a proton-transfer-mediated recognition process followed by salt-bridge-assisted bis-*endo*-complexation.



Capsular assemblies are supramolecular entities composed of two—or more, often identical—molecular receptors and one—or more—included guest species.[1] Their formation is the result of a concert of 'weak' noncovalent interactions, all combining to stabilize these multicomponent complexes, with an efficiency that increases and reaches its maximum when size and shape complementarity of host(s) and guest(s) is achieved.[2] Molecular encapsulation is highly desirable, as control over the uptake and release of an included guest may lead to new developments in drug delivery, catalysis, and membrane technology.[3]

Many different macrocyclic receptors, resorcinares,[4] calixarenes,[5] calixpyrroles,[6] cyclodextrins,[7] and cavitands[8] to name the most notable examples, have been successfully employed for the encapsulation of target substrates. The mechanism of capsule formation, however, may significantly differ even within the same macrocycle family. In some instances, the spontaneous formation of 'empty' (or solvent-filled) capsules has been reported,[9] whereas in others it is a given guest that induces a recognition-driven encapsulation process.[9,10] In the latter case, the search for the best capsule templating agent can be pursued either, or both, with the aid of computational methods, taking advantage of the Rebek–Mecozzi rule,[11] or by using 'molecular rulers',[12] i.e., a series of homologous compounds bearing suitable functionalities capable of interacting with both halves of the capsules.

We have recently reported[13] on a family of carboxylcalix[5]arene receptors able to selectively recognize and bind linear primary amines, as a result of a proton transfer followed by the formation of internally ion-paired (salt bridged) complexes. We have also taken advantage in the past of the molecular ruler approach to investigate the ability of penta-alkyl and penta-ester calix[5]arenes to form capsular complexes.[14] The same strategy has now been used to explore the tendency of carboxylcalix[5]arene **1**·H to form salt-bridged capsules, and the results of a combined solution and solid-state study are presented here.



1·H

$H_2NC_{10}H_{20}NH_2$

$H_2NC_{11}H_{22}NH_2$

$H_2NC_{12}H_{24}NH_2$

To gain a preliminary picture of the ability of calix[5]arene **1**·H to recognize linear α,ω-diamines of different length ($\mathbf{H_2NC_nH_{2n}NH_2}$, with n = 10–12), **1**·H was exposed to increasing amounts of diamino-guests, and the resulting solutions were investigated by ^{1}H NMR, 1D-TOCSY, and DOSY techniques. Host/guest (2:1 and 1:1) complex formation was conveniently followed by monitoring the included guest probe resonances present in the high-field region of the ^{1}H NMR spectra (Figure 1 for $\mathbf{H_2NC_{12}H_{24}NH_2}$; for titrations with $\mathbf{H_2NC_{11}H_{22}NH_2}$ and $\mathbf{H_2NC_{10}H_{20}NH_2}$, see Figures S3 and S5 in the Supporting Information (SI)).

Upon addition of 0.25 equiv of $\mathbf{H_2NC_{12}H_{24}NH_2}$ to a 5 mM solution of **1**·H ($CDCl_3$/CD_3OD, 9:1 v/v, 25 °C), two sets of resonances (one largely predominating over the other; see trace b of Figure 1) for the cavity-included methylene groups of the guest appeared in the δ = 0.7 to −2.0 ppm range, providing clear evidence that a host-to-guest proton transfer had taken place.[13] Specifically, the two amino groups of the guest underwent protonation, and the resulting diammonium dication was recognized and bound by the resulting negatively

Received: March 4, 2014
Published: April 11, 2014

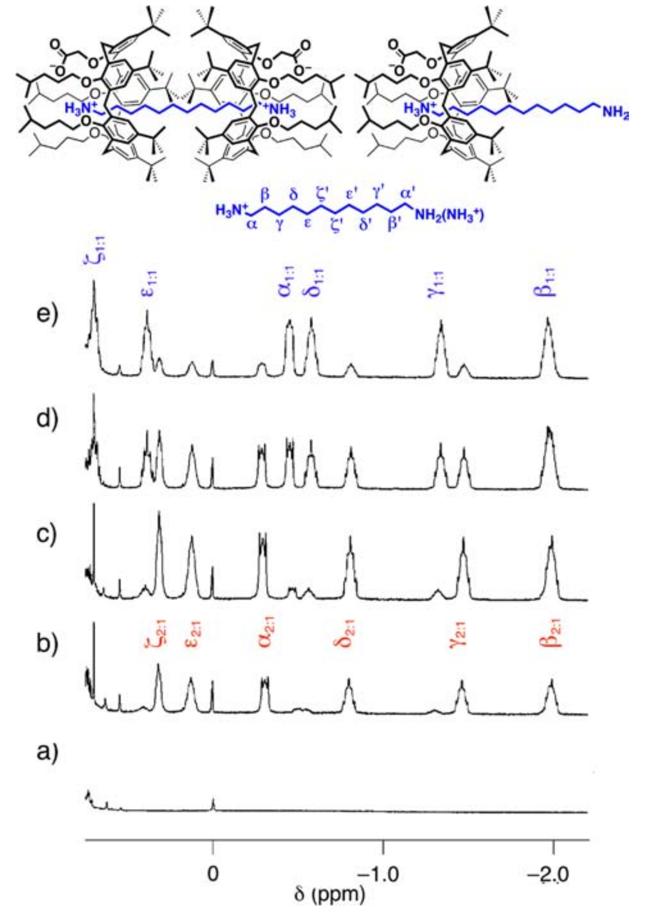


Figure 1. (Top) 2:1 and 1:1 complexes between calix[5]arene $\mathbf{1}\cdot H$ and $\mathbf{H_2NC_{12}H_{24}NH_2}$. (Bottom) High-field regions of the ^1H NMR spectra (500 MHz, $CDCl_3/CD_3OD$, 9:1 v/v, 25 °C) of a 5 mM solution of $\mathbf{1}\cdot H$ on its own (trace a) and upon addition of 0.25, 0.5, 0.8, and 2 equiv of $\mathbf{H_2NC_{12}H_{24}NH_2}$ (traces b to e, respectively).

charged calixarene receptor $\mathbf{1}^-$ by means of internal ion pairing. Further addition of $\mathbf{H_2NC_{12}H_{24}NH_2}$ diamino-guest (up to 2 equiv) resulted in a population inversion of the two sets of resonances.

According to a combined analysis of the ^1H NMR titration data and 1D-TOCSY experiments (Figures S1 and S2), the species formed at a high host/guest ratio displays a set of six resonances compatible with a dodecanediyldiammonium guest symmetrically held, at both ends, by the cavities of two calixarene molecules ($\mathbf{1^-\supset{}^+H_3NC_{12}H_{24}NH_3{}^+\subset1^-}$). Conversely, the species predominantly formed at a low host/guest ratio displays in its 1D-TOCSY spectra a set of 12 distinct correlated resonances, consistent with a desymmetrized guest molecule included inside a calixarene cavity only at one end ($\mathbf{H_2NC_{12}H_{24}NH_3{}^+\subset1^-}$). ^1H NMR diffusion-ordered spectroscopy (DOSY) experiments[15] on the same solution provided additional evidence for the formation of 2:1 and 1:1 complexes (Figure 2). In agreement with the different sizes of these two assemblies, the diffusion coefficients (D) extracted from the decay of the signals assigned to the bis-*endo*-cavity included guest methylene groups of $\mathbf{1^-\supset{}^+H_3NC_{12}H_{24}NH_3{}^+\subset1^-}$ were found to have lower values than those measured for the signals assigned to the *endo*-cavity included methylene groups of $\mathbf{H_2NC_{12}H_{24}NH_3{}^+\subset1^-}$.

When $\mathbf{H_2NC_{10}H_{20}NH_2}$ and $\mathbf{H_2NC_{11}H_{22}NH_2}$ were tested as guests, similar results were obtained; i.e., according to ^1H NMR and DOSY data, both shorter diamines formed host/guest ratio-dependent 2:1 and 1:1 complexes (Figures S3−S6). Interestingly, close inspection of the ^1H NMR spectra showed that the complexation-induced shifts (CISs) experienced by the resonances of the included $\mathbf{{}^+H_3NC_{11}H_{22}NH_3{}^+}$ and $\mathbf{{}^+H_3NC_{12}H_{24}NH_3{}^+}$ guests were very similar, suggesting that in solution these two penetrate the host cavities to a similar depth, freely reaching the bottom of both calixarene cavities to salt-bridge with the carboxylate anions.[13,16] In the case of the $\mathbf{1^-\supset{}^+H_3NC_{10}H_{20}NH_3{}^+\subset1^-}$ 2:1 complex, on the other hand, the guest appears to be too short to fully reach both cavity bottoms at the same time, without the two calixarene upper rims coming into contact. The calix[5]arene/alkanediyldiammonium encapsulation is a slow-exchanging process on the NMR time scale, and as a result, association constants for the three homologous 2:1 complexes $\mathbf{1^-\supset{}^+H_3NC_nH_{2n}NH_3{}^+\subset1^-}$ were determined by direct quantification of the different species present in solution at equilibrium.[17] K_a's were found to be $(1.20 \pm 0.30) \times 10^7$, $(1.33 \pm 0.31) \times 10^7$, and $(1.90 \pm 0.45) \times 10^7$ M^{-2} for $\mathbf{1^-\supset{}^+H_3NC_{10}H_{20}NH_3{}^+\subset1^-}$, $\mathbf{1^-\supset{}^+H_3NC_{11}H_{22}NH_3{}^+\subset1^-}$, and $\mathbf{1^-\supset{}^+H_3NC_{12}H_{24}NH_3{}^+\subset1^-}$, respectively,[18] indicating an affinity trend rather than a peak selectivity for any one guest.

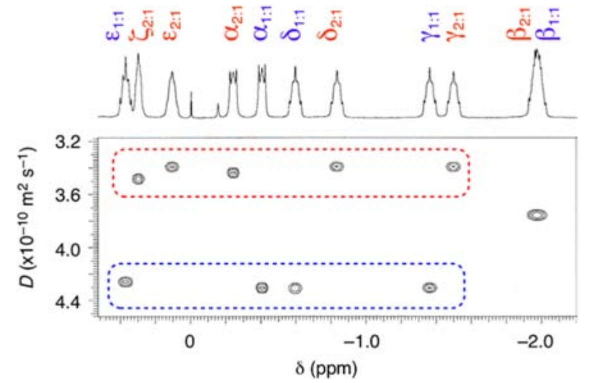


Figure 2. High-field region of the DOSY experiment (500 MHz, $CDCl_3/CD_3OD$, 9:1 v/v, 25 °C) on a mixture of $[\mathbf{1}\cdot H]$ = 5 mM and $[\mathbf{H_2NC_{12}H_{24}NH_2}]$ = 4 mM.

To answer the key question, "are these complexes capsular?", single crystals for the three 2:1 complexes were grown and investigated by X-ray diffractometry.[19] The solid-state structure of $\mathbf{1^-\supset{}^+H_3NC_{12}H_{24}NH_3{}^+\subset1^-}$ (Figure 3) confirmed that diamine complexation takes place via a preliminary host-to-

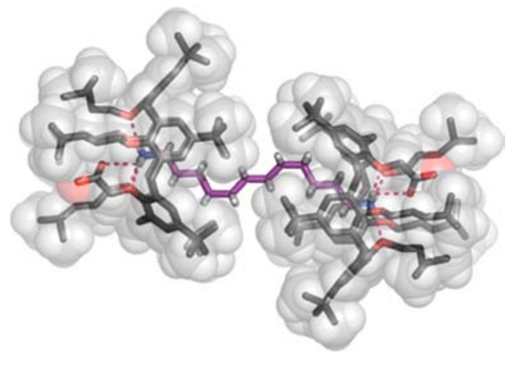


Figure 3. Solid-state structure of $\mathbf{1^-\supset{}^+H_3NC_{12}H_{24}NH_3{}^+\subset1^-}$. Values of selected H-bonds and CH−π interactions: $N\cdots O_{carbox}$ = 2.895(7) Å; $N\cdots O_{Ar}$ = 2.713(6), 2.825(6), 2.848(6) Å; α-, β-$CH_2\cdots Ar$ = 3.460(7) and 3.684(6) Å.

guest proton transfer. As a result of this, a tight supramolecular three-component ion-paired salt is formed whereby, in addition to a series of H-bonds and CH−π interactions,[20] oppositely charged host and guest moieties (namely, the carboxylates and the ammonium groups, respectively) are closely held together by very tight salt-bridge[13] interactions ($N\cdots O_{carbox}$ = 2.895(7) Å). The calix[5]arene units of this 2:1 complex are seen in a typical *cone-out* conformation[21] with the linear alkanediyldiammonium guest, connecting the two cavities, oriented slantwise to allow for optimal host−guest interaction. The two calixarene bowls are offset by 2.7 Å, while their bridging methylene mean planes lie at a distance of 14.8 Å from each other, forming a 79.6° angle with the dication guest axis. The overall shape of the complex is *quasi*-capsular, as the two host molecules strain to close the gap between their upper rim *p-tert*-butyl substituents to fully enclose the dodecanediyldiammonium guest, the latter being too long/bulky (V = 217 Å^3, *vide infra*) to comfortably fit within a 'sealed' capsular space. The guest, in turn, attempts to nest within this confined capsular space by adopting an eclipsed conformation[12a,22] (Figure S13) for two $C-CH_2-CH_2-C$ moieties that ultimately shortens the $N\cdots N$ distance (15.2 Å; for an all-*trans* conformation, calculated $N\cdots N$ = ca. 16.2 Å).

A different picture emerges from the solid-state structure of $\mathbf{1^{-}\supset{}^{+}H_3NC_{11}H_{22}NH_3{}^{+}\subset 1^{-}}$ (complex **I**,[23] Figure 4). The shorter undecanediyldiammonium chain fits perfectly within the capsule formed by the two calixarenes in a *cone-out* conformation, the two capsule halves being held together by an even tighter salt-bridge interaction ($N\cdots O_{carbox}$ = 2.736(7), 2.76(1) and 2.753(7), 2.750(6) Å in **I** and **II**, respectively), as well as H-bonds and CH−π interactions.[20] In this case, however, the upper rims of the two calixarenes are in van der Waals contact, with the distance between the two bridging methylene mean planes being shorter (13.0 and 13.4 Å in **I** and **II**, respectively) and the cavity offset being less pronounced (2.20 and 2.02 Å in **I** and **II**, respectively). In both crystallographic forms, the dicationic guest adopts a conformation with *gauche* turns to allow for a better fit within the cavity (Figure S13).

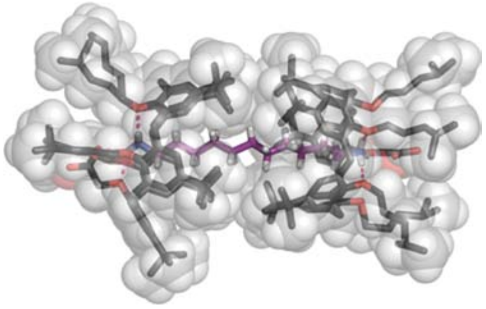


Figure 4. Solid-state structure of $\mathbf{1^{-}\supset{}^{+}H_3NC_{11}H_{22}NH_3{}^{+}\subset 1^{-}}$ (capsule **I**). Values of selected H-bonds, CH−π, and van der Waals interactions: $N\cdots O_{Ar}$ = 2.83(1)−2.89(1) Å; α-, β-$CH_2\cdots Ar$ = 3.564(7)−4.04(2) Å; $C(CH_3)_3\cdots C(CH_3)_3$ = 3.72(3)−3.94(2) Å.

An estimate of the capsular internal volume[24] (306.5 and 301.9 Å^3 for **I** and **II**, respectively) and the guest volume (199.8−204.5 Å^3) indicates a close-to-ideal (67%) cavity packing coefficient.[11] A closer look at these crystal structures reveals that the ammonium moieties take up a deeper position inside the calixarene cavities (−0.533(5), −0.749(7) in **I** vs −0.188 Å with respect to the calixarene mean plane present in $\mathbf{1^{-}\supset{}^{+}H_3NC_{12}H_{24}NH_3{}^{+}\subset 1^{-}}$) likely consistent with the presence of additional van der Waals attractive interactions, between the calixarene upper rims, pushing the nitrogen atoms further in, thus permitting capsule sealing.

$\mathbf{1^{-}\supset{}^{+}H_3NC_{10}H_{20}NH_3{}^{+}\subset 1^{-}}$ is also seen, in the solid state, as a capsular assembly, although with some noticeable differences from $\mathbf{1^{-}\supset{}^{+}H_3NC_{11}H_{22}NH_3{}^{+}\subset 1^{-}}$ (Figure 5). In this particular case, the shorter decanediyldiammonium guest adopts a fully extended conformation (Figure S13), mandatory to allow salt-bridge formation with the endohedral carboxylate anions. The two cavities are offset by as much as 4.84 Å, with the guest spanning the two cavities slantwise. The calixarene mean planes are seen 13.85 Å apart, forming a 70.8° angle with the axis of the encapsulated guest. Compared to the 1,11-undecanediamine assembly, the capsule here shrinks its inner volume[24] (from *ca.* 304 to 267 Å^3) to match the smaller guest size (191 Å^3), thus reaching a packing coefficient of 72%. In addition, the ammonium heads are seen in the same relative position as in the $\mathbf{1^{-}\supset{}^{+}H_3NC_{12}H_{24}NH_3{}^{+}\subset 1^{-}}$ case (−0.094(1) Å from the methylene mean plane; $N\cdots O_{carbox}$ = 2.900(7) Å)[20] indicating that also in this instance encapsulation of the guest is assisted by salt-bridge formation and H-bonds, CH−π, and attractive van der Waals interactions.

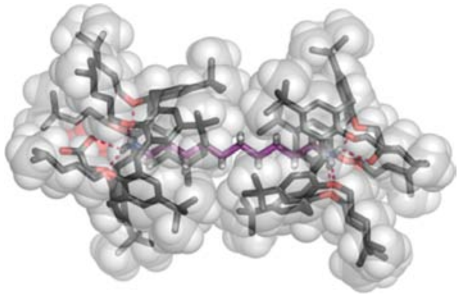


Figure 5. Solid-state structure of $\mathbf{1^{-}\supset{}^{+}H_3NC_{10}H_{20}NH_3{}^{+}\subset 1^{-}}$. Values of selected H-bonds, CH−π, and van der Waals interactions: $N\cdots O_{carbox}$ = 2.900(7) Å; $N\cdots O_{Ar}$ = 2.812(7), 2.825(8), 2.829(7) Å; α-, β-$CH_2\cdots Ar$ = 3.483(7)−3.708(7) Å; $C(CH_3)_3\cdots C(CH_3)_3$ = 3.66(2)−4.05(1) Å.

In conclusion, a very rare example (to the best of our knowledge the first ever) of substrate-induced capsule formation triggered by both molecular (acid−base proton transfer) and supramolecular (noncovalent) interactions is described. Overall, molecular encapsulation (of a diamine within two calix[5]arene molecules) takes place as a result of two protonation reactions and a total of 20 noncovalent interactions, including: two endohedral carboxylate-ammonium salt bridges, six hydrogen bonds, and eight CH−π contacts (all of them of the host-to-guest type), as well as four (host-to-host) van der Waals contacts. Capsule formation, albeit with different spatial requirements, occurs both in solution and in the solid state. In the latter case, owing to the remarkable adaptability of the two carboxylatocalix[5]arene units, both 1,10-decanediamine and 1,11-undecanediamine are recognized, protonated, and fully encapsulated with packing coefficients that closely match the ideal values for capsule formation, while 1,12-dodecanediamine is recognized and protonated, but is slightly too long to allow capsule sealing. In solution, on the other hand, given the lower filling coefficients allowed and the telltale CISs observed for the included guests, it is reasonable to assume that only 1,10-decanediamine is able to induce the formation of a tight capsule, with the other two longer diamines forming less compact capsular assemblies. The present findings demonstrate the potential of complementary ionizable host−guest pairs in the noncovalent synthesis of supramolecular architectures and provide an input for the development of higher-ordered polycapsular supramolecular polymers from tailor-made homoditopic components. Studies along these lines are currently in progress.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Full experimental details, additional figures for both X-ray and NMR experiments, and crystal data for $\mathbf{1^{-}\supset{}^{+}H_3NC_{10}H_{20}NH_3^{+}\subset 1^{-}}$, $\mathbf{1^{-}\supset{}^{+}H_3NC_{11}H_{22}NH_3^{+}\subset 1^{-}}$, and $\mathbf{1^{-}\supset{}^{+}H_3NC_{12}H_{24}NH_3^{+}\subset 1^{-}}$ (CCDC 988431-3). This material is available free of charge via the Internet at http://pubs.acs.org.

■ AUTHOR INFORMATION

Corresponding Authors

*E-mail: mparisi@unime.it.
*E-mail: sgeremia@units.it.

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

This paper is dedicated to Professor Maria Chiara Aversa (Dipartimento di Scienze Chimiche, Università di Messina, Italy) on the occasion of her retirement. MIUR (PRIN-2009A5Y3N9 project) and Università di Trieste (FRA-2013 project) are gratefully acknowledged for financial support of this research.

■ REFERENCES

(1) (a) *Molecular Encapsulation*; Brinker, U. H., Mieusset, J.-L., Eds.; John Wiley & Sons: Chichester, 2010. (b) Hof, F.; Craig, S. L.; Nuckolls, C.; Rebek, J., Jr. *Angew. Chem., Int. Ed.* **2002**, *41*, 1488−1508.

(2) Adriaenssens, L.; Ballester, P. *Chem. Soc. Rev.* **2013**, *42*, 3261−3277.

(3) (a) Ajami, D.; Rebek, J., Jr. *Acc. Chem. Res.* **2013**, *46*, 990−999. (b) Rieth, S.; Hermann, K.; Wang, B.-Y.; Badjic, J. D. *Chem. Soc. Rev.* **2011**, *40*, 1609−1622.

(4) (a) Avram, L.; Cohen, Y.; Rebek, J., Jr. *Chem. Commun.* **2011**, *47*, 5368−5375. (b) Aakeröy, C. B.; Rajbanshi, A.; Desper, J. *Chem. Commun.* **2011**, *47*, 11411−11413.

(5) (a) Bonaccorso, C.; Ciadamidaro, A.; Sgarlata, C.; Sciotto, D.; Arena, G. *Chem. Commun.* **2010**, *46*, 7139−7141. (b) Rudkevich, D. M. *Bull. Chem. Soc. Jpn.* **2002**, *75*, 393−413. (c) Shivanyuk, A.; Paulus, E. F.; Böhmer, V. *Angew. Chem., Int. Ed.* **1998**, *38*, 2906−2909.

(6) (a) Gil-Ramirez, G.; Chas, M.; Ballester, P. *J. Am. Chem. Soc.* **2010**, *132*, 2520−2521. (b) Ballester, P.; Gil-Ramirez, G. *Proc. Natl. Acad. Sci. U.S.A.* **2009**, *106*, 10455−10459.

(7) (a) Kida, T.; Iwamoto, T.; Asahara, H.; Hinoue, T.; Akashi, M. *J. Am. Chem. Soc.* **2013**, *135*, 3371−3374. (b) Harada, A. *Acc. Chem. Res.* **2001**, *34*, 456−464.

(8) (a) Yamanaka, M.; Kobayashi, K. *Asian J. Org. Chem.* **2013**, *2*, 276−289. (b) Tang, H.; de Oliveira, C. S.; Sonntag, G.; Gibb, C. L. D.; Gibb, B. C.; Bohne, C. *J. Am. Chem. Soc.* **2012**, *134*, 5544−5547. (c) Gan, H.; Gibb, B. C. *Chem. Commun.* **2012**, *48*, 1656−1658. (d) Busi, M.; Cantadori, B.; Boccini, F.; De Zorzi, R.; Geremia, S.; Dalcanale, E. *Eur. J. Org. Chem.* **2011**, 2629−2642. (e) Kulasekharan, R.; Ramamurthy, V. *Org. Lett.* **2011**, *13*, 5092−5095.

(9) (a) Mogck, O.; Paulus, E. F.; Böhmer, V.; Thondorf, I.; Vogt, W. *Chem. Commun.* **1996**, 2533−2534. (b) Shimizu, K. D.; Rebek, J., Jr. *Proc. Natl. Acad. Sci. U.S.A.* **1995**, *92*, 12403−12407.

(10) Cafeo, G.; Kohnke, F. H.; Valenti, L.; White, A. J. P. *Chem.—Eur. J.* **2008**, *14*, 11593−11600.

(11) Mecozzi and Rebek postulated that the ideal packing coefficient for capsule formation is 55% in solution and up to 70% in the solid state. See: Mecozzi, S.; Rebek, J., Jr. *Chem.—Eur. J.* **1998**, *4*, 1016−1022.

(12) (a) Espelt, M.; Ballester, P. *Org. Lett.* **2012**, *14*, 5708−5711. (b) Körner, S. K.; Tucci, F. C.; Rudkevich, D. M.; Heinz, T.; Rebek, J., Jr. *Chem.—Eur. J.* **2000**, *6*, 187−195.

(13) Capici, C.; Gattuso, G.; Notti, A.; Parisi, M. F.; Pappalardo, S.; Brancatelli, G.; Geremia, S. *J. Org. Chem.* **2012**, *77*, 9668−9675.

(14) (a) Gargiulli, C.; Gattuso, G.; Notti, A.; Pappalardo, S.; Parisi, M. F. *Tetrahedron Lett.* **2011**, *52*, 7116−7120. (b) Gattuso, G.; Notti, A.; Pappalardo, A.; Parisi, M. F.; Pisagatti, I.; Pappalardo, S.; Garozzo, D.; Messina, A.; Cohen, Y.; Slovak, S. *J. Org. Chem.* **2008**, *73*, 7280−7289. (c) Garozzo, D.; Gattuso, G.; Kohnke, F. H.; Notti, A.; Pappalardo, S.; Parisi, M. F.; Pisagatti, I.; White, A. J. P.; Williams, D. J. *Org. Lett.* **2003**, *5*, 4025−4028. (d) Garozzo, D.; Gattuso, G.; Kohnke, F. H.; Malvagna, P.; Notti, A.; Occhipinti, S.; Pappalardo, S.; Parisi, M. F.; Pisagatti, I. *Tetrahedron Lett.* **2002**, *43*, 7663−7667.

(15) Cohen, Y.; Avram, L.; Frish, L. *Angew. Chem., Int. Ed.* **2005**, *44*, 520−554.

(16) Brancatelli, G.; Pappalardo, S.; Gattuso, G.; Notti, A.; Piasagatti, I.; Parisi, M. F.; Geremia, S. *CrystEngComm* **2014**, *16*, 89−93.

(17) See the SI for full details.

(18) Even though no statistically significant difference between the K_a's was observed, a preference for $\mathbf{H_2NC_{12}H_{24}NH_2}$ was demonstrated by a direct 'competition' experiment on a $\mathbf{1{\cdot}H}$/$\mathbf{H_2NC_{10}H_{20}NH_2}$/$\mathbf{H_2NC_{12}H_{24}NH_2}$ 10:1:1 mixture (Figure S7), resulting in 59% vs 41% uptake of the longer diamine.

(19) Crystals were obtained from either $CHCl_3/CF_3CH_2OH$ or $CHCl_3/CF_3CH_2OH/CH_3OH$ solutions (see the SI).

(20) See Table S3 in the SI for full details.

(21) (a) Gattuso, G.; Notti, A.; Pappalardo, S.; Parisi, M. F.; Pilati, T.; Terraneo, G. *CrystEngComm* **2012**, *14*, 2621−2625. (b) Gattuso, G.; Notti, A.; Pappalardo, S.; Parisi, M. F.; Pilati, T.; Resnati, G.; Terraneo, G. *CrystEngComm* **2009**, *11*, 1204−1206.

(22) For typical examples of guest helical folding within a cylindrical capsule, see: (a) Asadi, A.; Ajami, D.; Rebek, J., Jr. *J. Am. Chem. Soc.* **2011**, *133*, 10682−10684. (b) Scarso, A.; Trembleau, L.; Rebek, J., Jr. *J. Am. Chem. Soc.* **2004**, *126*, 13512−13518 and references cited therein.

(23) The asymmetric unit contains two independent $\mathbf{1^{-}\supset{}^{+}H_3NC_{11}H_{22}NH_3^{+}\subset 1^{-}}$ capsular complexes (designated hereafter as **I** and **II**), both displaying very similar overall conformations. See the SI.

(24) The volumes of the inner cavity of the capsules were determined using the VOIDOO program; see: Kleywegt, G. J.; Jones, T. A. *Acta Crystallogr.* **1994**, *D50*, 178−185.