ChemPubSoc Europe

DOI: 10.1002/chem.201406492

CHEMISTRY
A European Journal
Communication

Host–Guest Systems

Twisted Baskets

Keith Hermann,[a] Yaowalak Pratumyot,[a] Shane Polen,[a] Alex M. Hardin,[a] Erdin Dalkilic,[b] Arif Dastan,[b] and Jovica D. Badjić*[a]

Abstract: A preparative procedure for obtaining a pair of twisted molecular baskets, each comprising a chiral framework with either right ((*P*)-$\mathbf{1}_{syn}$) or left ((*M*)-$\mathbf{1}_{syn}$) sense of twist and six ester groups at the rim has been developed and optimized. The racemic (*P*/*M*)-$\mathbf{1}_{syn}$ can be obtained in three synthetic steps from accessible starting materials. The resolution of (*P*/*M*)-$\mathbf{1}_{syn}$ is accomplished by its transesterification with (1*R*,2*S*,5*R*)-(−)-menthol in the presence of a Ti^{IV} catalyst to give diastereomeric $\mathbf{8}^{P}$ and $\mathbf{8}^{M}$. It was found that dendritic-like cavitands $\mathbf{8}^{P}$ and $\mathbf{8}^{M}$, in CD_2Cl_2, undergo self-inclusion (^{1}H NMR spectroscopy) with a menthol moiety occupying the cavity of each host. Importantly, the degree of inclusion of the menthol group was (^{1}H NMR spectroscopy) found to be greater in the case of $\mathbf{8}^{P}$ than $\mathbf{8}^{M}$. Accordingly, it is suggested that different folding characteristic of $\mathbf{8}^{P}$ and $\mathbf{8}^{M}$ ought to affect the physicochemical characteristics of the hosts to permit their effective separation by column chromatography. The absolute configuration of $\mathbf{8}^{P}$/$\mathbf{8}^{M}$, encompassing right- and left-handed "cups", was determined with the exciton chirality method and also verified in silico (DFT: B3LYP/TZVP). Finally, the twisted baskets are strongly fluorescent due to three naphthalene chromophores, having a high fluorescence quantum yield within the rigid framework of $\mathbf{8}^{P}$/$\mathbf{8}^{M}$.

The resolution of chiral drugs and drug intermediates[1] by fractional crystallization[2] of diastereomeric salts represents a form of stereoselective molecular recognition, allowing the production of enantiopure pharmaceuticals.[3] In line with this useful methodology, Newman and co-workers completed the separation of racemic (*P*/*M*)-hexahelicenes using a chiral derivative of fluorenone.[4] Allegedly, the aromatic fluorenone forms a charge-transfer complex with inherently chiral hexahelicenes[5] so that the attractive π–π interactions trigger the aggregation and consequently the precipitation of the less-soluble diastereomer. Furthermore, Cram and co-workers developed a semi-empirical approach, "the tripodal binding model", for predicting the complexation aptitude of C_2/D_2 symmetric 1,1′-binapthyl corands toward racemic amino acids.[6] In this vein, the classical three-point interaction model[7] or other variants[8] are employed to explain diastereoselectivity of drug–receptor interactions as well as inclusion complexations.[9] Indeed, artificial hosts with an enforced cavity—cavitands—are also capable of resolving chiral compounds[10] yet the experimental outcome of such recognition events is difficult to rationalize let alone predict.[11] As many naturally occurring molecules, drugs, metabolites, chemical weapons and commodity chemicals lack the rotation–reflection axis of symmetry, there exists a need to expand the scope of artificial chiral hosts[12] to selectively capture these substances[13] on the basis of their size, shape and electronic structure, as well as learn more about rules that govern the process of stereoselective recognition.[8b,14] Artificial chiral receptors could, furthermore, serve as counterparts to naturally occurring enzymes and antibodies for rapidly and accurately reporting on the presence of stereoisomeric substances in the environment[15] and promoting their transformation.[16] In line with a need for developing cup-shaped chiral hosts,[17] we recently described[18] a synthetic method for the preparation of novel cavitands possessing a nonfunctional hydrocarbon framework and twisted (Figure 1) inner space.[17a,c,d] In particular, a tandem of cyclialkylation reactions was promoted with strong acids to, via general-acid catalysis, give rise to baskets (akin to (*P*/*M*)-$\mathbf{1}_{syn}$ in Figure 1) comprising six stereogenic centers of the same kind (*R* or *S*) embedded in the host's bicyclic platform. In this study, we focused on developing a preparative procedure for obtaining a pair of functionalized baskets with right (*P*)-$\mathbf{1}_{syn}$ and left (*M*)-$\mathbf{1}_{syn}$ twisted frameworks (Figure 1) to learn about the resolution of such racemic host. Notably, chiral baskets of type **1** are C_3 symmetric and modular cavitands, possessing: 1) six esters at the rim for additional functionalization, 2) unique chiroptical characteristics, 3) photochemically sensitizing sidewalls for promoting photochirogenesis,[19] and 4) deep and twisted hydrophobic pockets[20] for discriminating chiral guests (Figure 1).[21]

To obtain basket **1**, we started with commercially available 5-indanol and converted it into compound **2** (Scheme 1)[22] following already known procedures (Scheme S3 in the Supporting Information).[23] The free-radical bromination of indane derivative **2** followed by, allegedly, E1 elimination of the bromoalkane intermediate gave indene **3**. Compound **3** was deprotonated with a strong base (*n*BuLi), at a low temperature, to act as a nucleophile in promoting the substitution of three iodine groups in 1,3,5-tris(iodomethyl)benzene. When these reactants were combined in the proportion of 6:1 (with

[a] K. Hermann, Y. Pratumyot, S. Polen, A. M. Hardin, Prof. J. D. Badjić
Department of Chemistry and Biochemistry
The Ohio State University, 100 West 18th Avenue (USA)
E-mail: badjic.1@osu.edu

[b] E. Dalkilic, Prof. A. Dastan
Ataturk University, Faculty of Sciences, Erzurum (Turkey)

Supporting information for this article is available on the WWW under http://dx.doi.org/10.1002/chem.201406492.

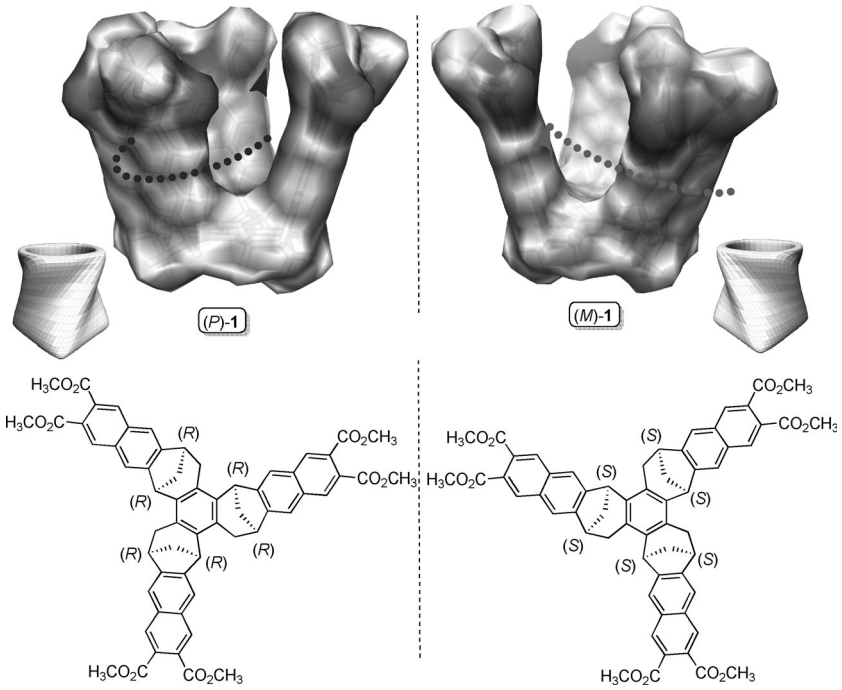
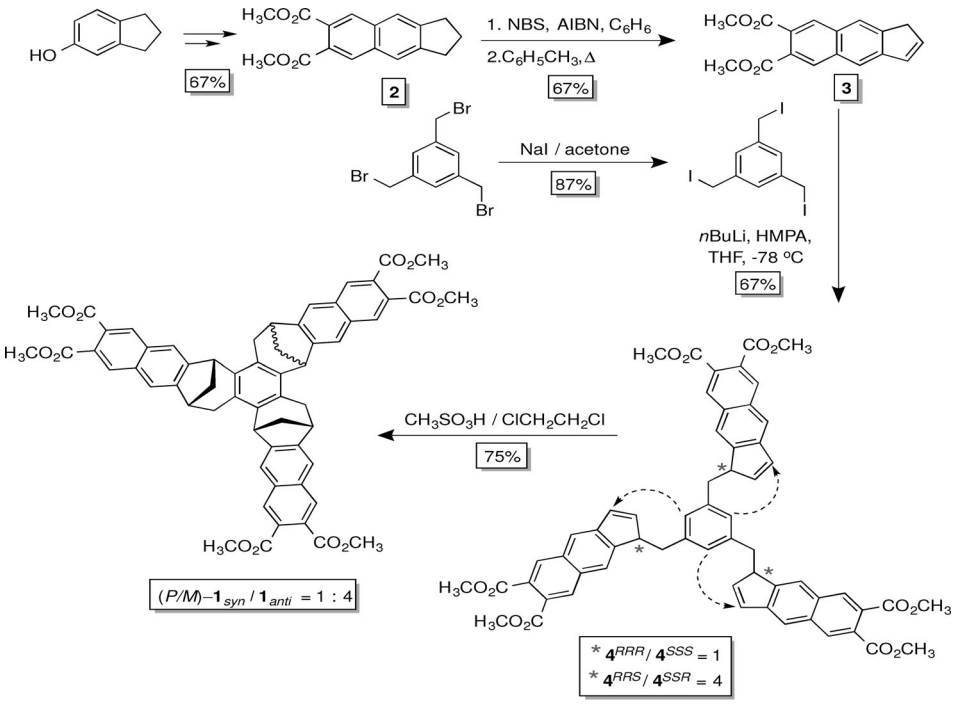


Figure 1. Energy-minimized structures (MMFFs) of twisted baskets (*P*)-$\mathbf{1}_{syn}$ and (*M*)-$\mathbf{1}_{syn}$ (top) and their chemical structures (bottom).

sixfold excess of indene **3**), two diastereomeric products $\mathbf{4}^{RRR}$/$\mathbf{4}^{SSS}$ and $\mathbf{4}^{RRS}$/$\mathbf{4}^{SSR}$ (Scheme S4 in the Supporting Information) formed in a ratio of 1:4, respectively. The cyclialkylation of the diastereomeric mixture of **4** was then catalyzed with methanesulfonic acid to give (*P*/*M*)-$\mathbf{1}_{syn}$ and $\mathbf{1}_{anti}$ (Scheme 1) in the same 1:4 proportion. On the basis of our earlier study,[18] we reasoned that this transformation is under kinetic control with homochiral $\mathbf{4}^{RRR}$/$\mathbf{4}^{SSS}$ giving the desired (*P*/*M*)-$\mathbf{1}_{syn}$ and heterochiral $\mathbf{4}^{RRS}$/$\mathbf{4}^{SSR}$ transforming into $\mathbf{1}_{anti}$ product; to optimize the yield of cup-shaped (*P*/*M*)-$\mathbf{1}_{syn}$, we examined the stereoselectivity of the conversion of **3** into **4**, and describe these efforts in Scheme S30 in the Supporting Information.

To resolve racemic (*P*/*M*)-$\mathbf{1}_{syn}$, we decided to investigate the transesterification[24] of (*P*/*M*)-$\mathbf{1}_{syn}$ with (1*R*,2*S*,5*R*)-(−)-menthol in the presence of titanium(IV) catalyst **7**[25] (Figure 2).[26] To ensure a complete transformation of the hexaester reactant into sterically hindered $\mathbf{8}^{P}$ and $\mathbf{8}^{M}$, with six menthol groups at the rim, we used menthol as solvent and ran the reaction at an elevated temperature (180 °C) for a prolonged period of time.[27] Importantly, the chromatographic separation of diastereomeric $\mathbf{8}^{P}$/$\mathbf{8}^{M}$ was facile with each compound having a distinct R_f value (R_f = 0.37 and 0.50, Figure 2).

^{1}H NMR spectra (400 MHz, CD_2Cl_2) of isolated $\mathbf{8}^{P}$ and $\mathbf{8}^{M}$ (Figure 3 A) revealed a single set of resonances corresponding to, in each case, a C_3 symmetric compound; note that there was no decoalescence of ^{1}H NMR signals at lower temperatures, suggesting a rapid rotation of the menthol moieties at the rim (from 273.0 to 233.0 K, Figures S28 and S29 in the Supporting Information). First, we assigned proton resonances of model compound **9** (Figure 3 A and B; for a full assignment see Figures S17–S19 in the Supporting Information) using its ^{1}H-^{1}H COSY NMR correlations (Figures S17–S19) in addition to the reported spectroscopic assignment for (1*R*,2*S*,5*R*)-(−)-menthol.[28] Next, we recorded ^{1}H-^{1}H COSY NMR spectra of $\mathbf{8}^{P}$/$\mathbf{8}^{M}$



Scheme 1. The synthesis of twisted basket (*P*/*M*)-$\mathbf{1}_{syn}$ can be completed in several steps from simple starting material.

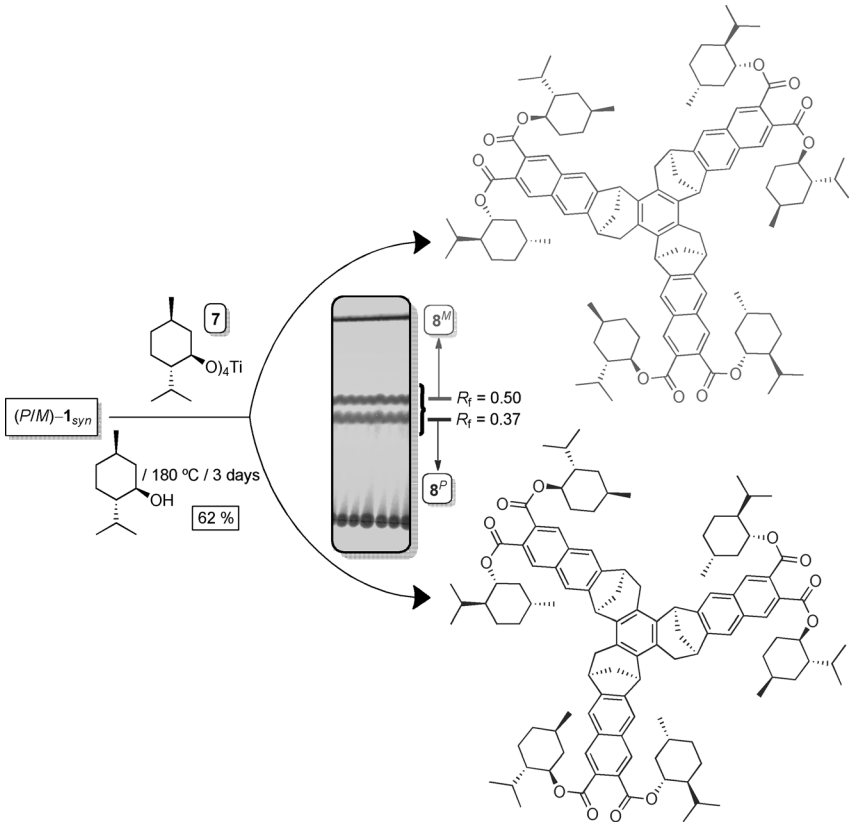


Figure 2. The chromatographic separation (SiO_2, hexanes/diethyl ether = 2:1) of $\mathbf{8}^P$ and $\mathbf{8}^M$, obtained by a Ti^{IV}-promoted transesterification of (*P*/*M*)-$\mathbf{1}_{syn}$, is facile, with each compound showing a separate band on a thin-layer chromatographic plate. Spectroscopic analyses of the chromatographic fractions are in line with the top band corresponding to $\mathbf{8}^M$ while the bottom one to $\mathbf{8}^P$.

(Figures S20–S27 in the Supporting Information) and assigned all of the observed resonances to proton nuclei within these diastereomeric compounds (Figure 3 A and B, for a full assignment see Figures S20–S27). A correlation between ^{1}H NMR spectra of C_2 symmetric **9** and C_3 symmetric $\mathbf{8}^P/\mathbf{8}^M$ is apparent yet we note an upfield shift of: 1) two doublets corresponding to $H_{a/b}$ nuclei, and 2) multiplet corresponding to the juxtaposed H_m proton, all as a part of the menthol substituents (Figure 3 A and B). To address the observation, we completed the Monte Carlo conformational study (MMFFs force field, Spartan) of $\mathbf{8}^P/\mathbf{8}^M$ with the calculation suggesting a conformational distribution being predominantly populated (> 95 % on the basis of the Boltzmann distribution at 298 K) with structures closely resembling those shown in Figure 3 C. That is to say, the $\mathbf{8}^P$ diastereomer places one of its menthol isopropyl groups in the cavity of the cup-shaped and twisted framework so that H_a/H_b and H_m nuclei reside in the shielding region of the surrounding naphthalene rings. On the contrary, the $\mathbf{8}^M$ stereoisomer positions an isopropyl group at top of the cavity (Figure 3 C) with H_a/H_b and H_m nuclei being less diamagnetically shielded with the basket's aromatics. It follows that the middle ^{1}H NMR spectrum in Figure 3 A should correspond to $\mathbf{8}^M$ ($R_f = 0.50$, Figure 2) having its H_a/H_b protons less diamagnetically shielded while the bottom one correlates with $\mathbf{8}^P$ ($R_f = 0.37$, Figure 2). Furthermore, we surmise that the two diastereomers eluted on silica at different times due to, in part, their distinctive folding characteristics with the more compact $\mathbf{8}^P$ being retained to a greater degree.

To additionally probe the absolute configuration of compounds $\mathbf{8}^P/\mathbf{8}^M$, encompassing right- and left-handed "cups" (Figure 3), we used the exciton chirality method (exciton coupled circular dichroism spectroscopy, ECCD).[29] In this regard, three naphthalene chromophores[30] that constitute the "sides" of twisted baskets $\mathbf{8}^P/\mathbf{8}^M$ are embedded in the bicyclic and chiral framework, formally belonging to the second chiral sphere.[31] Upon the absorption of light at about 220 nm (naphthalene's ^1B_b transition in the Platt's notation),[30] each of the juxtaposed naphthalenes should in $\mathbf{8}^P/\mathbf{8}^M$ develop a strong electric dipole transition moment positioned along the long axis of the aromatic ring (Figure 4 A).[32] In line with the ECCD,[31] there should be an exciton coupling of the ^1B_b transition dipole moments of the three degenerate chromophores to give rise to a bisignate spectrum with the rotational strengths and sign being a function of their interchromophoric distance (d) and orientation (Ω).[31] In particular, the sign of the couplet is based on the semi-empirical exciton chirality rule which states: the negative chirality (the longer wavelength component has $\Delta\varepsilon < 0$) is obtained when the chromophores are positioned in space so that a counterclockwise rotation of the front electric dipole moment by an acute angle brings it onto the exciton axis in the back.[33] Indeed, CD spectra of diastereomeric baskets $\mathbf{8}^P/\mathbf{8}^M$ (Figure 4 A) showed the expected ECCD couplets centered at 242 nm (π to π^* transition, Figure 4 A)[32] with two diastereomeric baskets having the opposite rotational strengths.[21] Specifically, the positive Cotton effect (CE) at 234 nm ($\Delta\varepsilon_1 = 284\ M^{-1}cm^{-1}$, blue spectrum in Figure 4 A) is accompanied with a negative CE at 251 nm ($\Delta\varepsilon_2 = -252\ M^{-1}cm^{-1}$, blue spectrum in Figure 4 A) to give the negative sign of exciton chirality, which is consistent with the position of exciton axis in $\mathbf{8}^P$ (Figure 4 A). As the blue spectrum (Figure 4 A) corresponds to basket $\mathbf{8}^P$ isolated as the chromatographic fraction with $R_f = 0.37$, Figure 3), the CD assignment corroborates the absolute chirality obtained from the ^{1}H NMR spectroscopic measurements (Figure 3). Furthermore, the large A value ($|\Delta\varepsilon_1| + |\Delta\varepsilon_2|$) of 535 indicates a through-space interaction of the naphthalene chromophores in $\mathbf{8}^P$ with a contribution from all three ECCD couplets[35] thereby following the

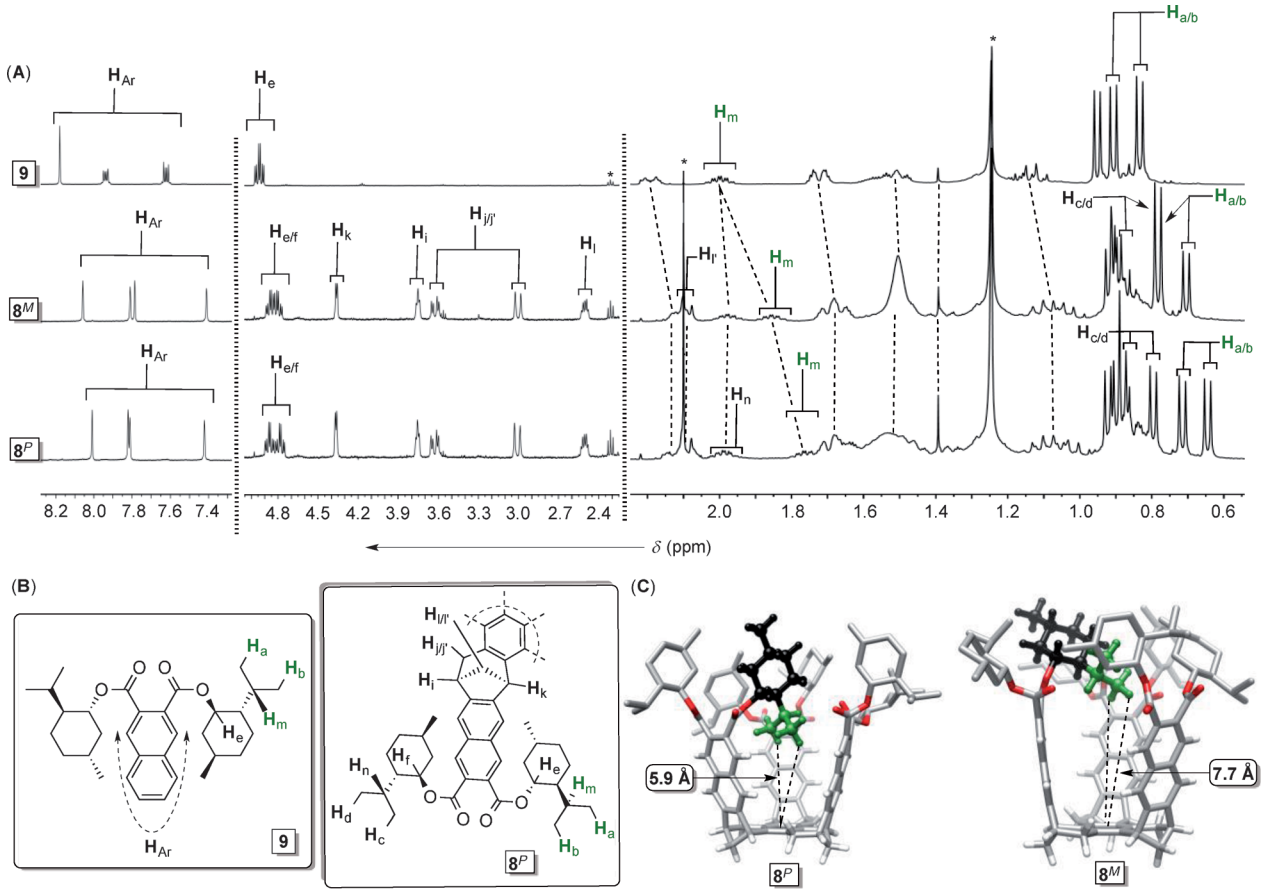


Figure 3. A) ^{1}H NMR spectra (400 MHz, CD_2Cl_2) of model compound **9** (top) and twisted baskets $\mathbf{8}^M$ (middle) and $\mathbf{8}^P$ (bottom). B) Chemical structures of **9** and $\mathbf{8}^P$ with selected protons labeled from H_a to H_n. C) Energy-minimized (MMFFs, Monte Carlo conformational search; 1000 steps) structures of $\mathbf{8}^M$ and $\mathbf{8}^P$, representing the most abundant conformers (>95%) obtained in the calculation; note that C–H–π centroid distances are shown, while some hydrogen atoms are removed for clarity.

pair-wise additivity principle.[31] By comparison, model compound **9** exhibits a featureless CD spectrum (black spectrum in Figure 4A) with low rotational strengths at all wavelengths. Two menthol units are, in the absence of the bicyclic chiral framework, exerting a negligible symmetry-breaking perturbation of the electronic states of **9**.[31] We also computed the UV/Vis and CD spectra of energy-minimized (*M*)-$\mathbf{1}_{syn}$ (Figure 4B) using time-dependent density functional theory (TD-B3LYP/TZVP).[34] Notably, there is a good agreement between the observed positive exciton chirality of $\mathbf{8}^M$ centered at 242 nm and the computed ECCD couplet of (*M*)-$\mathbf{1}_{syn}$. The absolute configuration of *P*/*M* twisted baskets is in this way confirmed and in line with the assignment from the ECCD method and NMR experiments. Finally, the emission spectra of diastereomeric $\mathbf{8}^P/\mathbf{8}^M$ are comparable ($\lambda_{exc.}=280$ nm, Figure S33 in the Supporting Information). Importantly, the signal intensities for the baskets ($I=282$ a.u. at $\lambda_{em.}=363$ nm, Figure S33) are seventy times stronger than for the model compound **9** ($I=4$ a.u. at $\lambda_{em.}=363$ nm, Figure S33). Given that the absorption extinction coefficients (ε, Figure 4) are at 280 nm three times greater for baskets than for the model compound, we reason that naphthalene chromophores ought to have a greater fluorescence quantum yield within the rigid framework of $\mathbf{8}^P/\mathbf{8}^M$.[36] Apparently, twisted baskets are well suited[20a,37] for building chiroptical sensors capable of reporting on the presence of minute quantities of chiral substances in the environment.[38]

In conclusion, we have completed the preparation of a novel cavitand comprising a twisted concave platform (*P* or *M*) and six ester groups at the rim. This host is modular, that is, prone to additional functionalization, with a deep and chiral hydrophobic pocket made of three photochemically active naphthalene rings. The functional and twisted baskets can now be used for: 1) building chiroptical sensors capable of reporting on the presence of minute quantities of chiral substances in the environment,[39] 2) resolving useful drugs and drug intermediates,[13] and/or 3) developing novel stereoselective supramolecular catalysts.[40]

Acknowledgements

This work was financially supported with funds obtained from the National Science Foundation under CHE-1305179. Computational support from the Ohio Supercomputer Center is gratefully acknowledged. E.D. is grateful for the predoctoral fellowship received from the Turkish National Science Foundation (TUBITAK).

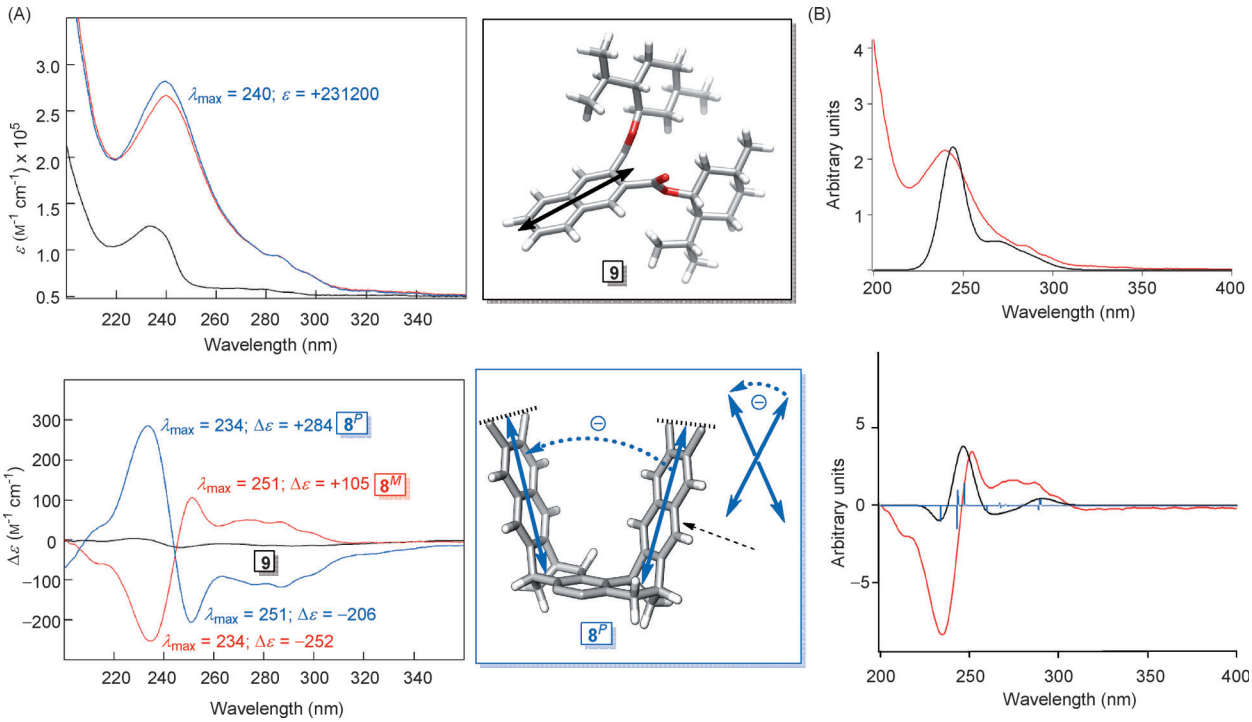


Figure 4. A) Absorption (UV/Vis, top left) and circular dichroism (CD, bottom left) spectra of 8^P (blue, 2.5 μM), 8^M (red, 2.5 μM) and **9** (black, 5.0 μM) in hexane at 298 K. Energy-minimized structure of model compound **9** (MMFFs, Spartan) with the ^1B_b transition dipole moment along the naphthalene chromophore (top right). The negative exciton chirality characterizes twisted basket 8^P since its three naphthalene chromophores (only two are shown) are positioned in space so that a counterclockwise rotation of the front electric dipole moment (blue) by an acute angle brings it onto the exciton axis in the back (bottom right). B) Computed DFT: B3LYP/TZVP (black)[34] UV/Vis (top) and CD (bottom) spectra of basket (*M*)-$\mathbf{1}_{syn}$; for comparison, UV/Vis (top) and CD (bottom) spectra of 8^M (red) are included. The blue sticks are computed electronic transitions that were subjected to Gaussian broadening (0.25 eV) and wavelength shift (−0.2 eV) for generating the computed spectra.

Keywords: cavitands · encapsulation · host–guest systems · stereoselective recognition · supramolecular chirality

[1] Chirality in Drug Research, in *Methods and Principles in Medicinal Chemistry* (Eds.: E. Francotte, W. Lindner) Wiley-VCH, Weinhem, **2006**, Vol. 33.
[2] E. L. Eliel, S. H. Wilen, L. N. Mander, *Stereochemistry of Organic Compounds*, **1994**, Wiley, New York, **1994**.
[3] Q.-D. You, *Chiral Drugs* **2011**, 137–194.
[4] a) M. S. Newman, D. Lednicer, *J. Am. Chem. Soc.* **1956**, *78*, 4765–4770; b) M. S. Newman, W. B. Lutz, D. Lednicer, *J. Am. Chem. Soc.* **1955**, *77*, 3420–3421.
[5] I. R. Mackay, J. M. Robertson, J. G. Sime, *J. Chem. Soc. D* **1969**, 1470–1471.
[6] *Container Molecules and Their Guests* (Eds.: D. J. Cram, J. M. Cram), RSC, Cambrige, **1997**.
[7] T. D. Booth, D. Wahnon, I. W. Wainer, *Chirality* **1997**, *9*, 96–98.
[8] a) S.-G. Kim, K.-H. Kim, J. Jung, S. K. Shin, K. H. Ahn, *J. Am. Chem. Soc.* **2002**, *124*, 591–596; b) C. Moberg, *Angew. Chem. Int. Ed.* **2006**, *45*, 4721–4723; *Angew. Chem.* **2006**, *118*, 4838–4840.
[9] a) M. Mikolajczyk, J. Drabowicz, *J. Am. Chem. Soc.* **1978**, *100*, 2510–2515; b) H. Bakirci, W. M. Nau, *J. Org. Chem.* **2005**, *70*, 4506–4509.
[10] a) A. Bouchet, T. Brotin, M. Linares, H. Aagren, D. Cavagnat, T. Buffeteau, *J. Org. Chem.* **2011**, *76*, 4178–4181; b) J. Yoon, D. J. Cram, *J. Am. Chem. Soc.* **1997**, *119*, 11796–11806; c) E. S. Barrett, J. L. Irwin, P. Turner, M. S. Sherburn, *Org. Lett.* **2002**, *4*, 1455–1458; d) A. J. Terpin, M. Ziegler, D. W. Johnson, K. N. Raymond, *Angew. Chem. Int. Ed.* **2001**, *40*, 157–160; *Angew. Chem.* **2001**, *113*, 755–758; e) C. Nuckolls, F. Hof, T. Martin, J. Rebek, Jr., *J. Am. Chem. Soc.* **1999**, *121*, 10281–10285; f) N. Li, F. Yang, H. A. Stock, D. V. Dearden, J. D. Lamb, R. G. Harrison, *Org. Biomol. Chem.* **2012**, *10*, 7392–7401; g) J. M. Rivera, T. Martin, J. Rebek, Jr., *Science* **1998**, *279*, 1021–1023; h) H. Singh, R. Warmuth, *Tetrahedron* **2002**, *58*, 1257–1264.
[11] K. Kano, *J. Phys. Org. Chem.* **1997**, *10*, 286–291.
[12] a) M. C. Schopohl, C. Siering, O. Kataeva, S. R. Waldvogel, *Angew. Chem. Int. Ed.* **2003**, *42*, 2620–2623; *Angew. Chem.* **2003**, *115*, 2724–2727; b) H. J. Schneider, *Angew. Chem. Int. Ed. Engl.* **1993**, *32*, 848–850; *Angew. Chem.* **1993**, *105*, 890–892; c) F. Fabris, L. Pellizzaro, C. Zonta, O. De Lucchi, *Eur. J. Org. Chem.* **2007**, 283–291; d) R. J. Pieters, F. Diederich, *Chem. Commun.* **1996**, 2255–2256; e) Y. Ferrand, A. M. Kendhale, B. Kauffmann, A. Grelard, C. Marie, V. Blot, M. Pipelier, D. Dubreuil, I. Huc, *J. Am. Chem. Soc.* **2010**, *132*, 7858-7859; f) M. T. Reetz, J. Rudolph, R. Mynott, *J. Am. Chem. Soc.* **1996**, *118*, 4494–4495.
[13] D. Ma, G. Hettiarachchi, D. Nguyen, B. Zhang, J. B. Wittenberg, P. Y. Zavalij, V. Briken, L. Isaacs, *Nat. Chem.* **2012**, *4*, 503–510.
[14] M. T. Reetz, *Pure Appl. Chem.* **1996**, *68*, 1279–1283.
[15] A. E. Hargrove, S. Nieto, T. Zhang, J. L. Sessler, E. V. Anslyn, *Chem. Rev.* **2011**, *111*, 6603–6782.
[16] a) J. K. M. Sanders, *Chem. Eur. J.* **1998**, *4*, 1378-1383; b) M. J. Wiester, P. A. Ulmann, C. A. Mirkin, *Angew. Chem. Int. Ed.* **2011**, *50*, 114–137; *Angew. Chem.* **2011**, *123*, 118–142.
[17] a) M. Havlík, B. Dolensky, J. Kessler, I. Cisarova, V. Kral, *Supramol. Chem.* **2012**, *24*, 127–134; b) B. Dolenský, M. Havlik, V. Kral, *Chem. Soc. Rev.* **2012**, *41*, 3839–3858; c) M. Valík, J. Cejka, M. Havlik, V. Kral, B. Dolensky, *Chem. Commun.* **2007**, 3835–3837; d) M. Valík, B. Dolensky, H. Petrickova, V. Kral, *Collect. Czech. Chem. Commun.* **2002**, *67*, 609–621.
[18] K. Hermann, D. A. Turner, C. M. Hadad, J. D. Badjic, *Chem. Eur. J.* **2012**, *18*, 8301–8305.
[19] a) G. Fukuhara, T. Mori, Y. Inoue, *J. Org. Chem.* **2009**, *74*, 6714–6727; b) G. Fukuhara, M. Imai, C. Yang, T. Mori, Y. Inoue, *Org. Lett.* **2011**, *13*, 1856–1859.

[20] a) S. Chen, Y. Ruan, J. D. Brown, J. Gallucci, V. Maslak, C. M. Hadad, J. D. Badjic, *J. Am. Chem. Soc.* **2013**, *135*, 14964 – 14967; b) J. H. Jordan, B. C. Gibb, *Chem. Soc. Rev.* **2014**, *44*, 547 – 585.
[21] G. Fukuhara, S. Madenci, J. Polkowska, F. Bastkowski, F.-G. Klaerner, Y. Origane, M. Kaneda, T. Mori, T. Wada, Y. Inoue, *Chem. Eur. J.* **2007**, *13*, 2473 – 2479.
[22] S. Kotha, P. Khedkar, *J. Org. Chem.* **2009**, *74*, 5667 – 5670.
[23] a) S. García-Rubín, C. Gonzalez-Rodriguez, C. Garcia-Yebra, J. A. Varela, M. A. Esteruelas, C. Saa, *Angew. Chem. Int. Ed.* **2014**, *53*, 1841 – 1844: Angew. Chem. **2014**, 126, 1872 – 1875; b) A. T. Biju, F. Glorius, *Angew. Chem. Int. Ed.* **2010**, *49*, 9761 – 9764; *Angew. Chem.* **2010**, *122*, 9955 – 9958; c) D. Peña, D. Perez, E. Guitián, L. Castedo, *J. Am. Chem. Soc.* **1999**, *121*, 5827 – 5828; d) B.-J. Pei, W.-H. Chan, A. W. M. Lee, *Org. Lett.* **2011**, *13*, 1774 – 1777.
[24] M. I. Siling, T. N. Laricheva, *Usp. Khim.* **1996**, *65*, 296 – 304.
[25] a) Y. S. Matveev, L. L. Frolova, N. A. Kataeva, A. V. Kuchin, *Russ. J. Gen. Chem.* **2007**, *77*, 1196 – 1203; b) Y. Pérez, I. del Hierro, M. Fajardo, A. Otero, *J. Organomet. Chem.* **2003**, *679*, 220 – 228.
[26] H. Urabe, F. Sato, in *Lewis Acids Organic Synthesis, Vol. 2* (Ed.: H. Yamamoto), Wiley-VCH, Weinheim, **2000**, pp. 653 – 798.
[27] P. Krasik, *Tetrahedron Lett.* **1998**, *39*, 4223 – 4226.
[28] E. E. Kwan, S. G. Huang, *Eur. J. Org. Chem.* **2008**, 2671 – 2688.
[29] N. Harada, K. Nakanishi, N. Berova, in *Comprehensive Chiroptical Spectroscopy, Vol. 2*, Wiley, New York, **2012**, pp. 115 – 166.
[30] M. Rubio, M. Merchan, E. Orti, B. O. Roos, *Chem. Phys.* **1994**, *179*, 395 – 409.
[31] N. Berova, L. Di Bari, G. Pescitelli, *Chem. Soc. Rev.* **2007**, *36*, 914 – 931.
[32] S. Jurinovich, G. Pescitelli, L. Di Bari, B. Mennucci, *Phys. Chem. Chem. Phys.* **2014**, *16*, 16407 – 16418.
[33] *Circular Dichroism: Principles and Applications* (Eds.: N. Berova, K. Nakanishi, R. W. Woody), Wiley-VCH, Weinheim, **2000**.
[34] S. Grimme, F. Furche, R. Ahlrichs, *Chem. Phys. Lett.* **2002**, *361*, 321 – 328.
[35] S. Stojanovic, D. A. Turner, A. I. Share, A. H. Flood, C. M. Hadad, J. D. Badjic, *Chem. Commun.* **2012**, *48*, 4429 – 4431.
[36] K. Hermann, S. Sardini, Y. Ruan, R. J. Yoder, M. Chakraborty, S. Vyas, C. M. Hadad, J. D. Badjic, *J. Org. Chem.* **2013**, *78*, 2984 – 2991.
[37] a) Y. Ruan, B.-Y. Wang, J. M. Erb, S. Chen, C. M. Hadad, J. D. Badjic, *Org. Biomol. Chem.* **2013**, *11*, 7667 – 7675; b) Y. Ruan, E. Dalkilic, P. W. Peterson, A. Pandit, A. Dastan, J. D. Brown, S. M. Polen, C. M. Hadad, J. D. Badjic, *Chem. Eur. J.* **2014**, *20*, 4251 – 4256.
[38] a) T. Nehira, C. A. Parish, S. Jockusch, N. J. Turro, K. Nakanishi, N. Berova, *J. Am. Chem. Soc.* **1999**, *121*, 8681 – 8691; b) K. Tanaka, G. Pescitelli, K. Nakanishi, N. Berova, *Monatsh. Chem.* **2005**, *136*, 367 – 395.
[39] a) J. W. Canary, S. Mortezaei, J. Liang, *Coord. Chem. Rev.* **2010**, *254*, 2249 – 2266; b) P. Metola, S. M. Nichols, B. Kahr, E. V. Anslyn, *Chem. Sci.* **2014**, *5*, 4278 – 4282.
[40] a) M. Raynal, P. Ballester, A. Vidal-Ferran, P. W. N. M. van Leeuwen, *Chem. Soc. Rev.* **2014**, *43*, 1734 – 1787; b) M. Raynal, P. Ballester, A. Vidal-Ferran, P. W. N. M. van Leeuwen, *Chem. Soc. Rev.* **2014**, *43*, 1660 – 1733.

Received: December 15, 2014
Published online on January 21, 2015