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Dynamic [2]Catenanes Based on a Hydrogen Bonding-Mediated Bis-Zinc Porphyrin Foldamer Tweezer: A Case Study

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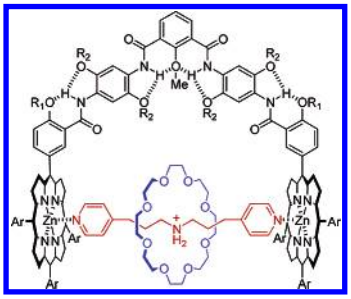

This paper describes the self-assembly of a new class of three-component dynamic [2]catenanes, which are driven or stabilized by intramolecular hydrogen bonding, coordination, and electrostatic interaction. One of the component molecules **2**, consisting of an aromatic oligoamide spacer and two peripheral zinc porphyrin units, was designed to adopt a folded preorganized conformation, which is stabilized by consecutive intramolecular three-centered hydrogen bonds. Component molecule **3** is a linear secondary ammonium bearing two peripheral pyridine units, which was designed to form a 1:1 complex with 24-crown-8 (**5**). The ^{1}H NMR and UV−vis experiments in $CDCl_3$−CD_3CN (4:1 v/v) revealed that, due to the preorganized U-shaped feature, **2** could efficiently bind **3** through the cooperative zinc−pyridine coordination to generate highly stable 1:1 complex **2·3**. Adding **5** to the 1:1 solution of **2** and **3** led to the formation of dynamic three-component [2]catenane **2·3·5** as a result of the threading of **3** through **5**. ^{1}H NMR studies indicated that in the 1:1:1 solution (3 mM) [2]catenane **2·3·5** was generated in 55% yield at 25 °C. The yield was increased with the reduction of the temperature and [2]catenane could be produced quantitatively in a 1:1:2 solution ([**2**] = 3 mM) at −13 °C. Replacing **3** with 1,2-bis(4,4′-bipyridinium)ethane (**4**) in the three-component solution could also give rise to similar dynamic [2]-catenane **2·4·5** albeit in slightly lower yield.

Introduction

Because of their unique molecular structures and potential applications in molecular machines and electronic devices, in the past two decades the self-assembly of catenanes and related supramolecular architectures has been of great interest to chemists.[1,2] On the basis of kinetically controlled covalent bond formation, a vast number of catenanes have been constructed. Recently, the strategy of dynamic covalent chemistry[3] has also been extensively exploited for the synthesis of discrete types of catenanes.[4] Catenanes generated via both approaches are kinetically stable,[5] that is, the component rings in these supramolecular structures, once formed, are interlocked irreversibly. Catenanes incorporating coordination bonds in their component rings represent another class of structurally unique supramolecular constructs because their self-assembly is thermodynamically controlled and the component rings in these

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(1) (a) Schill, G. *Catenanes, Rotaxanes and Knots*; Academic Press: New York, 1971. (b) Amabilino, D. B.; Stoddart, J. F. *Chem. Rev.* **1995**, *95*, 2725. (c) Sauvage, J.-P.; Dietrich-Buchecker, C., Eds. *Molecular Catenanes, Rotaxanes and Knots*; Wiley-VCH: Weinheim, Germany, 1999.

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catenanes are able to exchange reversibly in solution. Moreover, they are also potentially useful supramolecular platforms for exploring new dynamic combinatorial chemistry. However, examples of catenanes assembled from the formation of coordination bonds-incorporated rings are relatively few.[6−8] Therefore, it remains of importance to develop new efficient approaches for such types of dynamic interlocked systems.

Foldamers are linear molecules that are induced by noncovalent forces to adopt rigidified well-established secondary structures.[9] Due to its directionality and strength, hydrogen bonding is one of the ideal noncovalent forces for constructing such structurally elegant artificial structures. As a result of the rigid and planar features of the aromatic amide unit, hydrogen bonding-induced foldamers with the aromatic oligoamide backbones usually possess highly predictable compact conformation.[10−21] We recently initiated a program to explore their potentials as a new generation of preorganized scaffolds for supramolecular self-assembly.[9i] Previously, we utilized rationally designed rigidified aromatic amide oligomers as backbones for constructing fullerene-recognizing supramolecular tweezers.[22] More recently we also assembled a new series of highly stable artificial heteroduplexes by introducing simple self-binding amide sites into preorganized aromatic oligoamide skeletons.[23] We herein describe how a foldamer-based bis-zinc porphyrin tweezer is utilized to efficiently direct the self-assembly of a new series of dynamic [2]catenanes from three components via two discrete noncovalent interactions.

Results and Discussion

The strategy used for the construction of the new class of dynamic [2]catenanes involves three components, i.e., A, B, and C, and is shown in Figure 1. Component A, incorporating two zinc porphyrin units, is driven by intramolecular hydrogen

(2) (a) Vögtle, F.; Dünnwald, T.; Schmidt, T. *Acc. Chem. Res.* **1996**, *29*, 451. (b) Sambrook, M. R.; Beer, P. D.; Wisner, J. A.; Paul, R. L.; Cowley, A. R. *J. Am. Chem. Soc.* **2004**, *126*, 15364. (c) Schalley, C. A.; Weilandt, T.; Brüggemann, J.; Vögtle, F. *Top. Curr. Chem.* **2004**, *248*, 141. (d) Balzani, V.; Credi, A.; Ferrer, B.; Silvi, S.; Venturi, M. *Top. Curr. Chem.* **2005**, *262*, 1. (e) Collin, J.-P.; Heitz, V.; Sauvage, J.-P. *Top. Curr. Chem.* **2005**, *262*, 29. (f) Moonen, N. N. P.; Flood, A. H.; Fernández, J. M.; Stoddart, J. F. *Top. Curr. Chem.* **2005**, *262*, 99. (g) Kay, E. R.; Leigh, D. A. *Top. Curr. Chem.* **2005**, *262*, 133. (h) Beer, P. D.; Sambrook, M. R.; Curiel, D. *Chem. Commun.* **2006**, 2105. (i) Leigh, D. A.; Perez, E. M. *Top. Curr. Chem.* **2006**, *265*, 185. (j) Bonnet, S.; Collin, J.-P.; Koizumi, M.; Mobian, P.; Sauvage, J.-P. *Adv. Mater.* **2006**, *18*, 1239.

(3) (a) Lehn, J.-M.; Eliseev, A. V. *Science* **2001**, *291*, 2331. (b) Otto, S.; Furlan, R. L. E.; Sanders, J. K. M. *Science* **2002**, *297*, 590. (c) Rowan, S. J.; Cantrill, S. J.; Cousins, G. R. L.; Sanders, J. K. M.; Stoddart, J. F. *Angew. Chem., Int. Ed.* **2002**, *41*, 899. (d) Furlan, R. L. E.; Otto, S.; Sanders, J. K. M. *Proc. Natl. Acad. Sci. U.S.A.* **2002**, *99*, 4801. (e) Raehm, L.; Hamilton, D. G.; Sanders, J. K. M. *Synlett* **2002**, 1743. (f) Reymond, J.-L. *Angew. Chem., Int. Ed.* **2004**, *43*, 5577. (g) Cantrill, S. J.; Chichak, K. S.; Peters, A. J.; Stoddart, J. F. *Acc. Chem. Res.* **2005**, *38*, 1. (h) de Bruin, B.; Hauwert, P.; Reek, J. N. H. *Angew. Chem., Int. Ed.* **2006**, 45, 2660.

(4) For representative examples, see: (a) Kolchinski, A. G.; Alcock, N. W.; Roesner, R. A.; Busch, D. H. *Chem. Commun.* **1998**, 1437. (b) Kidd, T. J.; Leigh, D. A.; Wilson, A. J. *J. Am. Chem. Soc.* **1999**, *121*, 1599. (c) Weck, M.; Mohr, B.; Sauvage, J.-P.; Grubbs, R. H. *J. Org. Chem.* **1999**, *64*, 5463. (d) Furusho, Y.; Oku, T.; Hasegawa, T.; Tsuboi, A.; Kihara, N.; Takata, T. *Chem. Eur. J.* **2003**, *9*, 2895. (e) Wang, L. Y.; Vysotsky, M. O.; Bogdan, A.; Bolte, M.; Böhmer, V. *Science* **2004**, *304*, 1312. (f) Schalley, C. A. *Angew. Chem., Int. Ed.* **2004**, *43*, 4399. (g) Badjić, J. D.; Cantrill, S. J.; Grubbs, R. H.; Guidry, E. N.; Orenes, R.; Stoddart, J. F. *Angew. Chem., Int. Ed.* **2004**, *43*, 3273. (h) Guidry, E. N.; Cantrill, S. J.; Stoddart, J. F.; Grubbs, R. H. *Org. Lett.* **2005**, *7*, 2129. (i) Fuller, A. M. L.; Leigh, D. A.; Lusby, P. J.; Slawin, A. M. Z.; Walker, D. B. *J. Am. Chem. Soc.* **2005**, *127*, 12612. (j) Zhu, X.-Z.; Chen, C.-F. *J. Am. Chem. Soc.* **2005**, *127*, 13158. (k) Bogdan, A.; Rudzevich, Y.; Vysotsky, M. O.; Böhmer, V. *Chem. Commun.* **2006**, 2941. (l) Hutin, M.; Schalley, C. A.; Bernardinelli, G.; Nitschke, J. R. *Chem. Eur. J.* **2006**, *12*, 4069.

(5) The dynamic covalent approach employs reversible reactions as the final covalent bond-forming step in the synthesis of catenanes or rotaxanes. Nevertheless, the resulting interlocked architectures are usually stable in the absence of catalysts or other additives.

(6) (a) Fujita, M. *Acc. Chem. Res.* **1999**, *32*, 53. (b) Tashiro, S.; Tominaga, M.; Kusukawa, T.; Kawano, M.; Sakamoto, S.; Yamakuchi, Y.; Fujita, M. *Angew. Chem., Int. Ed.* **2003**, *42*, 3267. (c) Hori, A.; Yamada, K.-i.; Fujita, M. *Angew. Chem., Int. Ed.* **2004**, *43*, 5016.

(7) (a) Try, A. C.; Harding, M. M.; Hamilton, D. G.; Sanders, J. K. M. *Chem. Commun.* **1998**, 723. (b) Chas, M.; Pia, E.; Toba, R.; Peinador, C.; Quintela, J. M. *Inorg. Chem.* **2006**, *45*, 6117. (c) Habermehl, N. C.; Jennings, M. C.; McArdle, C. P.; Mohr, F.; Puddephatt, R. J. *Organometallics* **2005**, *24*, 5004.

(8) Gruter, G.-J.; de Kanter, F. J. J.; Markies, P. R.; Nomoto, T.; Akkerman, O. S.; Bickelhaupt, F. *J. Am. Chem. Soc.* **1993**, *115*, 12179.

(9) (a) Gellman, S. H. *Acc. Chem. Res.* **1998**, *31*, 173. (b) Stigers, K. D.; Soth, M. J.; Nowick, J. S. *Curr. Opin. Chem. Biol.* **1999**, *3*, 714. (c) Hill, D. J.; Mio, M. J.; Prince, R. B.; Hughes, T. S.; Moore, J. S. *Chem. Rev.* **2001**, *101*, 3893. (d) Cubberley, M. S.; Iverson, B. L. *Curr. Opin. Chem. Biol.* **2001**, *5*, 650. (e) Schmuck, C. *Angew. Chem., Int. Ed.* **2003**, *42*, 2448. (f) Huc, I. *Eur. J. Org. Chem.* **2004**, 17. (g) Sanford, A.; Yamato, K.; Yang, X. W.; Yuan, L. H.; Han, Y. H.; Gong, B. *Eur. J. Biochem.* **2004**, *271*, 1416. (h) Stone, M. T.; Heemstra, J. M.; Moore, J. S. *Acc. Chem. Res.* **2006**, *39*, 11. (i) Li, Z.-T.; Hou, J.-L.; Li, C.; Yi, H.-P. *Chem. Asian J.* **2006**, *1*, 766.

(10) Hamuro, Y.; Geib, S. J.; Hamilton, A. D. *J. Am. Chem. Soc.* **1996**, *118*, 7529.

(11) (a) Corbin, P. S.; Zimmerman, S. C.; Thiessen, P. A.; Hawryluk, N. A.; Murray, T. J. *J. Am. Chem. Soc.* **2001**, *123*, 10475. (b) Mayer, M. F.; Nakashima, S.; Zimmerman, S. C. *Org. Lett.* **2005**, *7*, 3005.

(12) (a) Sinkeldam, R. W.; van Houtem, M. H. C. J.; Koeckelberghs, G.; Vekemans, J. A. J. M.; Meijer, E. W. *Org. Lett.* **2006**, *8*, 383. (b) Sinkeldam, R. W.; van Houtem, M. H. C. J.; Pieterse, K.; Vekemans, J. A. J. M.; Meijer, E. W. *Chem. Eur. J.* **2006**, *12*, 6129.

(13) (a) Gong, B.; Zeng, H.; Zhu, J.; Yuan, L.; Han, Y.; Cheng, S.; Furukawa, M.; Parra, R. D.; Kovalevsky, A. Y.; Mills, J. L.; Skrzypczak-Jankun, E.; Martinovic, S.; Smith, R. D.; Zheng, C.; Szyperski, T.; Zeng, X. C. *Proc. Natl. Acad. Sci. U.S.A.* **2002**, *99*, 11583. (b) Yang, X. W.; Martinovic, S.; Smith, R. D.; Gong, B. *J. Am. Chem. Soc.* **2003**, *125*, 9932. (c) Yang, X. W.; Yuan, L. H.; Yamato, K.; Brown, A. L.; Feng, W.; Furukawa, M.; Zeng, X. C.; Gong, B. *J. Am. Chem. Soc.* **2004**, *126*, 3148. (d) Zhang, A.; Han, Y.; Yamato, K.; Zeng, X. C.; Gong, B. *Org. Lett.* **2006**, *8*, 803.

(14) Kolomiets, E.; Berl, V.; Odriozola, I.; Stadler, A.-M.; Kyritsakas, N.; Lehn, J.-M. *Chem. Commun.* **2003**, 2868.

(15) Recker, J.; Tomcik, D.; Parquette, J. R. *J. Am. Chem. Soc.* **2000**, *122*, 10298.

(16) Hunter, C. A.; Spitaleri, A.; Tomas, S. *Chem. Commun.* **2005**, 3691.

(17) Hu, Z.-Q.; Hu, H.-Y.; Chen, C.-F. *J. Org. Chem.* **2006**, *71*, 1131.

(18) Kanamori, D.; Okamura, T.; Yamamoto, H.; Ueyama, N. *Angew. Chem., Int. Ed.* **2005**, *44*, 969.

(19) Masu, H.; Sakai, M.; Kishikawa, K.; Yamamoto, M.; Yamaguchi, K.; Kohmoto, S. *J. Org. Chem.* **2005**, *70*, 1423.

(20) (a) Jiang, H.; Léger, J.-M.; Huc, I. *J. Am. Chem. Soc.* **2003**, *125*, 3448. (b) Garric, J.; Léger, J.-M.; Huc, I. *Angew. Chem., Int. Ed.* **2005**, *44*, 1954. (c) Dolain, C.; Zhan, C.; Léger, J.-M.; Daniels, L.; Huc, I. *J. Am. Chem. Soc.* **2005**, *127*, 2400. (d) Dolain, C.; Léger, J.-M.; Delsuc, N.; Gornitzka, H; Huc, I. *Proc. Natl. Acad. Sci. U.S.A.* **2005**, *102*, 16146. (e) Buffeteau, T.; Ducasse, L.; Poniman, L.; Delsuc, N.; Huc, I. *Chem. Commun.* **2006**, 2714.

(21) (a) Wu, Z.-Q.; Jiang, X.-K.; Zhu, S.-Z.; Li, Z.-T. *Org. Lett.* **2004**, *6*, 229. (b) Zhu, J.; Wang, X.-Z.; Chen, Y.-Q.; Jiang, X.-K.; Chen, X.-Z.; Li, Z.-T. *J. Org. Chem.* **2004**, *69*, 6221. (c) Hou, J.-L.; Shao, X.-B.; Chen, G.-J.; Zhou, Y.-X.; Jiang, X.-K.; Li, Z.-T. *J. Am. Chem. Soc.* **2004**, *126*, 12386. (d) Chen, Y.-Q.; Wang, X.-Z.; Shao, X.-B.; Hou, J.-L.; Chen, X.-Z.; Jiang, X.-K.; Li, Z.-T. *Tetrahedron* **2004**, *60*, 10253. (e) Yi, H.-P.; Shao, X.-B.; Hou, J.-L.; Li, C.; Jiang, X.-K.; Li, Z.-T. *New J. Chem.* **2005**, *29*, 1213. (f) Yi, H.-P.; Li, C.; Hou, J.-L.; Jiang, X.-K.; Li, Z.-T. *Tetrahedron* **2005**, *61*, 7974. (g) Wu, Z.-Q.; Jiang, X.-K.; Li, Z.-T. *Tetrahedron Lett.* **2005**, *46*, 8067. (h) Li, C.; Ren, S.-F.; Hou, J.-L.; Yi, H.-P.; Zhu, S.-Z.; Jiang, X.-K.; Li, Z.-T. *Angew. Chem., Int. Ed.* **2005**, *44*, 5725. (i) Li, C.-Z.; Zhu, J.; Wu, Z.-Q.; Hou, J.-L.; Li, C.; Shao, X.-B.; Jiang, X.-K.; Li, Z.-T.; Gao, X.; Wang, Q.-R. *Tetrahedron* **2006**, *62*, 6973.

(22) (a) Wu, Z.-Q.; Shao, X.-B.; Li, C.; Hou, J.-L.; Wang, K.; Jiang, X.-K.; Li, Z.-T. *J. Am. Chem. Soc.* **2005**, *127*, 17460. (b) Hou, J.-L.; Yi, H.-P.; Shao, X.-B.; Li, C.; Wu, Z.-Q.; Jiang, X.-K.; Wu, L.-Z.; Tung, C.-H.; Li, Z.-T. *Angew. Chem., Int. Ed.* **2006**, *45*, 796.

(23) Zhu, J.; Lin, J.-B.; Xu, Y.-X.; Shao, X.-B.; Jiang, X.-K.; Li, Z.-T. *J. Am. Chem. Soc.* **2006**, *128*, 12307.

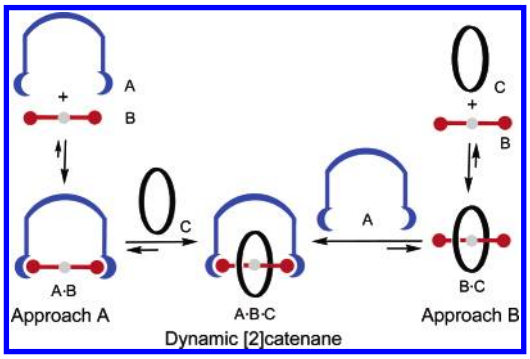


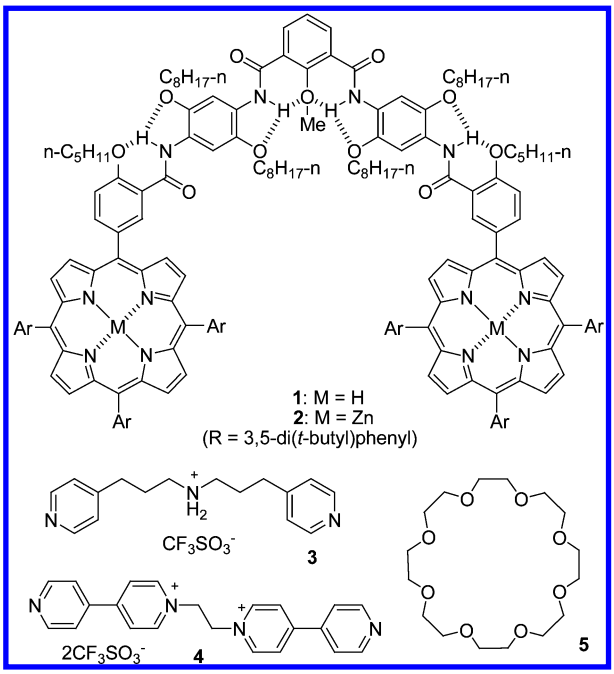
FIGURE 1. Self-assembling strategy for the dynamic three-component [2]catenanes.

bonding to adopt a preorganized U-shaped conformation. Component B is a linear secondary ammonium, which bears two peripheral pyridine units. Driven by two coordination bonds, A is able to efficiently bind B to form macrocylic complex A·B, while B can thread through C, 24-crown-8 in the present study, by the cation-macrocyclic polyether recognition to generate pseudo[2]rotaxane B·C.[24] If all three different noncovalent forces were strong enough, dynamic three-component [2]catenane A·B·C would be produced from the three-component solution.

To validate the above concept, compounds **1** and **2** were designed to possess the rigidified folded conformation of component A (Chart 1). Compound **3** was related to component B (Figure 1) and **4** was also prepared because Loeb et al. reported that this molecule could be driven by intermolecular $N^+\cdots O$ ion dipole interactions and $C-H\cdots O$ hydrogen bonds to thread through crown ether **5** to form modestly stable complex **4·5**.[25]

The synthetic route for **1** and **2** is provided in Scheme 1. Thus, hydroquinone **6** was first dioctylated in hot DMF to give **7** in 70% yield. The ether was then treated with nitric acid to produce **8** in 40% yield. Palladium-catalyzed hydrogenation of **8** in THF yielded diamine **9** quantitatively. The latter was then coupled with **10** in dichloromethane in the presence of DCC to afford **11** in 70% yield. Compound **11** was again reacted with **12**[22a] with EDCI as condensing reagent to produce **1** in 46% yield. Finally, porphyrin **1** was treated with zinc acetate in methanol and dichloromethane to give **2** quantitatively. For the synthesis of **3** (Scheme 2), prop-2-yn-1-amine **13** was first treated with di-*tert*-butyl dicarbonate in aqueous THF to give **14** in 75% yield. The latter was reacted with 3-bromoprop-1-yne in THF in the presence of sodium hydride to afford **15** in 50% yield. Palladium-catalyzed reaction of **15** with 4-iodopyridine in THF produced dipyridine **16** in 94% yield. The intermediate was then deprotected in trifluoroacetic acid to give **17**,[26] which was further hydrogenated to afford amine **18**. Finally, treatment of **18** with trifluoromethanesulfonic acid produced compound **3**.[27] Compound **4** was prepared based on the reported method.[25] Compounds **1**−**3** have been characterized by the ^{1}H, ^{13}C NMR, and (HR) mass spectroscopy or microanalysis.

CHART 1



Previous X-ray and spectroscopic investigations have revealed that the amide protons in **1** and **2** were involved in intramolecular three-centered hydrogen bonding.[21a,b,28] To further evidence the rigidified preorganized conformation of their aromatic oligoamide moiety, fragment molecules **19** and **20** were also prepared by the route as shown in Scheme 3. The X-ray crystal analysis of **19** and **20** showed the existence of consecutive intramolecular hydrogen bonds, which forced their backbones to adopt a rigidified planar conformation (Figure 2). The ^{1}H NMR spectrum of **2** in $CDCl_3-CD_3CN$ (4:1) was of high resolution and the signals of the amide protons appeared in the downfield area (9.97 and 10.62 ppm, respectively, 3.0 mM). Because the skeleton of **2** might be regarded as a combination of **19** and **20**, these results support that zinc porphyrin **2** adopts the proposed rigidified U-shaped conformation.

CPK modeling showed that the two porphyrin units of **2** in the folded state were roughly parallel to each other, forming a rigid molecular tweezer with a spatial separation of ca. 2 nm between the porphyrin units. Such a distance is suitable for complexing **3** or **4** through two Zn−N coordination bonds. Adding 1 equiv of **2** to the solution of **3** caused all the signals of **3** in the ^{1}H NMR spectrum to shift upfield greatly (Figure 3), supporting strong complexation occurring between two compounds.[29] The Job's plot obtained from the UV−vis experiments revealed a 1:1 binding stoichiometry.[30] UV−vis

(24) (a) Glink, P. T.; Schiavo, C.; Stoddart, J. F.; Williams, D. J. *Chem. Commun.* **1996**, 1483. (b) Clifford, T.; Abushamleh, A.; Busch, D. H. *Proc. Natl. Acad. Sci. U.S.A.* **2002**, *99*, 4830. (c) Schalley, C. A.; Weilandt, T.; Brueggemann, J.; Vögtle, F. *Top. Curr. Chem.* **2005**, *248*, 141.

(25) Tiburcio, J.; Davidson, G. J. E.; Loeb, S. J. *Chem. Commun.* **2002**, 1282.

(26) The salt of this amine was originally designed as the linear component, but found to be unstable at room temperature.

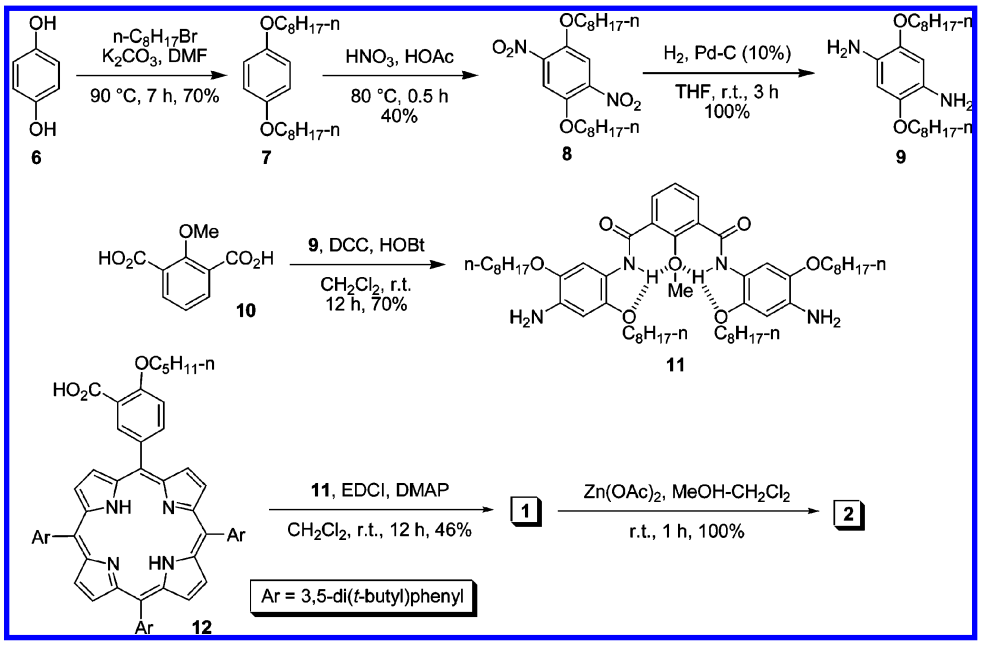
(27) The basicity of secondary amines is substantially stronger than that of 4-alkylatedpyridines ($\Delta pK_a \approx 7$). Therefore, monoprotonation of compound **3** should occur on the central nitrogen atom, see: (a) Bordwell, F. G.; Hughes, D. I. *J. Am. Chem. Soc.* **1986**, *108*, 7300. (b) Brown, H. C.; McDaniel, D. H.; Häflinger, O. *Determination of Organic Structures by Physical Methods*; Academic Press: New York, 1955; Vol. 1, p 567.

(28) Gong, B. *Chem. Eur. J.* **2001**, *7*, 4337.

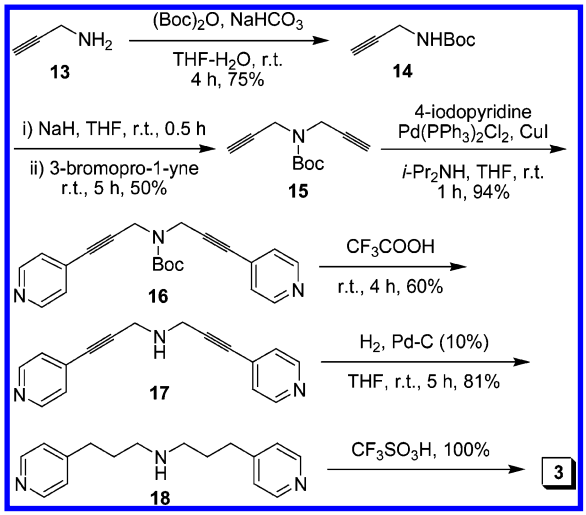
(29) (a) Sanders, J. K. M.; Bampos, N.; Clyde-Watson, Z.; Darling, S. L.; Hawley, J. C.; Kim, H.-J.; Mak, C. C.; Webb, S. J. *The Porphyrin Handbook;* Kadish, K. M., Smith, K. M., Guilard, R., Eds.; Academic Press: New York, 2000; Vol. 3, p 1. (b) Shao, X.-B.; Jiang, X.-K.; Zhao, X.; Zhao, C.-X.; Chen, Y.; Li, Z.-T. *J. Org. Chem.* **2004**, *69*, 899.

(30) Job, P. *Ann. Chim. Ser. 10* **1928**, *9*, 113.

SCHEME 1



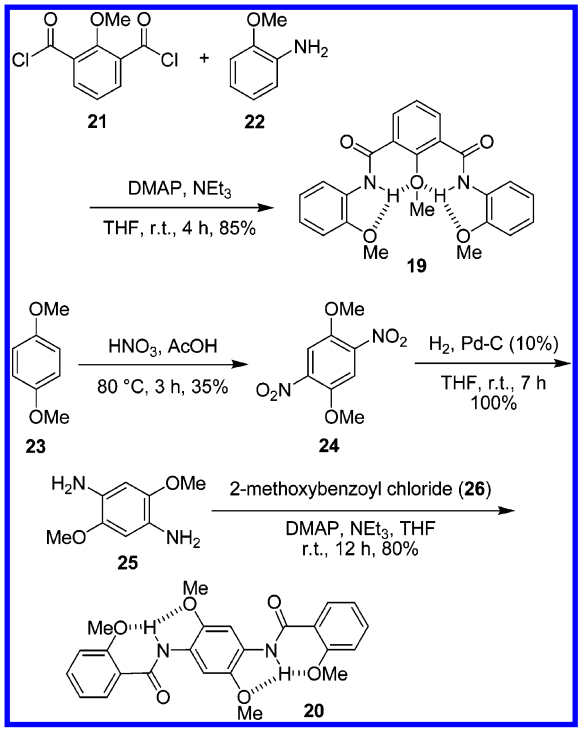
SCHEME 2



titration experiments (Figure 4) were then performed. Fitting the data to a 1:1 binding mode gave rise to an association constant K_{assoc} of 5.7(±0.7) × 10^6 M^{-1} for complex **2·3**.[31] The value is impressive considering the increased polarity of the binary solvent used compared to chloroform,[32] indicating the efficiency of the intramolecular hydrogen bonding-induced preorganization of **2**. Also on the base of UV−vis titration experiments, the K_{assoc} of complex **2·4** in $CDCl_3$−CD_3CN (4:1, v/v) was determined to be ca. 7.9(±0.9) × 10^4 M^{-1}, which is considerably smaller than that of **2·3** possibly as a result of the electron-withdrawing effect of the pyridinium units.

The recognition between secondary ammonium ions and crown ethers has been established to be an efficient templation for the synthesis of rotaxanes.[24] Mixing **3** and **5** (3 mM) resulted in pronounced change of the chemical shifting of **3** (Δδ: 0.33 and 0.16 ppm for NH and NCH_2, respectively) in the ^{1}H NMR spectrum (Figure 3). On the basis of the ^{1}H NMR dilution

SCHEME 3



experiments, a K_{assoc} of ca. 180 M^{-1} was determined for complex **3·5**. In a similar way, a notably larger K_{assoc} value (ca. 260 M^{-1}) was also established for the complex of **3** with dibenzo-24-crown-8. Because **5** displayed only one single peak in the ^{1}H NMR spectrum, which is perfect as a dynamic probe, we chose **5**, instead of dibenzo-24-crown-8, for the self-assembly of the dynamic [2]catenane.

The ^{1}H NMR spectrum in $CDCl_3$−CD_3CN (4:1, v/v) revealed that, in the presence of **2** and **3** (1:1), crown ether **5** displayed two single signals (3.48 and 2.83 ppm). Gradient experiments (Figure 5) established that the two signals corresponded to the free and catenated species **2·3·5** (Figure 6), respectively. 2D-NOESY experiments revealed a NOE connection of modest

(31) Conners, K. A. *Binding Constants*: *The Measurement of Molecular Complex Stability*; Wiley: New York, 1987.
(32) Satake, A.; Kobuke, Y. *Tetrahedron* **2005**, *61*, 13.

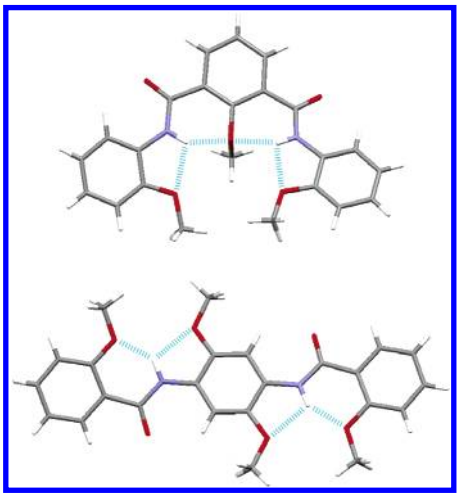


FIGURE 2. The solid-state structures of compounds **19** (upper) and **20** (down), highlighting the intramolecular hydrogen bonding and rigidified planar conformation.

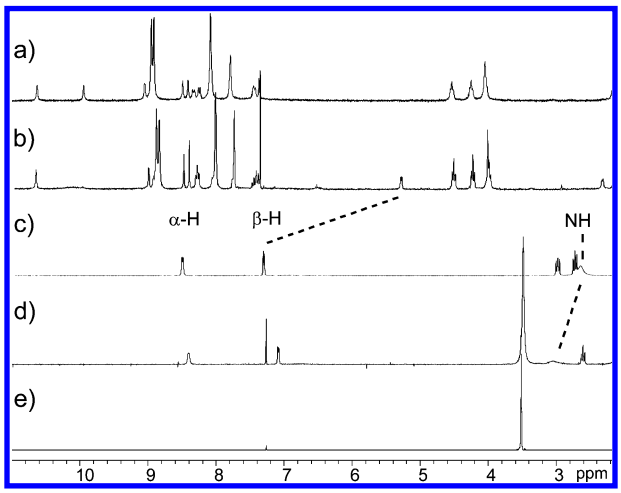


FIGURE 3. Partial ^{1}H NMR spectra (400 MHz) of the solution (3 mM) of (a) **2**, (b) **2** + **3** (1:1), (c) **3**, (d) **3** + **5** (1:1), and (e) **5** in $CDCl_3-CD_3CN$ (4:1, v/v) at 25 °C.

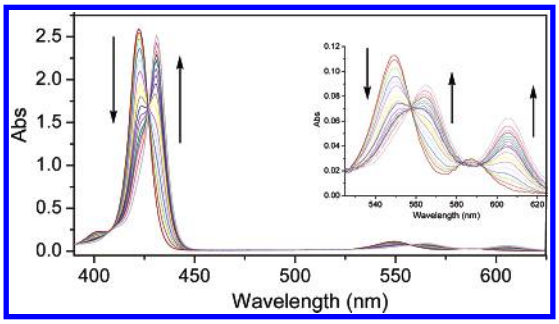


FIGURE 4. Absorption spectral changes of **2** (1.8×10^{-6} M^{-1}) on titration with **3** ($0-5.0 \times 10^{-5}$ M^{-1}) in $CDCl_3-MeCN$ (4:1, v/v) at 25 °C.

intensity between the signal of **5** at 2.83 ppm and the β-H signal of the pyridine units of **3** (Figure 6).[33] No such connection was displayed for the signal of **5** at 3.48 ppm. Under identical conditions, the 1:1 solution of **3** and **5** did not give similar NOE

(33) NOE connections could not be confirmed between the signal of **5** at 2.83 ppm and the signals of the methylene units of **3** due to overlapping of the methylene signals with other signals at the upfield area.

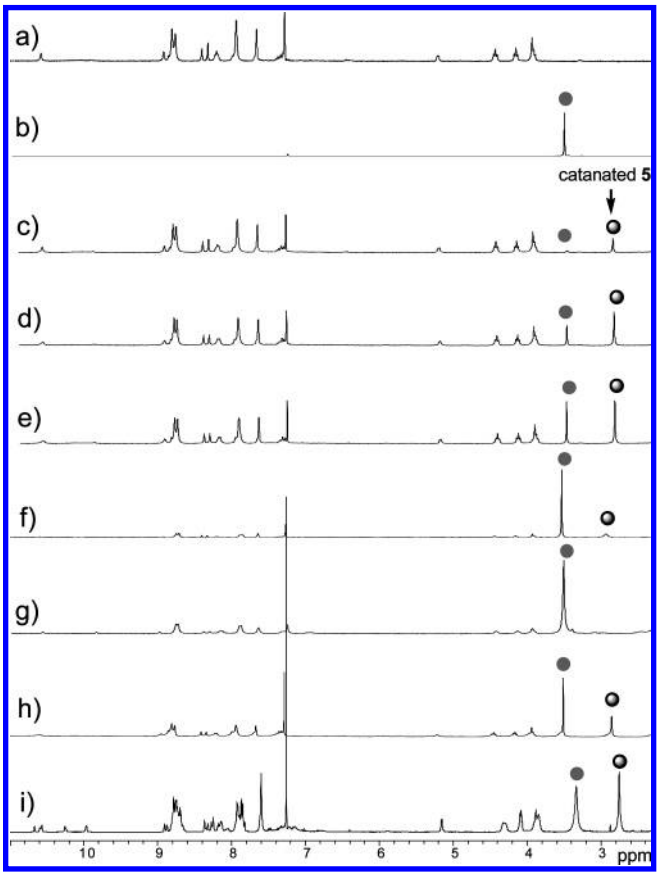


FIGURE 5. Partial ^{1}H NMR spectra (400 MHz) of (a) **2** + **3** (1:1, 3 mM), (b) **5** (3 mM), (c) **2** (3 mM) + **3** + **5** (1:1:0.2), (d) **2** (3 mM) + **3** + **5** (1:1:0.6), (e) **2** (3 mM) + **3** + **5** (1:1:1), (f) **2** (3 mM) + **3** + **5** + DABCO (1:1:1:1), (g) **2** (3 mM) + **3** + **5** + DABCO (1:1:1:5), (h) **2** (3 mM) + **3** + **5** (1:1:2) at 25 °C, and (i) **2** (3 mM) + **3** + **5** (1:1:2) at −13 °C in $CDCl_3-CD_3CN$ (4:1, v/v).

even at a concentration of 5.0 mM. Adding 1 equiv of DABCO to the 1:1:1 solution of **2**, **3**, and **5** caused a remarkable decrease of the intensity of the signal of **5** at 2.83 ppm (Figure 5f). Upon addition of 5 equiv of DABCO, the signal of **5** at 2.83 ppm vanished completely (Figure 5g). All these observations supported that the signal at 2.83 ppm was that of the crown ether threaded by linear **3**. Addition of DABCO caused de-protonation of **3** to yield neutral amine **18** and consequently de-threading of **5** from it, as shown in Figure 6.[34] Because 24-crown-8 **5** displayed only one signal in the 1:1 solution of **3** and **5** of the same concentration in the same solvent (Figure 3d) and compounds **2** and **3** could form a very stable complex, the above results supported that interlocked dynamic [2]catenane **2·3·5** was generated in the three-component solution through Approach A shown in Figure 1 and the exchange between the free and catenated **5** was slow on the NMR time scale. The result also suggested that catenation substantially increased the kinetic barrier of threading and de-threading of **3** through **5**. On the base of the integrated intensity, we determined that the dynamic [2]catenane was formed in ca. 55% and 84% yield in the 1:1:1 and 1:1:2 solution (Figure 5, parts e and h). Variable ^{1}H NMR investigations revealed that reducing the temperature remarkably

(34) Because DABCO is also a strong ligand, the de-catenation may also result from its competitive coordination to the zinc porphyrin units of **2**. Nevertheless, the result from both routes supported the formation of the dynamic [2]catenane in the solution.

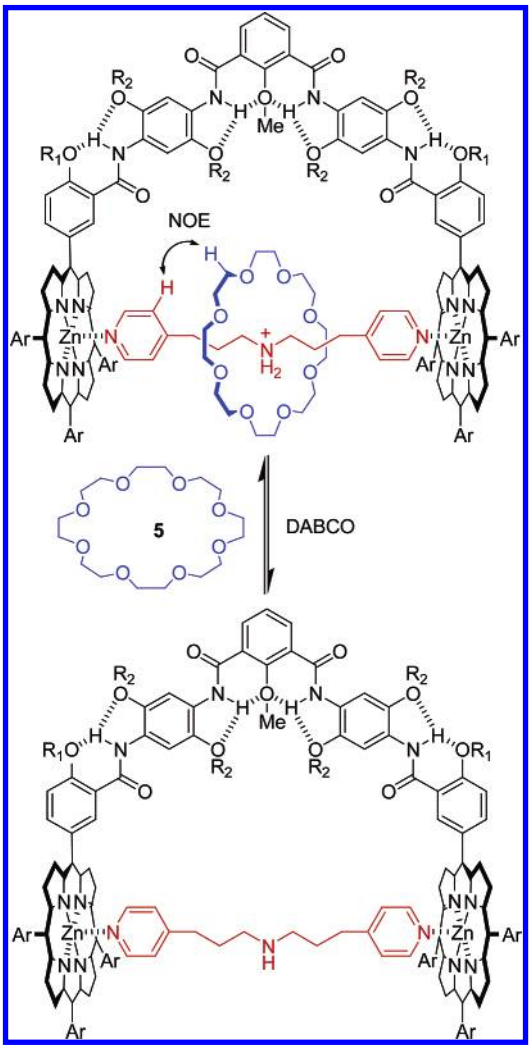


FIGURE 6. Proposed structures of dynamic [2]catenane **2·3·5** and de-catenation by the addition of DABCO. The intermolecular NOE connection between **3** and **5** is shown in the [2]catenane.

increased the yield of the dynamic [2]catenane. Quantitative formation of the dynamic [2]catenane was realized at −13 °C, as was evidenced by the 1:1 ratio of the integrated intensity of the signal of the free and catenated **5**, for the 1:1:2 solution (Figure 5i). At the same temperature, the yield of the dynamic [2]catenane was estimated to be ca. 75% for the 1:1:1 solution. Increasing the temperature of the mixture solution to 60 °C did not cause the two signals of **5** to coalesce, implying that the dynamic three-component [2]catenane was stable even at increased temperature.

Numerous attempts to detect the ion peak of the three-component assembly by the mass spectroscopy were unsuccessful. To collect more evidence for the formation of the dynamic [2]catenane, two-dimensional diffusion-ordered NMR (DOSY) investigations have been performed,[35] which gave rise to diffusion coefficients (D) of $3.9 \times e^{-9}$, $3.9 \times e^{-9}$, $4.3 \times e^{-9}$, and $6.0 \times e^{-9}$ m^2/s for **2**, **3**, and the two species of **5**, respectively (see the Supporting Information). It can be found that the first three values are quite close. However, the latter two values, which were produced from the two species of

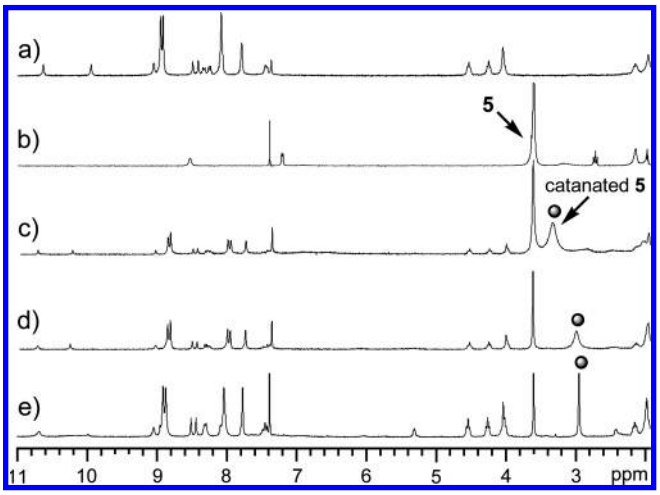


FIGURE 7. Partial ^{1}H NMR spectra (400 MHz) of the solution of (a) **2** (3.0 mM), (b) **3** + **5** (1:1), (c) **2** + **3** + **5** (0.2:1:1), (d) **2** + **3** + **5** (0.6:1:1), and (f) **2** + **3** + **5** (1:1:1) in $CDCl_3$−CD_3CN (4:1, v/v) at 25 °C ([**3**] = [**5**] = 3.0 mM).

complexed and free **5**, respectively, are greatly different. Considering the large difference in molecular size of **2**, **3**, and **5**, these results well supported that **2**, **3**, and the complexed **5** were bound tightly in the form of one single entity, i.e., the proposed dynamic [2]catenane.

Addition of an incremental amount of compound **2** to the 1:1 solution of **3** and **5** also caused **5** to display two signals in the ^{1}H NMR spectrum (Figure 7), which are obviously produced by the uncatenated and catenated species, respectively (Approach B, Figure 1). The signal of the catenated species is broad when the amount of **2** is low and became increasingly sharp and shifted upfield with the increase of **2**. This result could be rationalized by considering an increasingly enhanced coordination between the zinc porphyrins of **2** and the peripheral pyridines of **3**, which led to an increased shielding effect for **2** on **5** in the dynamic [2]catenane. In contrast, the chemical shift of the signal of the uncatenated **5** was not significantly affected by the addition of **2**.

It was reported that compounds **4** and **5** could form [2]-pseudorotaxane **4·5**, which was stabilized by intermolecular N^+···O ion dipole interactions and C−H···O hydrogen bonds.[25,36] Therefore, the possibility of the formation of a dynamic [2]-catenane from **2**, **4**, and **5** was also explored in $CDCl_3$−CD_3CN (4:3, v/v) (Figure 8). The content of CD_3CN in the binary solvent was increased to achieve a relatively high solubility for compound **4**. Different from the result of the 1:1 solution of **3** and **5** in $CDCl_3$−CD_3CN (4:1, v/v), which revealed a singlet for 24-crown-8 **5** in the ^{1}H NMR spectrum (Figure 3d), the ^{1}H NMR spectrum of the 1:1 solution of **4** and **5** in $CDCl_3$−CD_3CN (4:3, v/v) gave rise to two singlets (3.34 and 3.27 ppm) for **5** (Figure 8c), which corresponded to the free and threaded **5**, respectively. This observation implied that the exchanging process between the threading and de-threading **4** through **5** was slow on the ^{1}H NMR time scale. The ^{1}H NMR spectra of the solution of **2**, **4**, and a variable amount of **5** in $CDCl_3$−CD_3CN (4:3, v/v) are provided in Figure 8. Similar to the observations in the system of **2**, **3**, and **5**, crown ether **5** in the presence of **2** and **4** also displayed two single signals obviously

(35) (a) Gafni, A.; Cohen, Y. *J. Org. Chem.* **1997**, *62*, 120. (b) Gafni, A.; Cohen, Y. *J. Org. Chem.* **2002**, *67*, 2639. (c) Zhao, T.; Beckham, H. W.; Gibson, H. W. *Macromolecules* **2003**, *36*, 4833.

(36) (a) Loeb, S. J.; Wisner, J. A. *Angew. Chem., Int. Ed.* **1998**, *37*, 2838. (b) Loeb, S. J.; Tiburcio, J.; Vella, S. J.; Wisner, J. A. *Org. & Biomol. Chem.* **2006**, *4*, 667.

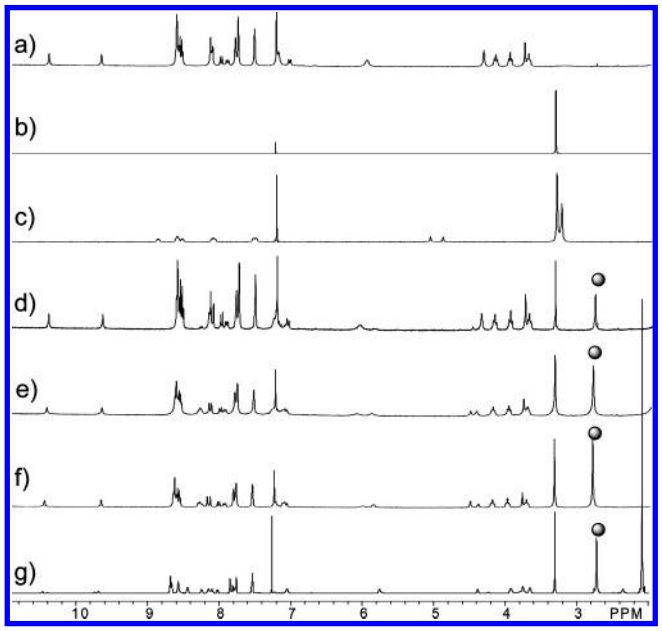
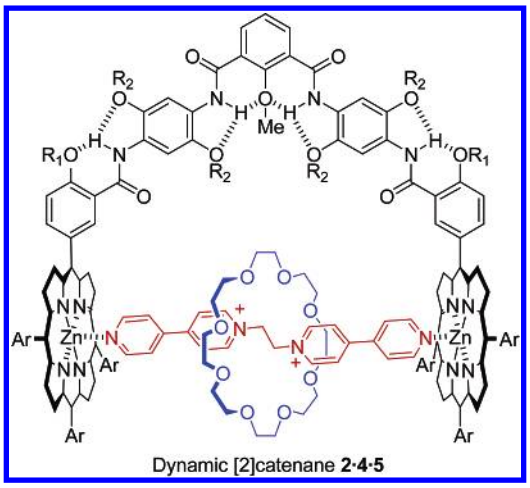


FIGURE 8. Partial ^{1}H NMR spectra (400 MHz) of the $CDCl_3-CD_3CN$ (4:3, v/v) solution of (a) **2** + **4** (1:1), (b) **5** (3.0 mM), (c) **4** + **5** (1:1), (d) **2** + **4** + **5** (1:1:0.2), (e) **2** + **4** + **5** (1:1:0.6), and (f) **2** + **4** + **5** (1:1:1) at 25 °C and (g) **2** + **4** + **5** (1:1:1) at −13 °C ([**2**] = [**4**] = 3.0 mM).

CHART 2



as a result of the formation of dynamic [2]catenane **2·4·5** (Chart 2), which corresponded to the signal at 2.72 ppm. Moreover, upon addition of a small amount of **2**, the signal of **5** at 3.27 ppm in the two-component complex **4·5** disappeared (Figure 8d). This result reflects that the formation of the dynamic [2]-catenae was quite favored. By comparing the integrated intensity of the two signals of **5**, we established that the yields of dynamic [2]catenane **2·4·5** in the 1:1:1 mixture solution (3.0 mM) at 25 and −13 °C were ca. 50% and 62%, respectively. These results show that compound **4** is slightly less efficient as an axle than **3** for the creation of the new series of dynamic [2]catenanes.

Conclusion

In summary, we have in this work illustrated a new concept of assembling dynamic [2]catenanes by making use of the preorganization of the hydrogen bonding-mediated oligoamide backbone to create the tweezer-styled key building block. Although three different noncovalent interactions are introduced and a coordination bond-incorporated macrocycle of 48 atoms is involved, the thermodynamically controlled creation of the new series of interlocked architectures is remarkably efficient.[37] The dynamic [2]catenane could be assembled quantitatively albeit at lowered temperature. The result demonstrates the potential of rigidified aromatic amide oligomers in supramolecular self-assembly. The extension of this strategy to the self-assembly of dynamic [3]catenanes and reversibly regulated interlocked architectures is currently under investigation.

Experimental Section

Compound 7. To a stirred solution of **6** (9.00 g, 82.0 mmol) and *n*-octyl bromide (30 mL, 0.17 mol) in DMF (90 mL) was added potassium carbonate (34.0 g, 0.25 mol). The suspension was stirred at 100 °C for 7 h and then cooled to room temperature. The solid was filtered and the filtrate was concentrated under reduced pressure. The resulting residue was triturated with ethyl acetate (200 mL). The organic phase was washed with saturated sodium bicarbonate solution (100 mL), water (3 × 100 mL), and brine (100 mL) and dried over sodium sulfate. The solvent was then removed under reduced pressure. The resulting crude product was recrystallized from ethyl acetate and petroleum ether to give compound **7** as a white solid (19.0 g, 70%). Mp 55−57 °C [lit.[38] mp 56 °C]. ^{1}H NMR (300 MHz, $CDCl_3$): δ 0.88−1.44 (m, 22 H), 1.59−1.56 (m, 4 H), 1.76−1.72 (m, 4 H), 3.91 (t, J = 6.6 Hz, 4 H), 6.83 (s, 4 H). MS (EI) *m/z*: 334 $[M]^+$.

Compound 8. To a stirred solution of compound **7** (17.0 g, 0.10 mol) in acetic acid (350 mL) was added slowly concentrated nitric acid (20 mL) at room temperature. The mixture was then stirred at 80 °C for 0.5 h and cooled to room temperature. The yellow precipitate formed was filtered and washed with water thoroughly. The solid was dried in vacuo and then recrystallized from ethyl acetate to give compound **8** as a yellow solid (6.00 g, 40%). Mp 89−91 °C. ^{1}H NMR (300 MHz, $CDCl_3$): δ 0.88−1.47 (m, 22 H), 1.59−1.54 (m, 4 H), 1.86−1.90 (m, 4 H), 4.09 (t, J = 6.3 Hz, 4 H), 7.51 (s, 2 H). MS (EI) *m/z*: 424 $[M]^+$. Anal. Calcd for $C_{22}H_{36}N_2O_6$: C, 62.24; H, 8.55; N, 6.60. Found: C, 62.23; H, 8.44; N, 6.49.

Compound 9. A suspension of compound **8** (0.50 g, 1.20 mmol) and Pd−C (10%, 50 mg) in THF (10 mL) was stirred under an atmosphere of hydrogen gas (1 atm) at room temperature for 1.5 h. The solid was then filtered off and the solution was concentrated in vacuo to give the desired compound as a white solid (0.44 g, 100%). The product was unstable in the air and used for the next step without further purification. ^{1}H NMR (300 MHz, $CDCl_3$): δ 0.85−1.46 (m, 22 H), 1.75−1.71 (t, 4 H), 2.07−2.03 (t, 4 H), 3.85 (t, J = 6.6 Hz, 4 H), 6.35 (t, J = 3.3 Hz, 2 H).

Compound 11. At room temperature, to a stirred solution of compound **10**[39] (88 mg, 0.45 mmol), HOBt (0.12 g, 0.90 mmol), and DCC (0.19 g, 0.90 mmol) in dichloromethane (20 mL) was added a solution of compound **9** (0.34 g, 0.90 mmol) in dichloromethane (10 mL). The solution was then stirred at room temperature for 12 h and concentrated under reduced pressure. The resulting residue was subjected to column chromatography (dichloromethane/methanol 200:1) to give compound **11** as a white solid (0.25 g, 70%). Mp 29−31 °C. ^{1}H NMR (300 MHz, $CDCl_3$): δ

(37) Several dynamic [2]rotaxanes with zinc porphyrin units as stoppers have been reported, see: (a) Gunter, M. J.; Farquhar, S. M.; Mullen, K. M. *New J. Chem.* **2004**, *28*, 1443. (b) Johnstone, K. D.; Yamaguchi, K.; Gunter, M. J. *Org. & Biomol. Chem.* **2005**, *3*, 3008. (c) Gunter, M. J. *Eur. J. Org. Chem.* **2004**, 1655. (d) Ikeda, T.; Asakawa, M.; Shimizu, T. *New J. Chem.* **2004**, *28*, 870.

(38) Nierengarten, J.-F.; Gu, T.; Hadziioannou, G.; Tsamouras, D.; Krasnikov, V. *Helv. Chim. Acta* **2004**, *87*, 2948.

(39) Venimadhavan, S.; Shelly, K. P.; Stewart, R. *J. Org. Chem.* **1989**, *54*, 2483.

0.79−1.47 (m, 24 H), 1.82−1.78 (m, 8 H), 3.78 (s, 3 H), 4.00 (t, J = 18.6 Hz, 8 H), 6.40 (s, 2 H), 7.39 (t, J = 8.1 Hz, 1 H), 8.17 (s, 2 H), 8.25 (d, J = 7.5 Hz, 2 H). ^{13}C NMR (300 MHz, $CDCl_3$): δ 14.0, 14.1, 22.6, 22.6, 26.0, 26.1, 29.2, 29.3, 29.3, 29.4, 29.5, 31.7, 31.8, 64.2, 69.2, 69.7, 100.5, 106.6, 119.1, 125.2, 128.4, 132.8, 134.6, 140.3, 142.7, 155.9, 161.9. MS (MALDI-TOF) *m/z*: 890 $[M + H]^+$, 902 $[M + Na]^+$. Anal. Calcd for $C_{53}H_{84}N_4O_7$: C, 71.58; H, 9.52; N, 6.30. Found: C, 71.40; H, 9.54; N, 6.07.

Compound 1. At room temperature, to a stirred solution of compounds **11** (0.11 g, 0.12 mmol), **12** (0.34 g, 0.32 mmol), and DMAP (2 mg) in dichloromethane (15 mL) was added EDCI (80 mg). The solution was stirred at room temperature for 12 h and then another portion of dichloromethane (10 mL) was added. The solution was washed with saturated sodium bicarbonate solution (10 mL), water (3 × 10 mL), and brine (10 mL) and then dried over sodium sulfate. Upon removal of the solvent under reduced pressure, the resulting residue was subjected to column chromatography (dichloromethane/petroleum ether 8:1) to give porphyrin **1** as a purple solid (0.17 g, 46%). Mp 142−144 °C. ^{1}H NMR (400 MHz, $CDCl_3$): δ 0.56−1.71 (m, 166 H), 1.89 (t, J = 7.5 Hz, 12 H), 2.07 (t, J = 8.1 Hz, 8 H), 3.99−4.02 (m, 7 H), 4.17 (t, J = 6.6 Hz, 4 H), 4.44 (t, J = 7.2 Hz, 4 H), 7.35 (d, J = 3.9 Hz, 4 H), 7.72 (s, 6 H), 8.03 (s, 12 H), 8.24 (d, J = 4.2 Hz, 4 H), 8.40 (s, 2 H), 8.48 (s, 2 H), 8.81 (d, d, J_1 = 12.9 Hz, J_2 = 6.3 Hz, 16 H), 9.08 (d, J = 2.4 Hz, 2 H), 9.93 (s, 2 H), 10.56 (s, 2 H). ^{13}C NMR (300 MHz, $CDCl_3$): δ 14.0, 14.1, 22.5, 22.6, 22.7, 28.2, 29.2, 29.3, 29.4, 29.6 (d), 29.7, 31.7, 31.8, 31.9, 35.1, 64.5, 69.6, 69.9, 70.3, 105.6, 105.7, 118.3, 121.0, 121.2, 121.5, 121.5, 123.4, 125.0, 128.4, 129.6, 129.8, 130.0, 135.7, 141.3, 141.4, 141.8, 141.9, 148.7, 148.8, 156.2, 156.6, 162.5, 163.4. MS (MALDI-TOF) *m/z*: 3014 $[M + H]^+$. Anal. Calcd for $C_{201}H_{256}N_{12}O_{11}$: C, 80.04; H, 8.55; N, 5.57. Found: C, 79.81; H, 8.69; N, 5.23.

Compound 2. A solution of compound **1** (56 mg, 0.016 mmol) and $Zn(OAc)_2 \cdot 2H_2O$ (39 mg, 0.16 mmol) in methanol and dichloromethane (5 mL, 1:10) was stirred at room temperature for 1 h and then concentrated in vacuo. The resulting residue was triturated in dichloromethane (20 mL). The organic phase was washed with water (2 × 5 mL) and brine (5 mL) and dried over sodium sulfate. Upon removal of the solvent under reduced pressure, the resulting solid was subjected to flash chromatography (dichloromethane/methanol 100:1) to give compound **2** as a purple solid (60 mg, 100%). Mp 196−198 °C. ^{1}H NMR (400 MHz, $CDCl_3$): δ 0.61−2.00 (m, 178 H), 1.97 (t, J = 6.0 Hz, 4 H), 2.16 (t, J = 7.5 Hz, 4 H), 4.03−4.09 (m, 7 H), 4.23 (t, J = 7.2 Hz, 4 H), 4.53 (t, J = 7.2 Hz, 4 H), 7.41 (d, J = 3.0 Hz, 4 H), 7.77 (s, 6 H), 8.09 (s, 12 H), 8.33 (d, d, J_1 = 10.2 Hz, J_2 = 4.2 Hz, 4 H), 8.45 (s, 2 H), 8.52 (s, 2 H), 8.97−9.02 (m, 16 H), 9.06 (d, J = 2.7 Hz, 2 H), 9.97 (s, 2 H), 10.62 (s, 2 H). ^{13}C NMR (300 MHz, $CDCl_3$): δ 13.9, 14.1, 14.2, 22.5, 22.6, 22.7, 26.0, 26.1, 28.2, 29.2, 29.3, 29.4, 29.6 (d), 31.6, 31.8, 31.9, 35.1, 64.5, 69.6, 69.9, 70.3, 105.6, 105.6, 111.3, 120.7, 121.0, 122.5, 123.3, 128.4, 129.5, 129.7, 129.9, 131.6, 132.1, 132.2, 132.4, 136.3, 138.1, 141.8, 141.9, 141.9, 148.5 (d), 148.6, 150.3, 150.4, 150.5 (d), 156.5, 162.4, 163.5. MS (MALDI-TOF) *m/z*: 3138 $[M + H]^+$. HRMS (MALDI-FT): Anal. Calcd for $C_{201}H_{252}N_{12}O_{11}Zn_2$ $[M + H]^+$ 3137.8106, found 3137.8082.

Compound 14. At room temperature, to a stirred solution of propargyl amine **13** (1.10 g, 20.0 mmol) in THF (12 mL) and water (12 mL) were added saturated sodium bicarbonate solution (1 mL) and di-*tert*-butyl dicarbonate (0.42 mL). The solution was stirred at room temperature for 4 h and then concentrated in vacuo. The resulting residue was triturated with ethyl acetate (20 mL). The solution was washed with water (3 × 10 mL) and brine (10 mL) and dried over sodium sulfate. Upon removal of the solvent in vacuo, compound **14** was obtained as a pale yellow solid (2.30 g, 75%). Mp 40−42 °C [lit.[40] mp 41−42 °C]. ^{1}H NMR (300 MHz, $CDCl_3$): δ 1.46 (s, 9 H), 2.23 (s, 1 H), 3.93 (s, 2 H), 4.73 (br, 1 H). MS (ESI) *m/z*: 178 $[M + Na]^+$.

Compound 15.[41] To a stirred solution of compound **14** (0.45 g, 2.90 mmol) in THF (4 mL) was added sodium hydride (60%, 0.15 g, 3.80 mmol). The suspension was stirred for 0.5 h and then propargyl bromide (0.59 g, 4.60 mmol) was added dropwise. The mixture was stirred at room temperature for 5 h and then quenched with saturated ammonium chloride solution. The solvent was removed under reduced pressure and the resulting residue triturated with ethyl acetate (30 mL). The organic phase was then washed with water (3 × 30 mL and brine (30 mL) and dried over sodium sulfate. After the solvent was removed in vacuo, the resulting material was subjected to flash chromatography (petroleum ether/dichloromethane 2:1) to give compound **15** as pale yellow liquid (0.28 g, 50%). ^{1}H NMR (300 MHz, $CDCl_3$): δ 1.53 (s, 9 H), 2.22 (s, 2 H), 4.16 (br, 4 H). MS (ESI) *m/z*: 216 $[M + Na]^+$.

Compound 16. A suspension of compound **15** (97 mg, 0.50 mmol), 4-iodopyridine hydrochloric acid salt (0.21 g, 1.00 mmol), $Pd(PPh_3)_2Cl_2$ (18 mg, 0.025 mmol), cupric iodide (7 mg, 0.0375 mmol), and DIPA (0.5 mL) in THF (2.0 mL) was stirred at room temperature for 1 h. The solvent was then removed under reduced pressure and the resulting residue triturated with dichloromethane (10 mL). The organic phase was washed with water (10 mL) and brine (10 mL) and dried over sodium sulfate. Upon removal of the solvent under reduced pressure, the crude product was purified by column chromatography (dichloromethane/methanol 50:1) to give compound **16** as pale yellow oil (0.16 g, 94%). Mp 87−88 °C. ^{1}H NMR (300 MHz, acetone-d_6): δ 1.50 (s, 9 H), 4.50 (s, 4 H), 7.35 (d, d, J_1 = 4.5 Hz, J_2 = 1.8 Hz, 4 H), 8.55 (d, d, J_1 = 4.5 Hz, J_2 = 1.8 Hz, 4 H). ^{13}C NMR (300 MHz, $CDCl_3$): δ 28.4, 36.5, 81.6, 89.4, 125.7, 130.9, 149.8, 154.3. MS (ESI) *m/z*: 348 $[M + H]^+$. HRMS (ESI): Anal. Calcd for $C_{21}H_{22}N_3O_2$ $[M]^+$ 348.1706, found 348.1706.

Compound 17. A solution of compound **16** (0.20 g, 0.60 mmol) in trifluoroacetic acid (2 mL) was stirred at room temperature for 4 h and then concentrated under reduced pressure. The resulting residue was triturated with dichloromethane (10 mL). The organic phase was washed with sodium hydroxide solution (1 M, 3 mL), water (2 × 5 mL), and brine (50 mL) and dried over sodium sulfate. Upon removal of the solvent in vacuo, the resulting residue was subjected to flash chromatography (dichloromethane/ methanol 50:1) to afford compound **17** as a pale yellow solid (0.12 g, 60%). Mp 68−70 °C. ^{1}H NMR (300 MHz, $CDCl_3$): δ 3.84 (s, 4 H), 7.29 (d, d, J_1 = 1.6 Hz, J_2 = 4.4 Hz, 4 H), 8.57 (d, d, J_1 = 1.6 Hz, J_2 = 4.4 Hz, 4 H). ^{13}C NMR (300 MHz, acetone-d_6): δ 38.1, 81.6, 93.4, 126.3, 131.9, 150.8. MS (ESI) *m/z*: 248 $[M + H]^+$. HRMS (ESI): Anal. Calcd for $C_{16}H_{14}N_3$ $[M]^+$ 248.1182, found 248.1186.

Compound 18. A suspension of compound **17** (0.12 g, 0.50 mmol) and Pd−C (10%, 60 mg) in THF (5 mL) was stirred under an atmosphere of hydrogen gas (1 atm) at room temperature for 5 h. The solid was filtered off and the filtrate concentrated under reduced pressure. The resulting residue was subjected to flash chromatography (dichloromethane/methanol 50:1) to give compound **18** as a pale yellow oil (0.10 g, 81%). ^{1}H NMR (300 MHz, $CDCl_3$): δ 2.00 (t, J = 7.5 Hz, 4 H), 2.65 (t, J = 7.6 Hz, 4 H), 2.75 (t, J = 7.2 Hz, 4 H), 7.11 (d, d, J_1 = 0.5 Hz, J_2 = 4.4 Hz, 4 H), 8.49 (d, d, J_1 = 0.5 Hz, J_2 = 4.4 Hz, 4 H). ^{13}C NMR (300 MHz, $CDCl_3$): δ 27.9, 32.3, 48.0, 123.7, 149.6, 149.9. MS (ESI) *m/z*: 256 $[M + H]^+$. HRMS (ESI): Anal. Calcd for $C_{16}H_{22}N_3$ $[M]^+$ 256.1808, found 256.1807.

Compound 3. Compound **18** (33 mg, 0.13 mmol) was dissolved in methanol (2 mL). Under stirring, a solution of trifluoromethanesulfuric acid (0.22 M, 0.59 mL) in water was added slowly. Stirring was continued for 10 min and then the solvent was removed under reduced pressure to give compound **3** as a pale yellow solid (52 mg, 100%). Mp 148−150 °C. ^{1}H NMR (300 MHz, CD_3CN-d_3): δ

(40) Cheng, S.; Tarby, C. M.; Comer, D. D.; Williams, J. P.; Caporale, L. H. *Bioorg. Med. Chem.* **1996**, *4*, 727.

(41) Boger, D. L.; Lee, J. K.; Goldberg, J.; Jin, Q. *J. Org. Chem.* **2000**, *65*, 1467.

1.93−1.99 (m, 4 H), 2.72 (t, J = 7.5 Hz, 4 H), 2.99 (t, J = 7.8 Hz, 4 H), 7.26 (d, d, J_1 = 1.5 Hz, J_2 = 7.5 Hz, 4 H), 8.51 (d, d, J_1 = 1.5 Hz, J_2 = 7.5 Hz, 4 H). ^{13}C NMR (300 MHz, $CDCl_3$): δ 27.01, 32.2, 48.4, 118.3, 124.9, 150.5. MS (ESI) *m/z*: 256 $[M + H]^+$. HRMS (ESI): Anal. Calcd for $C_{16}H_{22}N_3$ $[M]^+$ 256.1808, found 256.1808.

Compound 19. To a stirred solution of compound **22** (0.63 g, 5.20 mmol) and triethylamine (1 mL) in THF (10 mL) was added a solution of compound **21**[42] (0.58 g, 2.50 mmol) at room temperature. The solution was stirred for 4 h and then concentrated under reduced pressure. The resulting residue was triturated in dichloromethane (20 mL). The organic phase was washed with diluted hydrochloric acid (0.5 M, 10 mL), water (10 mL), saturated sodium bicarbonate solution (10 mL), and brine (10 mL) and dried over sodium sulfate. The solvent was then removed under reduced pressure and the crude product purified by recrystallization from EtOAc to give compound **19** as a colorless solid (0.81 g, 80%). Mp 170−172 °C. ^{1}H NMR (300 Hz, $CDCl_3$): δ 3.98 (s, 6 H), 4.03 (s, 3 H), 6.97 (d, d, J_1 = 1.5 Hz, J_2 = 7.9 Hz, 2 H), 7.06 (d, t, J_1 = 1.5 Hz, J_2 = 7.7 Hz, 2 H), 7.13 (d, t, J_1 = 1.8 Hz, J_2 = 7.7 Hz, 2 H), 7.43 (t, J = 7.8 Hz, 1 H), 8.29 (d, J = 7.8 Hz, 2 H), 8.60 (d, d, J_1 = 1.8 Hz, J_2 = 7.8 Hz, 2 H), 10.08 (s, 1 H). ^{13}C NMR (300 MHz, $CDCl_3$): δ 55.8, 64.2, 110.2, 120.6, 121.4, 124.2, 125.4, 128.0, 128.3, 135.2, 148.5, 155.9, 162.5. MS (ESI) *m/z*: 407 $[M + H]^+$, 429 $[M + Na]^+$. Anal. Calcd for $C_{23}H_{22}N_2O_5$: C, 67.76; H, 5.47; N, 6.64. Found: C, 67.97; H, 5.46; N, 6.89.

Compound 24. To a stirred solution of compound **23** (5.00 g, 36.0 mmol) in acetic acid (60 mL) was added concentrated nitric acid (15 mL) at room temperature. The solution was stirred at 80 °C for 0.5 h and then cooled to room temperature and poured into cold water (100 mL). The yellow precipitate formed was filtered and washed with water thoroughly. The crude product was dried under reduced pressure and then purified by flash chromatography (petroleum ether/EtOAc 10:1) to afford compound **24** as a yellow solid. Mp 203−205 °C [lit.[44] mp 200−210 °C]. ^{1}H NMR (300 MHz, $CDCl_3$): δ 3.99 (s, 6 H), 7.57 (s, 2 H). MS (EI) *m/z*: 228 $[M]^+$.

Compound 25. A suspension of compound **24** (0.43 g, 1.90 mmol) and Pd−C (50 mg, 10%) in THF (6 mL) was stirred under 1 atm of hydrogen gas at room temperature for 7 h. The solid was filtered and the filtrate concentrated to give compound **25**[43] as a purple oil (100%). The product was used for the next step without further purification. ^{1}H NMR (300 Hz, $CDCl_3$): δ 3.76 (s, 6 H), 6.28 (s, 2 H).

Compound 20. To a stirred solution of compound **25** (0.29 g, 1.70 mmol), DMAP (50 mg), and triethylamine (0.5 mL) in THF (5 mL) was added a solution of compound **26** (0.58 g, 3.40 mmol) in THF (5 mL). The solution was stirred at room temperature for 12 h and then concentrated under reduced pressure. The residue was triturated in ethyl acetate (15 mL). The organic solution was washed successively with dilute hydrochloric acid (0.5 N, 5 mL), saturated sodium bicarbonate solution (5 mL), water (10 mL), and brine (10 mL) and dried over sodium sulfate. Upon removal of the solvent in vacuo, the resulting crude product was purified by flash chromatography (petroleum ether/EtOAc 5:1) to give compound **20** as a white solid (80%). Mp >220 °C dec. ^{1}H NMR (300 MHz, $CDCl_3$): δ 4.01 (s, 6 H), 4.08 (s, 6 H), 7.05 (d, J = 8.2 Hz, 2 H), 7.14 (t, J = 7.5 Hz, 2 H), 7.49 (d, J = 7.2 Hz, 2 H), 8.30 (d, d, J_1 = 1.8 Hz, J_2 = 7.9 Hz, 2 H), 8.52 (s, 2 H), 10.71 (s, 2 H). ^{13}C NMR (300 MHz, $CDCl_3$): δ 56.1, 56.8, 77.2, 104.0, 111.6, 121.5, 122.2, 124.0, 132.2, 133.0, 142.3, 157.5, 162.8. MS (ESI) *m/z*: 436 $[M + Na]^+$.

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Supporting Information Available: The 2D DOSY spectrum of the solution of **2**, **3**, and **5** in $CDCl_3/CD_3CN$ (4:1, v/v), the general experimental method, and crystallographic information (CIF files) of compounds **19** and **20**. This material is available free of charge via the Internet at http://pubs.acs.org.

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(42) Wagner, P. J.; Meador, M. A.; Park, B.-S. *J. Am. Chem. Soc.* **1990**, *112*, 5199.
(43) Nose, M.; Suzuki, H. *Synthesis* **2000**, 1539.
(44) Doornbos, S. *Org. Prep. Proced. Int.* **1969**, *1*, 287.