



Synthesis of diamido-bridged bis-pillar[5]arenes and tris-pillar[5]arenes for construction of unique [1]rotaxanes and bis-[1]rotaxanes

Ying Han, Li-Ming Xu, Cui-Yun Nie, Shuo Jiang, Jing Sun and Chao-Guo Yan*

Full Research Paper

Open Access

Address:
College of Chemistry & Chemical Engineering, Yangzhou University,
Yangzhou 225002, P. R. China

Email:
Chao-Guo Yan* - cgyan@yzu.edu.cn

* Corresponding author

Keywords:
bis-[1]rotaxane; mechanically interlocked molecule; pillar[5]arene;
[1]rotaxane; self-assembly

Beilstein J. Org. Chem. **2018**, *14*, 1660–1667.
doi:10.3762/bjoc.14.142

Received: 17 April 2018
Accepted: 20 June 2018
Published: 04 July 2018

This article is part of the thematic issue "Macrocyclic and supramolecular chemistry".

Guest Editor: M.-X. Wang

© 2018 Han et al.; licensee Beilstein-Institut.
License and terms: see end of document.

Abstract

The pillar[5]arene mono- and di(oxyalkoxy)benzoic acids were successfully prepared in high yields by sequential alkylation of ω -bromoalkoxy-substituted pillar[5]arenes with methyl or ethyl *p*-hydroxybenzoate followed by a hydrolytic reaction under basic conditions. Under catalysis of HOBt/EDCI, the amidation reaction of pillar[5]arene mono(oxybutoxy)benzoic acid with monoamido-functionalized pillar[5]arenes afforded diamido-bridged bis-pillar[5]arenes. ¹H NMR and 2D NOESY spectra clearly indicated that [1]rotaxanes were formed by insertion of longer diaminoalkylene unit into the cavity of one pillar[5]arene with another pillar[5]arene acting as a stopper. The similar catalysed amidation reaction of pillar[5]arene di(oxybutoxy)benzoic acid with monoamido-functionalized pillar[5]arenes resulted in the diamido-bridged tris-pillar[5]arenes, which successfully form the unique bis-[1]rotaxanes bearing longer than diaminopropylene diamido bridges.

Introduction

The construction and dynamic motion of the mechanically interlocked molecules (MIMs) have attracted significant research interests due to their intrinsic self-assembled nature and potential applications in various aspects [1-4]. Pseudo[1]rotaxane and [1]rotaxane are one of particular supramolecular assembly system and are considered as an important building block in the construction of diverse MIMs [5-10]. [1]Rotaxane has a macro-

cyclic wheel component connected with a self-locked chain axle, and a bulky stopper at the terminal axle to prevent dissociation of the subcomponents. In recent years, many effects have been devoted to the construction and functionalization of pseudo[1]rotaxanes and [1]rotaxanes [11-20]. For this purpose, the well-known macrocycles such as crown ether [21-23], cyclodextrin [24-26], calixarene [27-29] and pillararene have

been successfully employed as the wheel subcomponent. Pillararenes are new star macrocyclic compounds with aromatic rings *para*-bridged by methylene units and have unique tubular shape rather than cone [30–32]. In recent years, an explosive development on the construction of various supramolecular devices and diverse responsive materials has been reported by using diverse functionalized pillararenes [33–35]. Due to easily preparation and suitable cavity, functionalized pillar[5]arenes were widely used as wheel component for constructing of the various interlocked molecules [36–42]. In the past few years, many elegant works on the construction of pseudo[1]rotaxanes and [1]rotaxanes have been developed on the basis of various mono-functionalized pillar[5]arenes [43–57]. Recently, we have successfully constructed a couple of pseudo[1]rotaxane and [1]rotaxane both in solution and in solid state developed by using mono-functionalized pillar[5]arene Schiff base, urea and pyridylimine derivatives [58–63]. In continuation of our effort on the development on the construction of [1]rotaxanes via various mono-functionalized pillar[5]arene derivatives, herein we wish to report the convenient synthesis of diamido-bridged bis-pillar[5]arenes and tris-pillar[5]arenes as well as formation of unique [1]rotaxanes and bis-[1]rotaxanes.

Results and Discussion

The synthetic route for the pillar[5]arene mono(oxyalkoxy)benzoic acids was illustrated in Scheme 1. Firstly, the alkylation of mono(bromoalkoxy)pillar[5]arene **1a–c** ($n = 4, 5, 6$) [64] with methyl or ethyl *p*-hydroxybenzoate was carried out in the refluxed medium of KI/K₂CO₃/CH₃CN for one day. The pillar[5]arene mono(oxyalkoxy)benzoates **2a–f** were successfully prepared in high yields. Then, basic hydrolysis of pillar[5]arene mono(oxyalkoxy)benzoates **2a–f** in ethanol in the presence of potassium hydroxide afforded the desired pillar[5]arene mono(oxyalkoxy)benzoic acids **3a–c**. The structures of the prepared pillar[5]arenes **2a–f** and **3a–c** were fully characterized by the spectroscopic methods. The single crystal

structures of the pillar[5]arenes **2a** (Figure 1), **2c**, **2d**, **2e** (Supporting Information File 1, Figure S1–S3) and **2f** (Figure 2) were successfully determined by X-ray diffraction. The same structural feature was obtained in the five single crystals. That is, the longer chain of methyl (ethyl) oxyalkoxybenzoate not only does not inserted in the cavity of the pillar[5]arene to form the pseudo[1]rotaxane, but also does not thread to the cavity of the neighbouring pillar[5]arene to form the supramolecular polymer. This result is consistent to the Cao's previously reported results in the series of pillar[5]arenes bearing aliphatic esters [49], in that they found the chain of methyl oxybutyrate did not threaded into the cavity of pillar[5]arene.

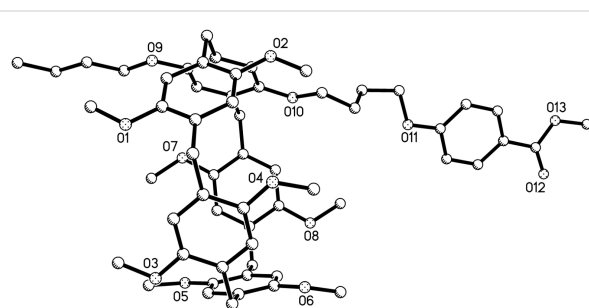


Figure 1: single crystal structure of pillar[5]arene **2a**.

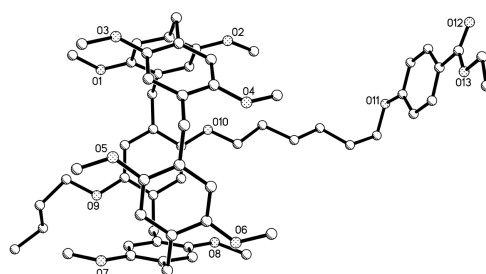
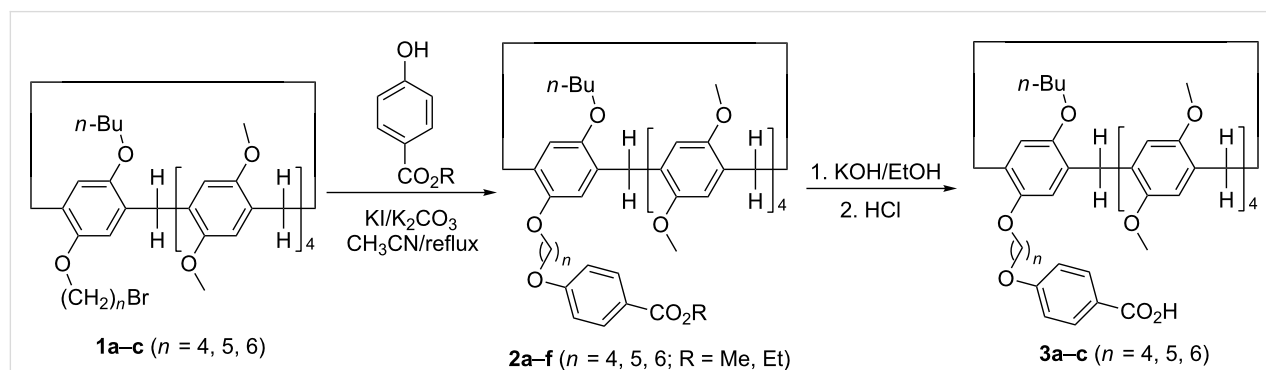
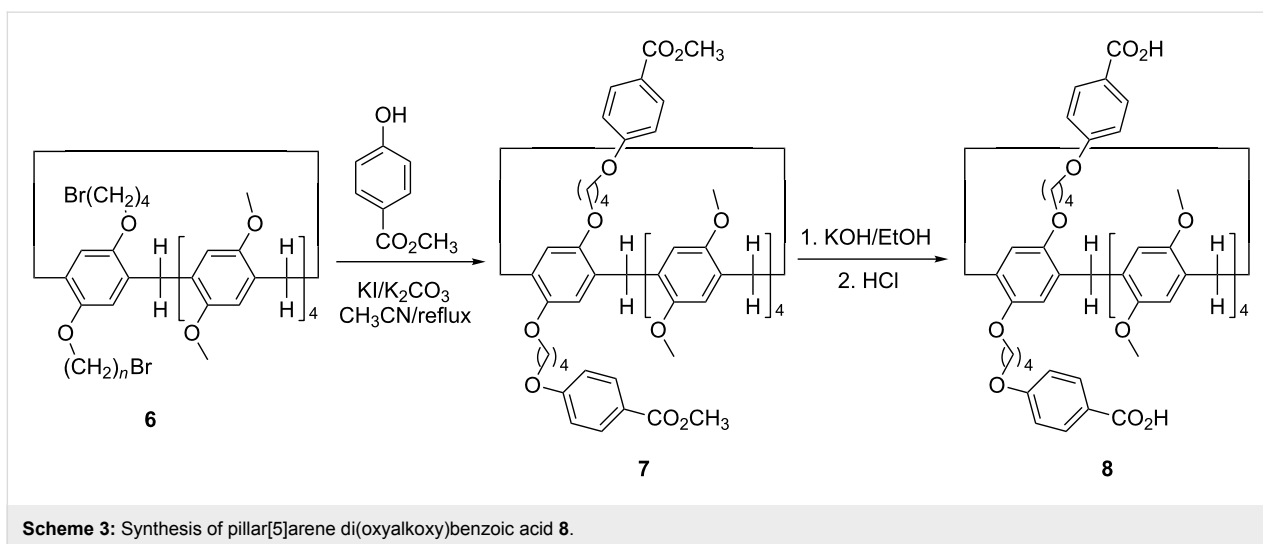
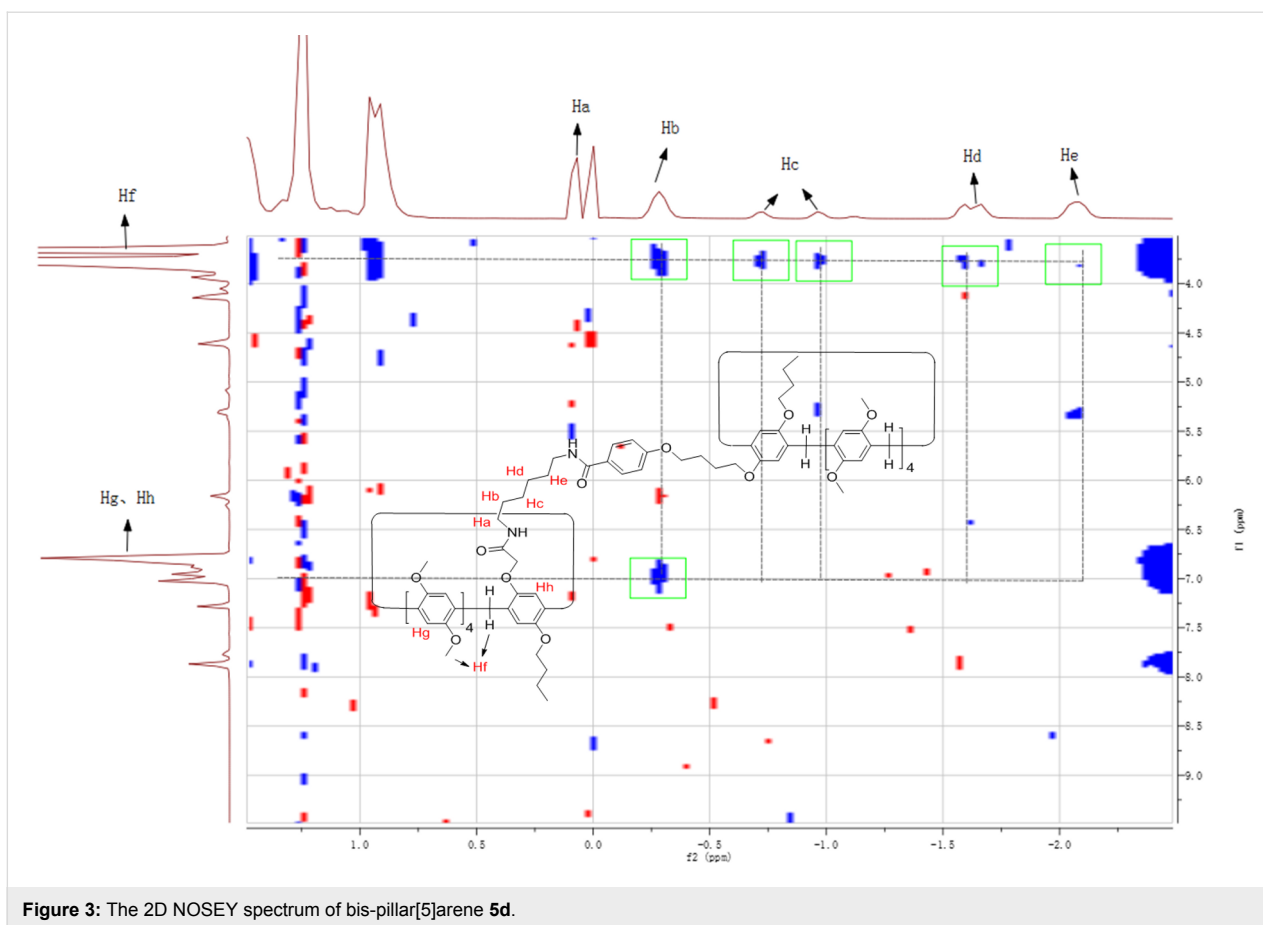


Figure 2: Single crystal structure of pillar[5]arene **2f**.



Scheme 1: Synthesis of pillar[5]arene mono(oxyalkoxy)benzoic acids **3a–c**.



pillar[5]arene di(oxybutoxy)benzoate **7** showed that the two chains of methyl oxybutoxybenzoate did not insert in the cavity of pillar[5]arene (Figure 4) as that of the above mentioned pillar[5]arene mono(oxybutoxy)benzoates **2a–f**. The two chains straight stretched to the opposite direction of central pillar[5]arene. It might be attribute to the electron-rich effect of

the methyl oxybutoxybenzoate unit, which kept it away from the electron-rich cavity of pillar[5]arene.

Under the combined catalysis of HOBt and EDCI, the amide reaction of pillar[5]arene di(oxybutoxy)benzoic acid **8a** with two molecular amido-functionalized pillar[5]arenes **4a–d** in

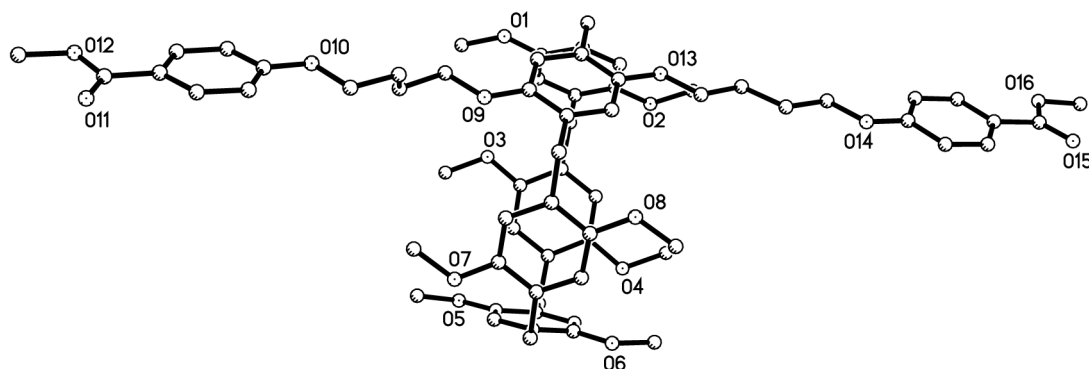
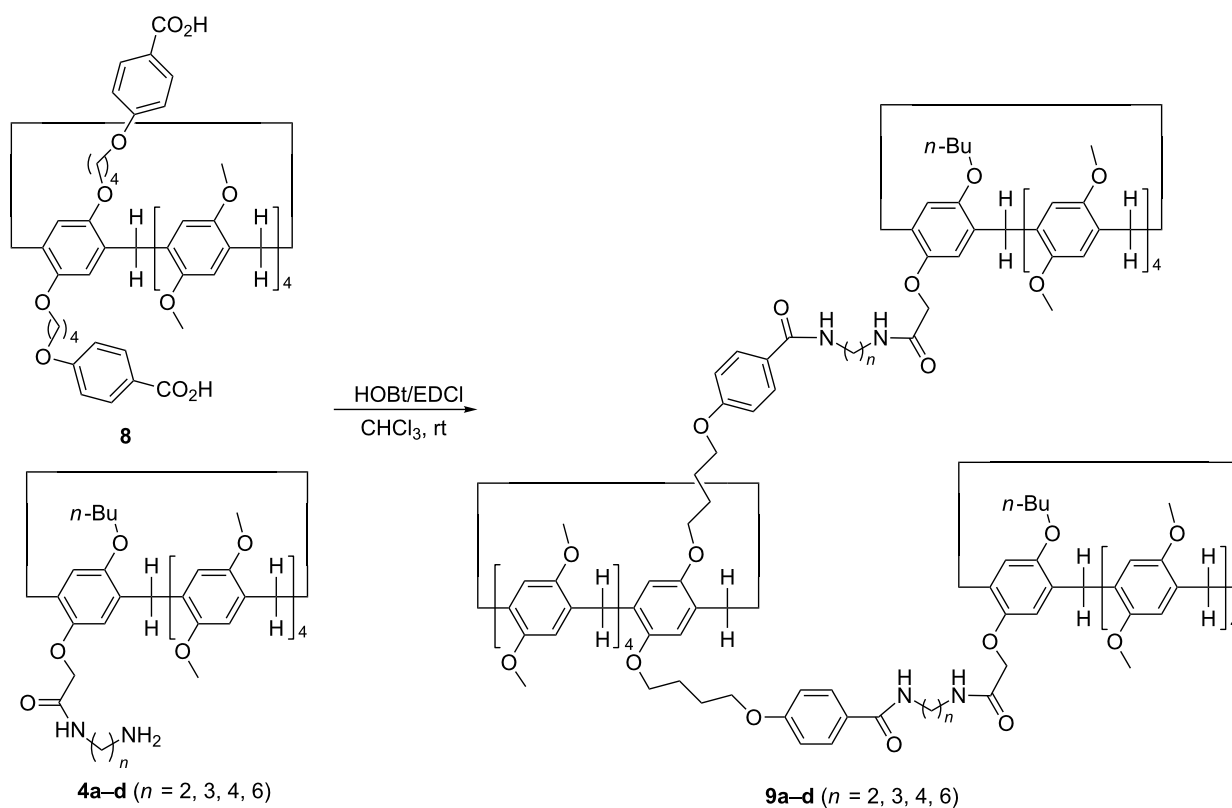


Figure 4: Single crystal structure of pillar[5]arene 7.

chloroform afforded tris-pillar[5]arenes **9a–d** in moderate yields (Scheme 4). The structures of the synthetic tris-pillar[5]arenes **9a–d** were fully characterized by IR, HRMS, ^1H and ^{13}C NMR spectra. The ^1H NMR spectra provided stronger evidence for the formation of fascinating bis-[1]rotaxanes. Because there are no peaks with negative chemical shift in the ^1H NMR spectra of the tris-pillar[5]arene **9a**, it can be concluded that the three

pillar[5]arenes are connected from the outsides by two diamido-ethylene-bridges. There is one broad peak at -1.80 ppm in tris-pillar[5]arene **9b**, a mixed peak at -2.00 ppm in tris-pillar[5]arene **9c**, and five broad peaks at -0.29 ppm, -0.74 ppm, -0.97 ppm, -1.62 ppm and -2.08 ppm in tris-pillar[5]arene **9d**. Therefore, ^1H NMR spectra of **9b–d** indicated that the diaminoalkylene chain ambiguously inserted in the



Scheme 4: Synthesis of diamido-bridged tris-pillar[5]arenes **9a–d**.

cavity of the pillar[5]arene. In other words, the fascinating bis-[1]rotaxane structures were formed in the tris-pillar[5]arenes **9b–d**. Here, the lengths of bridging chains played the critical role in the selflocked behaviour of pillar[5]arene-based [1]rotaxanes.

In order to confirm the formation of the bis-[1]rotaxanes, 2D NOESY spectra of the compounds **9a–d** were recorded. The 2D NOESY spectrum of compound **9d** was showed in Figure 5. There it can be seen that the NOE correlations were clearly observed between Ha, Hb, Hc, Hd, Hf, Hg, Hh protons of the bridging diaminohexylene chain and the protons Hi, Hj in the core of pillar[5]arene. Additionally, some correlations exists between protons Ha, He, Hd and Hh and active amino (N–H) group. These NOE correlations clearly indicated the two bridged diaminohexylene chain threading into the cavity of the two pillar[5]arenes to form the bis-[1]rotaxane. The similar correlations were also observed in the NOESY spectra of the tris-pillar[5]arene **9b** and **9c** (see Supporting Information File 1, Figures S5 and S6). However, there is no such correlation in the 2D NOESY spectrum of the compound **9a** (see Supporting Information File 1, Figure S4), which confirmed that the diamidoethylene bridge did not insert to the cavity of the

pillar[5]arene to form [1]rotaxanes. Thus, the 2D NOESY spectra provided stronger evidence for the formation of novel bis-[1]rotaxanes for the tris-pillar[5]arenes **9c–d** bearing longer than diaminopropylene diamido-bridges.

Conclusion

In summary, we have conveniently prepared several pillar[5]arene mono- and di(oxyalkoxy)benzoic acids and found that the chain of alkyl oxyalkoxybenzoate did not inserted to the cavity of pillar[5]arene. More importantly, a series of diamido-bridged bis-pillar[5]arenes and tris-pillar[5]arenes were efficiently synthesized by catalyzed amidation reaction of pillar[5]arene mono- and di(oxybutoxy)benzoic acids with monoamide-functionalized pillar[5]arenes. On the basis of ^1H NMR and 2D NOESY spectra, we successfully concluded that the chains longer than diaminopropylene threaded into the one or two cavities of the pillar[5]arenes to form the unique [1]rotaxane and bis-[1]rotaxanes. This work not only provided a fundamental self-assembly of the mechanically interlocked molecules, but also developed the potential applications of pillar[5]arene in supramolecular chemistry. The design and construction of diverse mechanically interlocked molecules are underway in our laboratory.

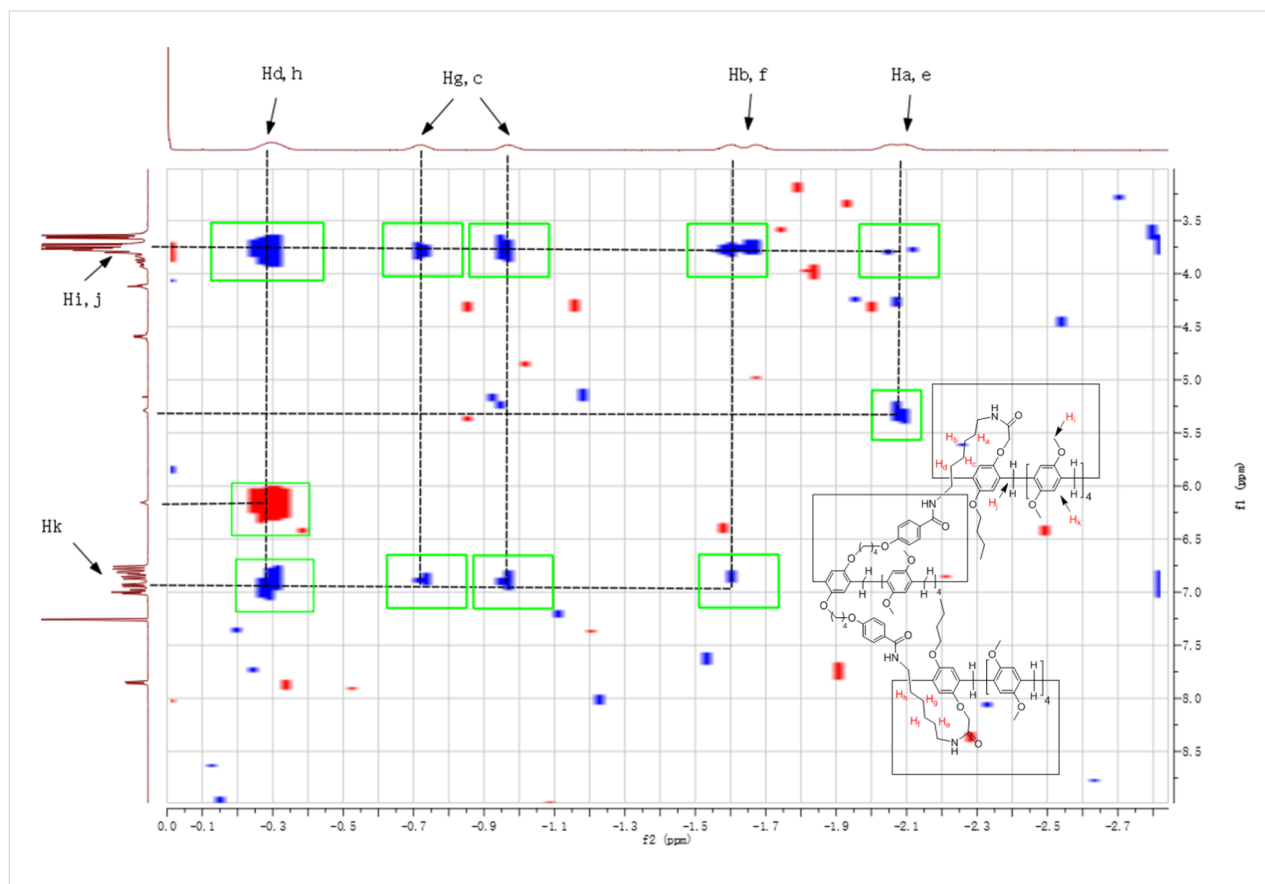


Figure 5: The 2D NOESY spectra of tris-pillar[5]arene **9d**.

Supporting Information

Experimental procedures, analytical data, and copies of the ^1H and ^{13}C NMR spectra, HRMS spectra for all new products. Single crystal data for **2a** (CCDC: 1837205), **2c** (CCDC: 1837206), **2d** (CCDC: 1837207), **2e** (CCDC: 1837208), **2f** (CCDC: 1837209) and **7** (CCDC: 1846692) have been deposited at the Cambridge Crystallographic Data Centre.

Supporting Information File 1

Experimental and analytical data.

[<https://www.beilstein-journals.org/bjoc/content/supplementary/1860-5397-14-142-S1.pdf>]

Acknowledgements

We are grateful to the financial support by the National Natural Science Foundation of China (Grant No. 2137219) and the Priority Academic Program Development of Jiangsu Higher Education Institutions.

References

- Wenz, G.; Han, B. H.; Müller, A. *Chem. Rev.* **2006**, *106*, 782–817. doi:10.1021/cr970027+
- Erbas-Cakmak, S.; Leigh, D. A.; McTernan, C. T.; Nussbaumer, A. L. *Chem. Rev.* **2015**, *115*, 10081–10206. doi:10.1021/acs.chemrev.5b00146
- Fahrenbach, A. C.; Bruns, C. J.; Li, H.; Trabolsi, A.; Coskun, A.; Stoddart, J. F. *Acc. Chem. Res.* **2014**, *47*, 482–493. doi:10.1021/ar400161z
- Bruns, C. J.; Stoddart, J. F. *Acc. Chem. Res.* **2014**, *47*, 2186–2199. doi:10.1021/ar500138u
- Langton, M. J.; Beer, P. D. *Acc. Chem. Res.* **2014**, *47*, 1935–1949. doi:10.1021/ar500012a
- Zhang, M.; Yan, X.; Huang, F.; Niu, Z.; Gibson, H. W. *Acc. Chem. Res.* **2014**, *47*, 1995–2005. doi:10.1021/ar500046r
- Qu, D.-H.; Wang, Q.-C.; Zhang, Q.-W.; Ma, X.; Tian, H. *Chem. Rev.* **2015**, *115*, 7543–7588. doi:10.1021/cr5006342
- Xue, M.; Yang, Y.; Chi, X.; Yan, X.; Huang, F. *Chem. Rev.* **2015**, *115*, 7398–7501. doi:10.1021/cr5005869
- Ogoshi, T.; Yamagishi, T.-a.; Nakamoto, Y. *Chem. Rev.* **2016**, *116*, 7937–8002. doi:10.1021/acs.chemrev.5b00765
- Wang, Y.; Ping, G.; Li, C. *Chem. Commun.* **2016**, *52*, 9858–9872. doi:10.1039/C6CC03999E
- Ma, X.; Tian, H. *Chem. Soc. Rev.* **2010**, *39*, 70–80. doi:10.1039/B901710K
- Lewis, J. E. M.; Galli, M.; Goldup, S. M. *Chem. Commun.* **2017**, *53*, 298–312. doi:10.1039/C6CC07377H
- Roberts, D. A.; Pilgrim, B. S.; Nitschke, J. R. *Chem. Soc. Rev.* **2018**, *47*, 626–644. doi:10.1039/C6CS00907G
- Han, X.; Liu, G.; Liu, S. H.; Yin, J. *Org. Biomol. Chem.* **2016**, *14*, 10331–10351. doi:10.1039/C6OB01581F
- Lewis, J. E. M.; Beer, P. D.; Loeb, S. J.; Goldup, S. M. *Chem. Soc. Rev.* **2017**, *46*, 2577–2591. doi:10.1039/C7CS00199A
- Li, S.-H.; Zhang, H.-Y.; Xu, X.; Liu, Y. *Nat. Commun.* **2015**, *6*, No. 7590. doi:10.1038/ncomms8590
- Chi, X.; Yu, G.; Shao, L.; Chen, J.; Huang, F. *J. Am. Chem. Soc.* **2016**, *138*, 3168–3174. doi:10.1021/jacs.5b13173
- Eichstaedt, K.; Jaramillo-Garcia, J.; Leigh, D. A.; Marcos, V.; Pisano, S.; Singleton, T. A. *J. Am. Chem. Soc.* **2017**, *139*, 9376–9381. doi:10.1021/jacs.7b04955
- De Bo, G.; Dolphijn, G.; McTernan, C. T.; Leigh, D. A. *J. Am. Chem. Soc.* **2017**, *139*, 8455–8457. doi:10.1021/jacs.7b05640
- Wang, Y.; Sun, J.; Liu, Z.; Nassar, M. S.; Botros, Y. Y.; Stoddart, J. F. *Chem. Sci.* **2017**, *8*, 2562–2568. doi:10.1039/C6SC05035B
- Hiratani, K.; Kaneyama, M.; Nagawa, Y.; Koyama, E.; Kanosato, M. *J. Am. Chem. Soc.* **2004**, *126*, 13568–13569. doi:10.1021/ja046929r
- Ogawa, T.; Nakazono, K.; Aoki, D.; Uchida, S.; Takata, T. *ACS Macro Lett.* **2015**, *4*, 343–347. doi:10.1021/acsmacrolett.5b00067
- Ogawa, T.; Usuki, N.; Nakazono, K.; Koyama, Y.; Takata, T. *Chem. Commun.* **2015**, *51*, 5606–5609. doi:10.1039/C4CC08982K
- Xue, Z.; Mayer, M. F. *J. Am. Chem. Soc.* **2010**, *132*, 3274–3276. doi:10.1021/ja9077655
- Waelés, P.; Clavel, C.; Fournel-Marotte, K.; Coutrot, F. *Chem. Sci.* **2015**, *6*, 4828–4836. doi:10.1039/C5SC01722J
- Schröder, H. V.; Wollschläger, J. M.; Schalley, C. A. *Chem. Commun.* **2017**, *53*, 9218–9221. doi:10.1039/C7CC05259F
- Li, H.; Zhang, H.; Zhang, Q.; Zhang, Q.-W.; Qu, D.-H. *Org. Lett.* **2012**, *14*, 5900–5903. doi:10.1021/ol302826g
- Li, H.; Zhang, J.-N.; Zhou, W.; Zhang, H.; Zhang, Q.; Qu, D.-H.; Tian, H. *Org. Lett.* **2013**, *15*, 3070–3073. doi:10.1021/ol401251u
- Li, H.; Li, X.; Agren, H.; Qu, D.-H. *Org. Lett.* **2014**, *16*, 4940–4943. doi:10.1021/ol502466x
- Ma, X.; Qu, D.; Ji, F.; Wang, Q.; Zhu, L.; Xu, Y.; Tian, H. *Chem. Commun.* **2007**, 1409–1411. doi:10.1039/b615900a
- Ma, X.; Wang, Q.; Tian, H. *Tetrahedron Lett.* **2007**, *48*, 7112–7116. doi:10.1016/j.tetlet.2007.07.209
- Yamauchi, K.; Miyawaki, A.; Takashima, Y.; Yamaguchi, H.; Harada, A. *Org. Lett.* **2010**, *12*, 1284–1286. doi:10.1021/ol1001736
- Ogoshi, T.; Kanai, S.; Fujinami, S.; Yamagishi, T.-a.; Nakamoto, Y. *J. Am. Chem. Soc.* **2008**, *130*, 5022–5023. doi:10.1021/ja711260m
- Cao, D.; Kou, Y.; Liang, J.; Chen, Z.; Wang, L.; Meier, H. *Angew. Chem., Int. Ed.* **2009**, *48*, 9721–9723. doi:10.1002/anie.200904765
- Liu, Z.; Nalluri, S. K. M.; Stoddart, J. F. *Chem. Soc. Rev.* **2017**, *46*, 2459–2478. doi:10.1039/C7CS00185A
- Zhang, H.; Strutt, N. L.; Stoll, R. S.; Li, H.; Zhu, Z.; Stoddart, J. F. *Chem. Commun.* **2011**, *47*, 11420–11422. doi:10.1039/c1cc14934b
- Zhang, H.; Liu, Z.; Xin, F.; Hao, A. *Chin. J. Org. Chem.* **2012**, *32*, 219–229. doi:10.6023/cjoc1107141
- Zhang, H.; Zhao, Y. *Chem. – Eur. J.* **2013**, *19*, 16862–16879. doi:10.1002/chem.201301635
- Zhang, H.; Ma, X.; Nguyen, K. T.; Zhao, Y. *ACS Nano* **2013**, *7*, 7853–7863. doi:10.1021/nn402777x
- Zhang, H.; Ma, X.; Guo, J.; Nguyen, K. T.; Zhang, Q.; Wang, X.-J.; Yan, H.; Zhu, L.; Zhao, Y. *RSC Adv.* **2013**, *3*, 368–371. doi:10.1039/C2RA22123C
- Zhang, H.; Nguyen, K. T.; Ma, X.; Yan, H.; Guo, J.; Zhu, L.; Zhao, Y. *Org. Biomol. Chem.* **2013**, *11*, 2070–2074. doi:10.1039/c2ob27340c
- Zhang, H.; Ma, X.; Nguyen, K. T.; Zeng, Y.; Tai, S.; Zhao, Y. *ChemPlusChem* **2014**, *79*, 462–469. doi:10.1002/cplu.201300408
- Chen, H.; Fan, J.; Hu, X.; Ma, J.; Wang, S.; Li, J.; Yu, Y.; Jia, X.; Li, C. *Chem. Sci.* **2015**, *6*, 197–202. doi:10.1039/C4SC02422B

44. Ma, J.; Meng, Q.; Hu, X.; Li, B.; Ma, S.; Hu, B.; Li, J.; Jia, X.; Li, C. *Org. Lett.* **2016**, *18*, 5740–5743. doi:10.1021/acs.orglett.6b03005
45. Sun, Y.; Fu, W.; Chen, C.; Wang, J.; Yao, Y. *Chem. Commun.* **2017**, *53*, 3725–3728. doi:10.1039/C7CC00291B
46. Li, B.; Meng, Z.; Li, Q.; Huang, X.; Kang, Z.; Dong, H.; Chen, J.; Sun, J.; Dong, Y.; Li, J.; Jia, X.; Sessler, J. L.; Meng, Q.; Li, C. *Chem. Sci.* **2017**, *8*, 4458–4464. doi:10.1039/C7SC01438D
47. Ping, G.; Wang, Y.; Shen, L.; Wang, Y.; Hu, X.; Chen, J.; Hu, B.; Cui, L.; Meng, Q.; Li, C. *Chem. Commun.* **2017**, *53*, 7381–7384. doi:10.1039/C7CC02799K
48. Ogoshi, T.; Demachi, K.; Kitajima, K.; Yamagishi, T.-a. *Chem. Commun.* **2011**, *47*, 7164–7166. doi:10.1039/c1cc12333e
49. Chen, Y.; Cao, D.; Wang, L.; He, M.; Zhou, L.; Schollmeyer, D.; Meier, H. *Chem. – Eur. J.* **2013**, *19*, 7064–7070. doi:10.1002/chem.201204628
50. Xia, B.; Xue, M. *Chem. Commun.* **2014**, *50*, 1021–1023. doi:10.1039/C3CC48014C
51. Ni, M.; Hu, X.-Y.; Jiang, J.; Wang, L. *Chem. Commun.* **2014**, *50*, 1317–1319. doi:10.1039/C3CC47823H
52. Guan, Y.; Liu, P.; Deng, C.; Ni, M.; Xiong, S.; Lin, C.; Hu, X.-Y.; Ma, J.; Wang, L. *Org. Biomol. Chem.* **2014**, *12*, 1079–1089. doi:10.1039/c3ob42044b
53. Wu, X.; Ni, M.; Xia, W.; Hu, X.-Y.; Wang, L. *Org. Chem. Front.* **2015**, *2*, 1013–1017. doi:10.1039/C5QO00159E
54. Wu, X.; Gao, L.; Sun, J.; Hu, X.-Y.; Wang, L. *Chin. Chem. Lett.* **2016**, *27*, 1655–1660. doi:10.1016/j.ccllet.2016.05.004
55. Sun, C.-L.; Xu, J.-F.; Chen, Y.-Z.; Niu, L.-Y.; Wu, L.-Z.; Tung, C.-H.; Yang, Q.-Z. *Chin. Chem. Lett.* **2015**, *26*, 843–846. doi:10.1016/j.ccllet.2015.05.030
56. Du, X.-S.; Wang, C.-Y.; Jia, Q.; Deng, R.; Tian, H.-S.; Zhang, H.-Y.; Meguellati, K.; Yang, Y.-W. *Chem. Commun.* **2017**, *53*, 5326–5329. doi:10.1039/C7CC02364B
57. Cheng, M.; Wang, Q.; Cao, Y.; Pan, Y.; Yang, Z.; Jiang, J.; Wang, L. *Tetrahedron Lett.* **2016**, *57*, 4133–4137. doi:10.1016/j.tetlet.2016.07.038
58. Han, Y.; Huo, G.-F.; Sun, J.; Xie, J.; Yan, C.-G.; Zhao, Y.; Wu, X.; Lin, C.; Wang, L. *Sci. Rep.* **2016**, *6*, No. 28748. doi:10.1038/srep28748
59. Huo, G.-F.; Han, Y.; Sun, J.; Yan, C.-G. *J. Inclusion Phenom. Macrocyclic Chem.* **2016**, *86*, 231–240. doi:10.1007/s10847-016-0652-x
60. Han, Y.; Huo, G.-F.; Sun, J.; Yan, C.-G.; Lu, Y.; Lin, C.; Wang, L. *Supramol. Chem.* **2017**, *29*, 547–552. doi:10.1080/10610278.2017.1287367
61. Jiang, S.; Han, Y.; Sun, J.; Yan, C.-G. *Tetrahedron* **2017**, *73*, 5107–5114. doi:10.1016/j.tet.2017.07.001
62. Jiang, S.; Han, Y.; Zhao, L.-L.; Sun, J.; Yan, C.-G. *Supramol. Chem.* **2018**, *30*, 642–647. doi:10.1080/10610278.2018.1427238
63. Jiang, S.; Han, Y.; Cheng, M.; Sun, J.; Yan, C.-G.; Jiang, J.; Wang, L. *New J. Chem.* **2018**, *42*, 7603–7606. doi:10.1039/c7nj05192a
64. Yin, C.-B.; Han, Y.; Huo, G.-F.; Sun, J.; Yan, C.-G. *Chin. Chem. Lett.* **2017**, *28*, 431–436. doi:10.1016/j.ccllet.2016.09.008

License and Terms

This is an Open Access article under the terms of the Creative Commons Attribution License (<http://creativecommons.org/licenses/by/4.0>), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

The license is subject to the *Beilstein Journal of Organic Chemistry* terms and conditions:

(<https://www.beilstein-journals.org/bjoc>)

The definitive version of this article is the electronic one which can be found at:

[doi:10.3762/bjoc.14.142](https://doi.org/10.3762/bjoc.14.142)