ChemComm

Cite this: *Chem. Commun.*, 2012, **48**, 8532–8534

www.rsc.org/chemcomm

COMMUNICATION

Novel [2]pseudorotaxanes constructed by self-assembly of bis-urea-functionalized pillar[5]arene and linear alkyl dicarboxylates†

Qunpeng Duan, Wei Xia, Xiaoyu Hu, Mengfei Ni, Juli Jiang, Chen Lin, Yi Pan and Leyong Wang*

Received 6th June 2012, Accepted 2nd July 2012
DOI: 10.1039/c2cc34049f

A bis-urea-functionalized pillar[5]arene has been synthesized and shown to form [2]pseudorotaxanes spontaneously with linear alkyl dicarboxylates in highly polar solvent DMSO, in which the hydrogen bonding interactions between the bis-urea hydrogens and dicarboxylate oxygens play an important role in stabilizing the novel [2]pseudorotaxanes alongside C–H···π interactions.

One of the most important aspects of self-assembly is the formation of threaded structures, such as rotaxanes, pseudorotaxanes and catenanes, due to their potential applications in nanotechnology and molecular machines.[1] As the basic threaded structures, pseudorotaxanes[2] have been a topic of great interest in recent years because they are not only the fundamental precursors for the preparation of novel supramolecular species, such as rotaxanes and catenanes,[3] but also the prototypes of simple molecular machines.[1c,4] Therefore, the design and preparation of pseudorotaxanes with novel macrocyclic hosts (the 'wheels') and linear guests (the 'axles') to form the templated-pseudorotaxane is highly desirable for both supramolecular chemistry and the fabrication of molecule-based devices. Pillar[5]arenes, firstly synthesized by Ogoshi's group,[5] are a new class of macrocyclic hosts,[6] which have a unique, rigid and symmetrical pillar architecture, and have been widely used as macrocyclic hosts (wheels) in the construction of pseudorotaxanes with various guests (axles) from cationic molecules[5,7] to neutral compounds.[8] However, the linear anionic guest recognition based on pillararenes is rarely reported.[9] Therefore, searching for new linear anionic guests as axles to pillararene-based hosts is very fascinating. On the other hand, the urea functional group has been widely studied as an anion receptor moiety,[10] and urea-based heteroditopic receptors have been reported to act as wheels to form pseudorotaxane-type complexes with the dialkylviologen salts as axles.[11] Hence, we envisioned that by introducing two urea groups into pillar[5]arene, a bis-urea-functionalized pillar[5]arene (**H**) could be obtained (see Fig. 1), and then novel [2]pseudorotaxanes could be constructed by self-assembly of the above macrocyclic host (wheel) with linear alkyl dicarboxylates (axles) through N–H···O hydrogen bonding interactions.

Herein we present the host–guest complexation of a bis-urea-functionalized pillar[5]arene (**H**) with linear alkyl dicarboxylates (**G*n***) (**G*n***, *n*: carbon number, $n = 5, 7, 9, 11–15, 20$) (Fig. 1). By self-assembly of **H** and **G*n***, [2]pseudorotaxanes were formed in highly polar solvent DMSO. To the best of our knowledge, it is the first example of the design and preparation of such pillar[5]arene-based pseudorotaxanes by self-assembly through the hydrogen bonding interactions between the bis-urea hydrogens and dicarboxylate oxygens.

The bis-urea-functionalized pillar[5]arene (**H**) was prepared from diamino functionalized pillar[5]arene[12] with *p*-tolyliso-cyanate in excellent yield (Scheme S1, ESI†). The studies of host–guest complexation of **H** with **G*n*** were carried out by ^{1}H NMR in DMSO-d_6. All dicarboxylates were employed as their bis-tetrabutylammonium (TBA) salts. Fig. 2b shows the ^{1}H NMR titration result of **G13** into a solution of **H** in DMSO-d_6. With the addition of **G13**, four new signals (marked with 1, 2, 3 and 4, respectively, in ^{1}H NMR titration spectra, Fig. 2b) were observed (for example, their chemical shifts are δ: −2.01, −1.41, −0.35 and 0.53 ppm, respectively, in the presence of 1.0 equivalent of **G13**) in the upfield area, which are corresponding to the seven methylene groups (identified by integration and symmetrically connected to the central methylene group, marked with 1, 2, 3 and 4, respectively, Fig. 2a) of the linear alkyl chain of **G13**. Because only the strong inclusion-induced shielding effects by the bis-urea-functionalized cyclophane could lead to such large upfield shifts of those seven methylene groups of **G13**,[13] it provided the direct evidence that these seven methylene groups were threaded within the cavity of **H**. Meanwhile, large

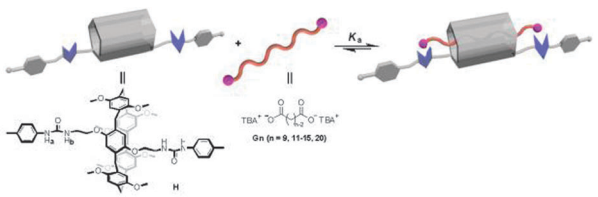

Fig. 1 Graphical representation of the formation of [2]pseudorotaxanes from **H** and **G*n***.

Key Laboratory of Mesoscopic Chemistry of MOE, Center for Multimolecular Chemistry, School of Chemistry and Chemical Engineering, Nanjing University, Nanjing 210093, P. R. China. E-mail: lywang@nju.edu.cn; Fax: +86 025 83597090; Tel: +86 025 83592529

† Electronic supplementary information (ESI) available: Synthesis, 2D NOESY, additional NMR spectra, ESI-MS spectra, Job plot and determination of the association constants. See DOI: 10.1039/c2cc34049f

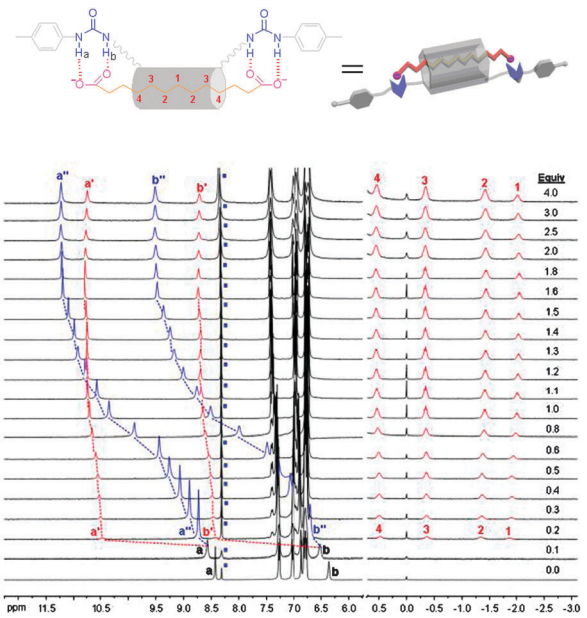

Fig. 2 (a) Graphical representation of the formation of [2]pseudorotaxane from **H** and **G13**. (b) Partial ^{1}H NMR spectra (400 MHz, DMSO-d_6, 298 K) of **H** at a concentration of 10 mM with different equivalents of **G13**. (a′ and b′: signals of urea protons from interpenetrated **H**; a″ and b″: signals of urea protons from non-interpenetrated **H**; **1**–**4**: signals from methylene protons of encapsulated **G*n***; the peaks marked with ■ are ascribed to chloroform.)

downfield shift changes for the host ureido protons H_a and H_b were also observed compared to the free host, which suggests their involvement in hydrogen bonding. Furthermore, peaks of H_a and H_b of the free **H** were further split into two separated peaks (Fig. 2b, a′, a″, b′ and b″) after the addition of 0.2 equiv. of **G13**, corresponding to the urea protons that bind to encapsulated dicarboxylate **G13** (a′ and b′) and non-encapsulated dicarboxylate **G13** (a″ and b″), respectively. The above results indicated that **H** and **G13** formed either a pseudorotaxane-type inclusion complex or external complicated complexes (Scheme S2, ESI†), both of such complexes are based on the hydrogen bonding interactions between the bis-urea hydrogens and dicarboxylate oxygens, and it also revealed that the formation of the pseudorotaxane is a slow exchange process on the NMR spectroscopy timescale. However, different from the general slow exchange process,[7a,h,14] no uncomplexed signals were observed. From 2D NOESY analysis (Fig. S19, ESI†), NOE correlations were observed between the seven methylene protons (H_1, H_2, H_3 and H_4) of **G13** and the aromatic protons of **H**, which also confirmed the interpenetrated geometry. In addition, the Job plot based on proton NMR data demonstrated that the complex was of 1 : 1 stoichiometry (Fig. S20, ESI†). All of these results suggested that the linear alkyl dicarboxylate **G13** was threaded through the cavity of **H** to form a [2]pseudorotaxane, in which the carboxylate groups of **G13** bound to the bis-urea groups of **H** *via* four hydrogen bonds, and the middle seven methylene groups of **G13** (marked with 1, 2, 3 and 4, respectively, Fig. 2a) were encapsulated in the cavity of **H**.

With respect to the equimolar solutions of both **G5** and **G7** with **H** in DMSO-d_6, the ^{1}H NMR spectra showed that the signals of the urea protons H_a and H_b of **H** shifted downfield notably (Fig. S21, ESI†). However, the signals of the middle methylene units of **G5** and **G7** did not show obvious shift, indicating that they did not thread within the cavity of **H**. This should be due to that the chain lengths of both **G5** and **G7** were too short to be fitted for site separation of the bis-urea groups. The substantial downfield shifts of the urea protons H_a and H_b can be attributed to the non-encapsulated formation of external hydrogen bonds between the bis-urea hydrogens of **H** and dicarboxylate oxygens of **G5** and **G7**, respectively. However, in the case of **G9**, **G11**, **G12**, **G14** and **G15** with a longer alkyl chain, bis-urea-functionalized pillar[5]arene inclusion-induced shielding effects were observed in DMSO-d_6 (Fig. 3 and Fig. S22–S26 (ESI†)), which are similar to **G13**⊂**H**. Remarkably, longer **G*n*** of up to 20 carbons could also thread through the cavity of **H** in DMSO-d_6 (Fig. 3 and Fig. S27 (ESI†)). These inclusion complexes can be considered to have [2]pseudorotaxane structures.

In the above [2]pseudorotaxane-type complexes, the four N–H···O hydrogen bonds may be the main driving force for the formation of the interpenetrated complexes. Additionally, C–H···π interactions[15] may also play an important role in stabilizing the inclusion complexes. The evidence for the presence of N–H···O hydrogen bonds upon complexation was the large (>1 ppm) changes in the chemical shifts of urea N*H* protons with the added guest.

Regardless of which **G*n*** (n = 9, 11–15, 20) was employed, a 1 : 1 complexation stoichiometry was determined by direct integration of the urea N*H* peaks of interpenetrated **H** and the encapsulated methylene peaks exhibited in Fig. 3. Electrospray ionization mass spectrometry (ESI-MS) provided further evidence for this 1 : 1 binding stoichiometry. In all cases, two significant m/z peaks were observed – one corresponding to [**G*n***⊂**H**–TBA]$^-$ and the other one to [**G*n*** ⊂ **H**–2TBA]$^{2-}$ ions (Fig. S28–S34 and also see ESI†, Table S1). While no peaks with other complexation stoichiometries were found.

To quantitatively assess the inclusion complexation behavior of these compounds, ^{1}H NMR spectra of the 1 : 1 solutions of **H** and **G*n*** ($n \geq 9$) in DMSO-d_6 were recorded (Fig. 3).

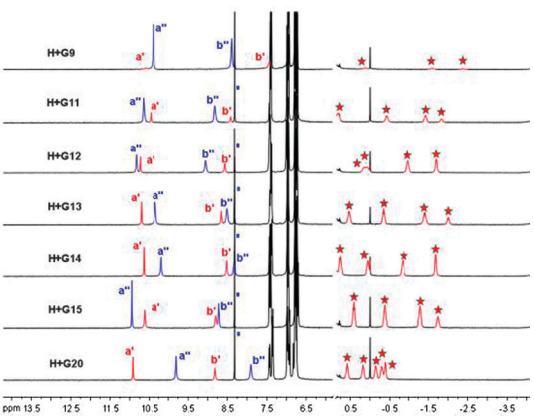

Fig. 3 Partial ^{1}H NMR spectra (400 MHz, 298 K) of **H** (10 mM) and its mixture with **G*n*** (10 mM) in DMSO-d_6. (a′ and b′: signals of urea protons from interpenetrated **H**; a″ and b″: signals of urea protons from non-interpenetrated **H**; ★: signals from methylene protons of encapsulated **G*n***; the peaks marked with ■ are ascribed to chloroform.)

Table 1 Association constants[a] (K_a) for 1 : 1 inclusion complexation of **G*n*** with **H** determined by ^{1}H NMR in DMSO-d_6 at 298 K

Bis-TBA salts of dicarboxylates [**G*n***]	K_a (M^{-1})
Glutarate (**G5**)	—[b]
Pimelate (**G7**)	—[b]
Azelate (**G9**)	—[c]
Undecanedioate (**G11**)	2.8×10^1 (0.6)
Dodecanedioate (**G12**)	6.9×10^1 (0.8)
Tridecanedioate (**G13**)	7.1×10^1 (2.5)
Tetradecanedioate (**G14**)	1.4×10^2 (4.9)
Pentadecanedioate (**G15**)	1.5×10^2 (4.5)
Eicosanedioate (**G20**)	7.6×10^1 (2.0)

[a] Average values are shown with standard deviations from three independent measurements by the single-point method using a 10 mM concentration in DMSO-d_6. [b] No binding of **G5** and **G7** inside the inner cavity of the host. [c] The K_a value was too small to be calculated.

The spectra of the mixture of **H** with **G*n*** ($n \geq 9$) displayed two sets of signals corresponding to two types of compounds (pseudorotaxane-type inclusion complexes and external complexes). From integration of the urea N*H* peaks of interpenetrated **H** and non-interpenetrated **H** exhibited in Fig. 3, binding constants (K_a) can be calculated using the single point method.[16] The K_a data are listed in Table 1. It was found that the chain length of **G*n*** was a dominant factor for the binding affinities of encapsulated **G*n*** and **H**. It may be attributed to structural complementarity between the dianionic guest and the bis-urea-functionalized host in which the two binding subunits cooperate for guest binding. The terminal anionic groups of the dicarboxylate would each interact with a urea unit of the host, the polymethylene chain stretching through the cavity of the host. Highest stability of the threaded complex corresponds to the best fit between guest length and site separation of the bis-urea groups, as schematically represented by Fig. 1. Guests that are either too short or too long lead to formation of less stable interpenetrated complexes.

In summary, we have demonstrated that ureido functional groups can easily be introduced into pillar[5]arene to yield bis-urea-functionalized pillar[5]arene, which can be utilized as a novel wheel to form a series of [2]pseudorotaxanes with axles derived from linear alkyl dicarboxylates containing nine to twenty carbons in highly competitive solvent DMSO. This novel binding motif affords the first example of pseudorotaxanes stabilized mainly by the hydrogen bonding interactions between the bis-urea hydrogens and dicarboxylate oxygens alongside C–H$\cdots\pi$ interactions, which might be applicable to the future fabrication of interlocked structures and molecular devices.

This work was supported by the National Natural Science Foundation of China (No. 20932004, 21072093, 21102073), the National Basic Research Program of China (2011CB808600), and Jiangsu Provincial Natural Science Foundation of China (BK2011055, BK2011551).

Notes and references

1 (*a*) *Molecular Catenanes, Rotaxanes and Knots*, ed. J.-P. Sauvage and C.Dietrich-Buchecker, Wiley-VCH, Weinheim, 1999; (*b*) V. Balzani, A. Credi and M. Venturi, *Molecular Devices and Machines—Concepts and Perspectives for the Nanoworld*, Wiley-VCH, Weinheim, 2008; (*c*) V. Balzani, A. Credi, F. M. Raymo and J. F. Stoddart, *Angew. Chem., Int. Ed.*, 2000, **39**, 3348; (*d*) A. Harada, A. Hashidzume, H. Yamaguchi and Y. Takashima, *Chem. Rev.*, 2009, **109**, 5974.

2 (*a*) F. M. Raymo and J. F. Stoddart, *Chem. Rev.*, 1999, **99**, 1643; (*b*) Z. Niu and H. W. Gibson, *Chem. Rev.*, 2009, **109**, 6024; (*c*) P. D. Beer, M. R. Sambrook and D. Curiel, *Chem. Commun.*, 2006, 2105; (*d*) K. D. Hänni and D. A. Leigh, *Chem. Soc. Rev.*, 2010, **39**, 1240.

3 (*a*) S. Anderson, H. L. Anderson and J. K. M. Sanders, *Acc. Chem. Res.*, 1993, **26**, 469; (*b*) R. Cacciapaglia and L. Mandolini, *Chem. Soc. Rev.*, 1993, **22**, 221; (*c*) J. P. Schneider and J. W. Kelly, *Chem. Rev.*, 1995, **95**, 2169.

4 (*a*) V. Balzani, M. Gomez-Lopez and J. F. Stoddart, *Acc. Chem. Res.*, 1998, **31**, 405; (*b*) J.-P. Sauvage, *Acc. Chem. Res.*, 1998, **31**, 611.

5 T. Ogoshi, S. Kanai, S. Fujinami, T. Yamagishi and Y. Nakamoto, *J. Am. Chem. Soc.*, 2008, **130**, 5022.

6 M. Xue, Y. Yang, X. Chi, Z. Zhang and F. Huang, *Acc. Chem. Res.*, 2012, DOI: 10.1021/ar2003418.

7 (*a*) C. Li, Q. Xu, J. Li, F. Yao and X. Jia, *Org. Biomol. Chem.*, 2010, **8**, 1568; (*b*) C. Li, L. Zhao, J. Li, X. Ding, S. Chen, Q. Zhang, Y. Yu and X. Jia, *Chem. Commun.*, 2010, **46**, 9016; (*c*) C. Han, F. Ma, Z. Zhang, B. Xia, Y. Yu and F. Huang, *Org. Lett.*, 2010, **12**, 4360; (*d*) T. Ogoshi, M. Hashizume, T.-a. Yamagishi and Y. Nakamoto, *Chem. Commun.*, 2010, **46**, 3708; (*e*) T. Ogoshi, D. Yamafuji, T. Aoki and T.-a. Yamagishi, *J. Org. Chem.*, 2011, **76**, 9497; (*f*) T. Ogoshi, S. Tanaka, T.-a. Yamagishi and Y. Nakamoto, *Chem. Lett.*, 2011, 96; (*g*) Z. Zhang, Y. Luo, B. Xia, C. Han, Y. Yu, X. Chen and F. Huang, *Chem. Commun.*, 2011, **47**, 2417; (*h*) C. Li, X. Shu, J. Li, S. Chen, K. Han, M. Xu, B. Hu, Y. Yu and X. Jia, *J. Org. Chem.*, 2011, **76**, 8458; (*i*) C. Han, G. Yu, B. Zhang and F. Huang, *Org. Lett.*, 2012, **14**, 1712; (*j*) Y. Ma, X. Chi, X. Yan, J. Liu, Y. Yao, W. Chen, F. Huang and J. Hou, *Org. Lett.*, 2012, **14**, 1532.

8 (*a*) Z. Zhang, B. Xia, C. Han, Y. Yu and F. Huang, *Org. Lett.*, 2010, **12**, 3285; (*b*) N. L. Strutt, R. S. Forgan, J. M. Spruell, Y. Y. Botros and J. F. Stoddart, *J. Am. Chem. Soc.*, 2011, **133**, 5668; (*c*) X. Hu, L. Chen, W. Si, Y. Yu and J. Hou, *Chem. Commun.*, 2011, **47**, 4694; (*d*) C. Li, S. Chen, J. Li, K. Han, M. Xu, B. Hu, Y. Yu and X. Jia, *Chem. Commun.*, 2011, **47**, 11294; (*e*) T. Ogoshi, K. Demachi, K. Kitajima and T.-a. Yamagishi, *Chem. Commun.*, 2011, **47**, 10290; (*f*) X. Shu, S. Chen, J. Li, Z. Chen, L. Weng, X. Jia and C. Li, *Chem. Commun.*, 2012, **48**, 2967; (*g*) X. Shu, J. Fan, J. Li, X. Wang, W. Chen, X. Jia and C. Li, *Org. Biomol. Chem.*, 2012, **10**, 3393; (*h*) C. Li, K. Han, J. Li, H. Zhang, J. Ma, X. Shu, Z. Chen, L. Weng and X. Jia, *Org. Lett.*, 2012, **14**, 42.

9 Y. Ma, X. Ji, F. Xiang, X. Chi, C. Han, J. He, Z. Abliz, W. Chen and F. Huang, *Chem. Commun.*, 2011, **41**, 12340.

10 (*a*) P. A. Gale, Amide and Urea based Anion Receptors, in *The Encyclopaedia of Supramolecular Chemistry*, ed. J. L. Atwood and J. W. Steed, Dekker, New York, 2004, pp. 31–41; (*b*) J. L. Sessler, P. A. Gale and W.-S. Cho, *Anion Receptor Chemistry*, Royal Society of Chemistry, Cambridge, UK, 2006; (*c*) V. Amendola, L. Fabbrizzi and L. Mosca, *Chem. Soc. Rev.*, 2010, **39**, 3889.

11 (*a*) A. Arduini, R. Ferdani, A. Pochini, A. Secchi and F. Ugozzoli, *Angew. Chem., Int. Ed.*, 2000, **39**, 3453; (*b*) A. Arduini, F. Ciesa, M. Fragassi, A. Pochini and A. Secchi, *Angew. Chem., Int. Ed.*, 2005, **44**, 278; (*c*) K. Zhu, S. Li, F. Wang and F. Huang, *J. Org. Chem.*, 2009, **74**, 1322; (*d*) A. Arduini, R. Bussolati, D. Masseroni, G. Royal and A. Secchi, *Eur. J. Org. Chem.*, 2012, 1033.

12 X. Hu, P. Zhang, X. Wu, W. Xia, T. Xiao, J. Jiang, C. Lin and L. Wang, *Polym. Chem.*, 2012, DOI: 10.1039/c2py20285a.

13 (*a*) G. Arena, S. Gentile, F. G. Gulino, D. Sciotto and C. Sgarlata, *Tetrahedron Lett.*, 2004, **45**, 7091; (*b*) N. Kon, N. Iki and S. Miyano, *Org. Biomol. Chem.*, 2003, **1**, 751; (*c*) Y. Liu, D.-S. Guo, H.-Y. Zhang, Y.-H. Ma and E.-C. Yang, *J. Phys. Chem. B*, 2006, **110**, 3428.

14 (*a*) S. J. Loeb and J. A. Wisner, *Angew. Chem., Int. Ed.*, 1998, **37**, 2838; (*b*) L. Li and G. J. Clarkson, *Org. Lett.*, 2007, **9**, 497; (*c*) D. Castillo, P. Astudillo, J. Mares, F. J. González, A. Vela and J. Tiburcio, *Org. Biomol. Chem.*, 2007, **5**, 2252.

15 Z. Zhang, Y. Luo, J. Chen, S. Dong, Y. Yu, Z. Ma and F. Huang, *Angew. Chem., Int. Ed.*, 2011, **50**, 1397.

16 J. C. Adrian Jr and C. S. Wilcox, *J. Am. Chem. Soc.*, 1991, **113**, 678.

