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Da-Hui Qu *et al.*

One-pot synthesis of a [c2]daisy-chain-containing hetero[4]rotaxane via a self-sorting strategy

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One-pot synthesis of a [c2]daisy-chain-containing hetero[4]rotaxane *via* a self-sorting strategy†

Xin Fu,‡ Qi Zhang,‡ Si-Jia Rao, Da-Hui Qu* and He Tian

The construction and efficient synthesis of hetero[n]rotaxanes with high structural complexity are always attractive challenges. Herein, we demonstrate a facile one-pot preparation of a hetero[4]rotaxane, by employing a self-sorting strategy, which contains an interpenetrated dibenzo-24-crown-8 (DB24C8) based [c2]daisy chain structure and is ended with a benzo-21-crown-7 (B21C7) based rotaxane at each side. The key to the design involved encoding the selective threading using a steric hindrance-related "language", where highly selective self-assemblies occurred in a three-component self-sorting process, which included the threading of a benzylalkylammonium into a B21C7 and interpenetrated dimerized formation of a DB24C8 based [c2]daisy chain simultaneously; the precise pre-assembled system resulted in the efficient synthesis of hetero[4]rotaxane with a high-level of structural complexity under the "CuAAC" reaction.

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Introduction

In the last twenty years, a variety of mechanically interlocked molecules (MIMs), especially rotaxanes and catenanes, have been delicately designed and constructed.¹ The unique structural features of MIMs are utilized by scientists to birth elegant functional molecules,² indicating the great potential of MIMs in functional materials. As a modification platform for functional groups, the structural complexity of MIMs significantly provides infinite possibilities in designing novel functional molecular machines.³ Hence, the construction and efficient synthesis of MIMs with high structural complexity have been greatly attractive but challenging.⁴ Recently, much attention has been focused on the topological,^{3a} interpenetrating,⁵ knotted⁶ structures of MIMs with high structural complexity. In this intriguing family, [c2] daisy chain molecules,⁵ a class of rotaxanes constructed from the dimerization of AB-type linear monomers with two self-complementary units, A (host) and B (guest), have shown their talent in mimicking the contraction and extension movements of natural biological machines.^{5f} Various elegant [c2] daisy chain molecules have been reported based on different host–guest systems including versatile macrocycles, such as crown ethers,^{5b,e,h} cucurbit[n]uril,⁵ⁱ cyclodextrins,^{5a,c,d} pillarenes,^{5g,m,p} and cyclophanes.^{5o}

A variety of hetero[n]rotaxanes, especially those comprising two or more different types of ring moiety, have been designed and constructed,⁷ some even in a one-step strategy.^{7b,d} This aroused our interest to integrate muscle-like daisy chain structures with hetero[n]rotaxanes to breed a hetero[n]rotaxane with a novel structural topology. However, it is difficult to synthesize this novel hetero[n]rotaxane based on traditional strategies for rotaxane synthesis,⁸ which are efficient in the preparation of typical [2]rotaxane but complicated when there is more than one type of ring moiety, due to them being "non-selective". The key challenge is the dramatically increased complexity of the interpenetration process in the formation of a [c2]daisy chain when additional recognition sites and rings are incorporated into the multi-component self-assembling system. Hence, a programming language for highly selective self-assembly is desperately needed to integrate hetero[n]rotaxane with the daisy chain structure.

Self-sorting strategies have the unique capability of selective self-assembly in complex supramolecular systems.⁹ Schalley and co-workers¹⁰ have developed an efficient integrative self-sorting strategy for selective self-assembly to simultaneously incorporate two kinds of polyether macrocycles into a single axle molecule comprising two kinds of secondary ammoniums which, as a result, form a cascade-stoppered hetero[3]rotaxane. This self-sorting strategy has been proved to be very efficient in constructing many hetero[n]rotaxanes with increased structural complexity.¹¹ However, to the best of our knowledge, this self-sorting strategy has not been proved to be appropriate for a system simultaneously involving both threading and interpenetration, which are known for the formation of pseudorotaxanes and daisy chain structures, respectively.

Herein, a facile one-pot synthesis of hetero[4]rotaxane **5** is successfully realized *via* a three-component (**1**, **2** and B21C7 in

Key Laboratory for Advanced Materials and Institute of Fine Chemicals, East China University of Science and Technology, 130 Meilong Road, Shanghai, 200237, China.
E-mail: dahui_qu@ecust.edu.cn

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‡ X. F. and Q. Z. contributed equally.

Scheme 1 Schematic representation of the preparation of hetero[4]rotaxane **5** using a three-component modularized self-sorting system of **1**, **2** and **B21C7**. Only one main stereoisomer of hetero[4]rotaxane **5**, which is derived from the three possible [c2]daisy chain stereoisomers,^{5e} is shown here.

Scheme 1) self-sorting strategy. In principle, these initial components (**1**, **2** and **B21C7** in Scheme 1) could assemble into several self-assembly species, while only two kinds of precursors, [c2]daisy chain **3** and [2]semi-rotaxane **4**, were successfully formed through the highly selective self-assembly process as determined by ¹H NMR studies. In this pre-assembly process, both the self-interpenetration of compound **1** to form [c2]daisy chain **3** and the threading of **2** into the cavity of **B21C7** to form [2]semi-rotaxane **4** occurred simultaneously. Then the highly symmetrical hetero[4]rotaxane **5** containing [c2]daisy chain could be obtained by the following facile one-pot CuAAC click reaction.^{8d} We believe that the facile one-pot synthesis of hetero[4]rotaxane **5** would inspire the successful construction of MIMs with fascinating structures and potential functions.

Results and discussion

The rational design of block building is a prerequisite to realizing the precise construction of a multi-component system. As shown in Scheme 1, initial substrates include compound **1** (the synthesis information from compounds **7** and **8** can be found in the ESI†), which contains a **DB24C8** macrocycle modified with

a secondary dibenzylammonium branched chain; a secondary benzylalkylammonium **2**; and **B21C7**. The key part of the design involves the dibenzylammonium recognition site in compound **1**, where the phenyl group encodes the secondary ammonium as a selective site that only can be included by the larger macrocyclic **DB24C8**, but not by **B21C7**.^{7b,10,12} Therefore, even in one system, **B21C7** would not affect the formation of the [c2]daisy chain **3**. Meanwhile, this phenyl group also makes the secondary ammonium in compound **1** a preferred recognition site for **DB24C8**, over that in compound **2**.¹⁰ Considering the precise 1 : 1 proportion of **DB24C8** and the secondary ammonium in compound **1**, compound **2** would not affect the formation of [c2]daisy chain **3** from monomer molecule **1**, which has been proved by the ¹H NMR measurements (Fig. S1†). As a result, the self-assembly of the initial molecules was precisely encoded, where the self-sorting process included simultaneous threading and interpenetration, and then [2] semi-rotaxane **4** and [c2]daisy chain **3** were generated, respectively. Finally, in the presence of Cu(MeCN)₄PF₆, the subsequent CuAAC click reaction between [c2]daisy chain **3** and [2]semi-rotaxane **4** afforded the formation of hetero[4]rotaxane **5** in a one-pot strategy. In the obtained hetero[4]rotaxane **5**, two

B21C7 rings can be stopped by the outer phenyl groups, while the central [c2]daisy chain structures are cascade-stopped by the **B21C7** rings.

We performed ^1H NMR experiments to confirm the self-sorting behaviours in this three-component system, as shown in Fig. 1. The ^1H NMR spectra revealed that **1** existed as a monomer in polar solvents, such as $[\text{D}_6]\text{DMSO}$ (Fig. 1a), with normal and simple ^1H NMR signals. While in less polar solvents, such as $[\text{D}_3]\text{acetonitrile}$ (Fig. 1b), [c2]daisy chain **3** became the predominant species. The ^1H NMR signals of the NH_2^+ protons and crown ether moiety shifted and split, becoming much broader and more complicated. As shown in Fig. 1b, two sets of signals for the NH_2^+ protons were observed at $\delta = 7.0$ – 7.4 ppm, attributed to each ammonium facing the two non-symmetrical ends of the axle. According to the previous studies about the analogous [c2]daisy chains,^{13,14} there are three dimeric interlocked stereoisomers arising from the unsymmetrical substitution of the **DB24C8** ring, which were also observed in the ^1H NMR spectrum of [c2]daisy chain **3** (Fig. 1b). As shown in Fig. 1, the aromatic protons of **DB24C8** also become split, especially protons H_1 and H_3 . H_1 splits into two sets of double peaks (H_{1a} , 6.4 ppm and H_{1b} , 6.9 ppm), and H_3 splits into two sets of single peaks (H_{3a} , 6.8 ppm and H_{3b} , 6.2 ppm) with the ratio of 5 : 1, indicating the major supramolecular stereoisomer of the “meso” type, shown in Scheme 1, which is consistent with the previous report.^{5e} Meanwhile, the formation of [2]semi-rotaxane **4** from compound **2** and **B21C7** has been detected using the ^1H NMR spectra shown in Fig. 2. After mixing compound **2** and **B21C7** in a 1 : 1 molar ratio, the signals of the NH_2^+ protons shifted upfield with a $\Delta\delta$ of -0.97 ppm, and the signals of H_a , H_b and H_c shifted downfield with a $\Delta\delta$ of 0.26, 0.24 and 0.07 ppm, respectively, suggesting the formation of [2]semi-rotaxane **4**.¹² Then, the three compounds **1**, **2** and **B21C7** were mixed in $[\text{D}_3]\text{acetonitrile}$ in a molar ratio of 1 : 1 : 1. ^1H NMR spectra (Fig. 3) showed that the signals of H_{1a} , H_{3b} , H_4 and H_5 in [c2]daisy chain **3**, as well as those of H_a , H_b and H_c in [2]semi-rotaxane **4**, remain constant. These observations indicate that the two pseudorotaxanes still exist as the predominant species in this three-component self-sorting system.

Fig. 1 Partial ^1H NMR spectra (400 MHz, 298 K) of compound **1** in (a) $[\text{D}_6]\text{DMSO}$, and (b) $[\text{D}_3]\text{acetonitrile}$.

Fig. 2 Partial ^1H NMR spectra (400 MHz, 298 K, $[\text{D}_3]\text{acetonitrile}$) of (a) **B21C7**, (b) a 1 : 1 mixture of **2** and **B21C7**, and (c) compound **2**.

The synthetic route for hetero[4]rotaxane **5** is outlined in Scheme 1. At room temperature, the CuAAC reaction between [c2]daisy chain **3** and [2]semi-rotaxane **4** successfully afforded the formation of a white solid, hetero[4]rotaxane **5**, with a yield exceeding 50% in the presence of $\text{Cu}(\text{MeCN})_4\text{PF}_6$. As shown in Fig. 4a and b, the terminal alkynyl proton H_{11} of **3** disappeared after the CuAAC click reaction, indicating the successful formation of the triazole. The resonance for the triazole proton H_f appeared at $\delta = 7.72$ ppm and the adjacent protons H_{10} , H_b , H_d and H_e shifted downfield with a $\Delta\delta$ of 0.38, 0.22, 0.12 and 0.89 ppm, respectively. All of these changes demonstrated the importance of the CuAAC click reaction for the formation of hetero[4]rotaxane **5**, as illustrated in Scheme 1.¹⁵ The high resolution mass spectrum (HRMS) of hetero[4]rotaxane **5** showed major signals at m/z 628.0955, 885.7819 and 1401.1543, which correspond to the product after the loss of 4, 3 and 2PF_6^- ions, *i.e.* $[\text{M} - 4\text{PF}_6]^{4+}$, $[\text{M} - 3\text{PF}_6]^{3+}$ and $[\text{M} - 2\text{PF}_6]^{2+}$, respectively. The molecular ion peaks of $[\text{M} - 4\text{PF}_6]^{4+}$ and $[\text{M} - 3\text{PF}_6]^{3+}$, as well as the results of ^1H NMR, give enough evidence to show the formation of hetero[4]rotaxane **5**.¹⁵

Fig. 3 Partial ^1H NMR spectra (400 MHz, 298 K, $[\text{D}_3]\text{acetonitrile}$) of (a) compound **1**, (b) a 1 : 1 : 1 mixture of **1**, **2** and **B21C7**, and (c) a 1 : 1 mixture of **2** and **B21C7**.

Fig. 4 Partial ^1H NMR spectra (400 MHz, 298 K, $[\text{D}_3]\text{acetonitrile}$) of (a) a 1 : 1 : 1 mixture of **1**, **2** and **B21C7**, (b) hetero[4]rotaxane **5**, and (c) [2]rotaxane **6**.

For further understanding of the self-sorting process and confirming the chemical structure of hetero[4]rotaxane **5**, the dibenzylammonium site in compound **1** was protected with a BOC group to yield compound **9** (Scheme 2), leading to a recognition failure between macrocyclic **DB24C8** and the DBA site. As a result, there was only one type of secondary

Scheme 2 Synthetic route for [2]rotaxane **6**.

ammonium recognition site in the mixed systems of compound **9**, compound **2** and **B21C7**, meaning that a non-self-sorting process would occur among these building blocks. Then, a CuAAC click reaction of compound **9** and [2]semi-rotaxane **4** successfully afforded [2]rotaxane **10** in the presence of $\text{Cu}(\text{MeCN})_4\text{PF}_6$ in a 1 : 1 volume ratio of dichloromethane/acetonitrile at room temperature. After being treated with trifluoroacetic acid, the reference compound [2]rotaxane **6** with an unoccupied **DB24C8** ring was obtained. The HRMS spectrum of [2]rotaxane **6** shows major signals at m/z 1400.6526, corresponding to the product after a loss of the PF_6^- ion, confirming the interlocked structure. Furthermore, we compared all of the resonances between hetero[4]rotaxane **5** and [2]rotaxane **6** by analysing their ^1H NMR spectra (Fig. 4b and c). As shown in the ^1H NMR spectra of **5** and **6** in $[\text{D}_3]\text{acetonitrile}$ (Fig. 4b and c), the protons H_1 , H_2 , H_3 and H_j of [2]rotaxane **6** shifted downfield with a $\Delta\delta$ of about 0.2 ppm, and the stereoisomer signals of H_{1a} and H_{3b} disappeared, which was attributed to the fact that the DBA site was not surrounded by the **DB24C8** macrocycle to give a simple chemical shift environment. It is notable that the DBA protons in [2]rotaxane **6** cannot be detected because there are no hydrogen bonding interactions between the crown ether and the DBA hydrogen atoms.¹⁶ Compared with the ^1H NMR spectrum of hetero[4]rotaxane **5**, H_4 and H_5 which are adjacent to the DBA site were observed to shift upfield with a $\Delta\delta$ of -0.53 ppm in the ^1H NMR spectrum of [2]rotaxane **6**, which confirmed that the DBA sites were not bound by the host macrocycle **DB24C8**. Therefore, the phenyl-stopped **B21C7** played an important role in inhibiting the dethreading of the daisy chain structure in the middle, this is also called a cascade-stopped strategy.^{10,7b} Importantly, this inhibiting behaviour also caused the stable structure of hetero[4]rotaxane **5** instead of a meta-stable pseudorotaxane.

Meanwhile, 2D NOESY spectra of hetero[4]rotaxane **5** and [2]rotaxane **6** validated their chemical structures. The NOESY spectrum of **6** in $[\text{D}_3]\text{acetonitrile}$ (Fig. S1†) shows two cross-peaks (peak F and G) between the phenyl protons H_L and ethylene protons of **B21C7**, thus clearly indicating that **B21C7** is located on the outer ammonium site which is far away from the **DB24C8** ring. In the meantime, no cross-peaks between **DB24C8** and the inner DBA site were found. Nevertheless, in the NOESY spectrum of **5** (Fig. S2†), we found not only cross-peaks (peaks P, Q, R and S) between the phenyl protons H_L and ethylene protons of **B21C7**, but also cross-peaks (peak N and O) between the phenyl protons H_7 and ethylene protons of **DB24C8**, and cross-peaks (peak T and U) between the phenyl protons H_6 and ethylene protons of **DB24C8**, thus clearly indicating the existence of a [c2]daisy chain structure in **5**.

Conclusion

In conclusion, a novel hetero[4]rotaxane containing a [c2]daisy chain can be facilely synthesized in one pot by employing a multi-component self-sorting strategy followed by the well-known CuAAC stopping reaction. The highly selective self-assembling process that occurred among the three kinds of building blocks provides the possibility for the formation of

only two kinds of rotaxane precursors, by employing a steric hindrance-related “language”. This work serves as one of few successful examples of the construction of hetero[n]rotaxane with a [c2]daisy chain cored structure directed by a self-sorting strategy. Significantly, the integration of hetero[n]rotaxane and a [c2]daisy chain structure enlarges the family of mechanically interlocked molecules and this synthetic methodology can be utilized in the preparation of mechanically interlocked compounds with increasingly complicated structures and functions.

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Notes and references

- (a) S. J. Loeb, *Chem. Soc. Rev.*, 2007, **36**, 226–235; (b) C. F. Lee, D. A. Leigh, R. G. Pritchard, D. Schultz, S. J. Teat, G. A. Timco and R. E. Winpenny, *Nature*, 2009, **458**, 314–318; (c) J. F. Stoddart, *Angew. Chem., Int. Ed.*, 2014, **53**, 11102–11104; (d) K. Zhu, C. A. O’Keefe, V. N. Vukotic, R. W. Schurko and S. J. Loeb, *Nat. Chem.*, 2015, **7**, 514–519; (e) G. Ragazzon, M. Baroncini, S. Silvi, M. Venturi and A. Credi, *Nat. Nanotechnol.*, 2015, **10**, 70–75; (f) C. Cheng, P. R. McGonigal, S. T. Schneebeli, H. Li, N. A. Vermeulen, C. Ke and J. F. Stoddart, *Nat. Nanotechnol.*, 2015, **10**, 547–553; (g) G. Gil-Ramírez, D. A. Leigh and A. J. Stephens, *Angew. Chem., Int. Ed.*, 2015, **54**, 6110–6150; (h) M. Xue, Y. Yang, X. Chi, X. Yan and F. Huang, *Chem. Rev.*, 2015, **115**, 7398–7501; (i) T. Heinrich, C. H. H. Traulsen, M. Holzweber, S. Richter, V. Kunz, S. K. Kastner, S. O. Krabbenborg, J. Huskens, W. E. S. Unger and C. A. Schalley, *J. Am. Chem. Soc.*, 2015, **137**, 4382–4390; (j) S. H. Li, H. Y. Zhang, X. Xu and Y. Liu, *Nat. Commun.*, 2015, **6**, 7590; (k) E. R. Kay and D. A. Leigh, *Angew. Chem., Int. Ed.*, 2015, **54**, 10080–10088; (l) J. M. Abendroth, O. S. Bushuyev, P. S. Weiss and C. J. Barrett, *ACS Nano*, 2015, **9**, 7746–7768; (m) S. Erbas-Cakmak, D. A. Leigh, C. T. McTernan and A. L. Nussbaumer, *Chem. Rev.*, 2015, **115**, 10081–10206.
- (a) B. Lewandowski, G. D. Bo, J. W. Ward, M. Papmeyer, S. Kuschel, M. J. Aldegunde, P. M. E. Gramlich, D. Heckmann, S. M. Goldup, D. M. D’Souza, A. E. Fernandes and D. A. Leigh, *Science*, 2013, **339**, 189–193; (b) J. N. Zhang, H. Li, W. Zhou, S. L. Yu, D. H. Qu and H. Tian, *Chem.-Eur. J.*, 2013, **19**, 17192–17200; (c) H. Li, X. Li, Z. Q. Cao, D. H. Qu, H. Ågren and H. Tian, *ACS Appl. Mater. Interfaces*, 2014, **6**, 18921–18929; (d) M. J. Langton and P. D. Beer, *Acc. Chem. Res.*, 2014, **47**, 1935–1949; (e) Z. Q. Cao, Q. Miao, Q. Zhang, H. Li, D. H. Qu and H. Tian, *Chem. Commun.*, 2015, **51**, 4973–4976.
- (a) W. Wang, L. J. Chen, X. Q. Wang, B. Sun, X. Li, Y. Zhang, J. Shi, Y. Yu, L. Zhang, M. Liu and H. B. Yang, *Proc. Natl. Acad. Sci. U. S. A.*, 2015, **112**, 5597–5601; (b) S. F. M. van Dongen, S. Cantekin, J. A. A. W. Elemans, A. E. Rowan and R. J. M. Nolte, *Chem. Soc. Rev.*, 2014, **43**, 99–122; (c) R. J. Bordoli and S. M. Goldup, *J. Am. Chem. Soc.*, 2014, **136**, 4817–4820; (d) D. A. Leigh, R. G. Pritchard and A. J. Stephens, *Nat. Chem.*, 2014, **6**, 978–982; (e) Z. Meng, Y. Han, L. N. Wang, J. F. Xiang, S. G. He and C. F. Chen, *J. Am. Chem. Soc.*, 2015, **137**, 9739–9745.
- (a) J. D. Badjić, V. Balzani, A. Credi, S. Silvi and J. F. Stoddart, *Science*, 2004, **303**, 1845–1849; (b) H. Li, X. Li, H. Ågren and D. H. Qu, *Org. Lett.*, 2014, **16**, 4940–4943; (c) P. Waelès, C. Clavel, K. Fournel-Marotte and F. Coutrot, *Chem. Sci.*, 2015, **6**, 4828–4836; (d) M. J. Langton, J. D. Matichak, A. L. Thompson and H. L. Anderson, *Chem. Sci.*, 2011, **2**, 1897–1901.
- (a) T. Fujimoto, Y. Sakata and T. Kaneda, *Chem. Commun.*, 2000, 2143–2144; (b) J. Wu, K. C. F. Leung, D. Benitez, J. Y. Han, S. J. Cantrill, L. Fang and J. F. Stoddart, *Angew. Chem., Int. Ed.*, 2008, **47**, 7470–7474; (c) Y. Liu, Z.-X. Yang and Y. Chen, *J. Org. Chem.*, 2008, **73**, 5298–5304; (d) R. E. Dawson, S. F. Lincoln and C. J. Easton, *Chem. Commun.*, 2008, **34**, 3980–3982; (e) F. Coutrot, C. Romuald and E. Busseron, *Org. Lett.*, 2008, **10**, 3741–3744; (f) P. G. Clark, M. W. Day and R. H. Grubbs, *J. Am. Chem. Soc.*, 2009, **131**, 13631–13633; (g) Z. Zhang, Y. Luo, J. Chen, S. Dong, Y. Yu, Z. Ma and F. Huang, *Angew. Chem., Int. Ed.*, 2011, **50**, 1397–1401; (h) G. Du, E. Moulin, N. Jouault, E. Buhler and N. Giuseppone, *Angew. Chem., Int. Ed.*, 2012, **51**, 12504–12508; (i) L. Cao and L. Isaacs, *Org. Lett.*, 2012, **14**, 3072–3075; (j) Z. Zhang, C. Han, G. Yu and F. Huang, *Chem. Sci.*, 2012, **3**, 3026–3031; (k) J. Rotzler and M. Mayor, *Chem. Soc. Rev.*, 2013, **42**, 44–62; (l) C. J. Bruns and J. F. Stoddart, *Acc. Chem. Res.*, 2014, **47**, 2186–2199; (m) Q. Zhang, C. H. Zhang, J. H. Yang, P. Y. Xin, X. P. Xuan, J. G. Wang, N. N. Ma, H. M. Guo and G. R. Qu, *Chem. Commun.*, 2015, **51**, 15253–15256; (n) A. Coujon, G. Du, E. Moulin, G. Fuks, M. Maaloum, E. Buhler and N. Giuseppone, *Angew. Chem., Int. Ed.*, 2016, **55**, 703–707; (o) C. J. Bruns, M. Frascioni, J. Iehl, K. J. Hartlieb, S. T. Schneebeli, C. Cheng, S. I. Stupp and J. F. Stoddart, *J. Am. Chem. Soc.*, 2014, **136**, 4714–4723; (p) L. Gao, Z. Zhang, B. Zheng and F. Huang, *Polym. Chem.*, 2014, **5**, 5734–5739.
- (a) J. F. Ayme, J. E. Beves, C. J. Campbell and D. A. Leigh, *Chem. Soc. Rev.*, 2013, **42**, 1700–1712; (b) J. F. Ayme, J. E. Beves, D. A. Leigh, R. T. McBurney, K. Rissanen and D. Schultz, *Nat. Chem.*, 2012, **4**, 15–20; (c) J. F. Ayme, J. E. Beves, C. J. Campbell, G. Gil-Ramírez, D. A. Leigh and A. J. Stephens, *J. Am. Chem. Soc.*, 2015, **137**, 9812–9815.
- (a) E. J. F. Klotz, T. D. W. Claridge and H. L. Anderson, *J. Am. Chem. Soc.*, 2006, **128**, 15374–15375; (b) Z. J. Zhang, H. Y. Zhang, H. Wang and Y. Liu, *Angew. Chem., Int. Ed.*, 2011, **50**, 10834–10838; (c) C. Ke, R. A. Smaldone, T. Kikuchi, H. Li, A. P. Davis and J. F. Stoddart, *Angew. Chem., Int. Ed.*, 2013, **52**, 381–387; (d) X. Hou, C. Ke, C. Cheng, N. Song, A. K. Blackburn, A. A. Sarjeant,

- Y. Y. Botros, Y. W. Yang and J. F. Stoddart, *Chem. Commun.*, 2014, **50**, 6196–6199; (e) P. N. Chen, C. C. Lai and S. H. Chiu, *Org. Lett.*, 2011, **13**, 4660–4663; (f) G. Celtek, M. Artar, O. A. Scherman and D. Tuncel, *Chem.–Eur. J.*, 2009, **15**, 10360–10363; (g) C. Ke, R. A. Smaldone, T. Kikuchi, H. Li, A. P. Davis and J. F. Stoddart, *Angew. Chem., Int. Ed.*, 2013, **52**, 381–387; (h) Q. F. Luo, L. Zhu, S. J. Rao, H. Li, Q. Miao and D. H. Qu, *J. Org. Chem.*, 2015, **80**, 4704–4709.
- 8 (a) M. C. Fyfe and J. F. Stoddart, *Acc. Chem. Res.*, 1997, **30**, 393–401; (b) S. J. Rowan, S. J. Cantrill and J. F. Stoddart, *Org. Lett.*, 1999, **1**, 129–132; (c) S. J. Rowan and J. F. Stoddart, *J. Am. Chem. Soc.*, 2000, **122**, 164–165; (d) K. D. Hänni and D. A. Leigh, *Chem. Soc. Rev.*, 2010, **39**, 1240–1251.
- 9 (a) A. Wu and L. Isaacs, *J. Am. Chem. Soc.*, 2003, **125**, 4831–4835; (b) F. Wang, C. Han, C. He, Q. Zhou, J. Zhang, C. Wang, N. Li and F. Huang, *J. Am. Chem. Soc.*, 2008, **130**, 11254–11255; (c) M. M. Safont-Sempere, G. Fernández and F. Würthner, *Chem. Rev.*, 2011, **111**, 5784–5814; (d) W. Wang, Y. Zhang, B. Sun, L. Chen, X. D. Xu, M. Wang, X. Li, Y. Yu, W. Jiang and H. B. Yang, *Chem. Sci.*, 2014, **5**, 4554–4560; (e) D. Račkauskaitė, R. Gegevičius, Y. Matsuo, K. Wärnmark and E. Orentas, *Angew. Chem., Int. Ed.*, 2016, **55**, 208–212.
- 10 W. Jiang, H. D. F. Winkler and C. A. Schalley, *J. Am. Chem. Soc.*, 2008, **130**, 13852–13853.
- 11 (a) W. Jiang and C. A. Schalley, *Proc. Natl. Acad. Sci. U. S. A.*, 2009, **106**, 10425–10429; (b) W. Jiang, A. Schäfer, P. C. Mohr and C. A. Schalley, *J. Am. Chem. Soc.*, 2010, **132**, 2309–2320; (c) W. Jiang, D. Sattler, K. Rissanen and C. A. Schalley, *Org. Lett.*, 2011, **13**, 4502–4505; (d) W. Jiang, K. Nowosinski, N. L. Löw, E. V. Dzyuba, F. Klautzsch, A. Schäfer, J. Huuskonen, K. Rissanen and C. A. Schalley, *J. Am. Chem. Soc.*, 2012, **134**, 1860–1868; (e) B. Zheng, F. Klautzsch, M. Xue, F. H. Huang and C. A. Schalley, *Org. Chem. Front.*, 2014, **1**, 532–540; (f) Z. He, W. Jiang and C. A. Schalley, *Chem. Soc. Rev.*, 2015, **44**, 779–789.
- 12 C. J. Zhang, S. J. Li, J. Q. Zhang, K. L. Zhu, N. Li and F. Huang, *Org. Lett.*, 2007, **9**, 5553–5556.
- 13 A. Wolf, E. Moulin, J. J. Cid, A. Goujon, G. Du, E. Busseron, G. Fuks and N. Giuseppone, *Chem. Commun.*, 2015, **51**, 4212–4215.
- 14 C. J. Bruns, M. Frasconi, J. Iehl, K. J. Hartlieb, S. T. Schneckeli, C. Cheng, S. I. Stupp and J. F. Stoddart, *J. Am. Chem. Soc.*, 2014, **136**, 4714–4723.
- 15 B. Zheng, M. Zhang, S. Dong, J. Liu and F. Huang, *Org. Lett.*, 2012, **14**, 306–309.
- 16 H. Li, X. Li, Y. Wu, H. Ågren and D. H. Qu, *J. Org. Chem.*, 2014, **79**, 6996–7004.