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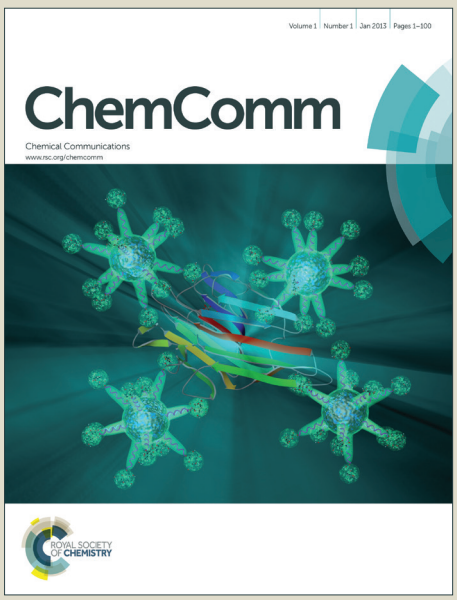

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Communication

Novel pseudo[2]rotaxanes constructed by self-assembly of dibenzyl tetramethylene bis-carbamate derivatives and per-ethylated pillar[5]arene

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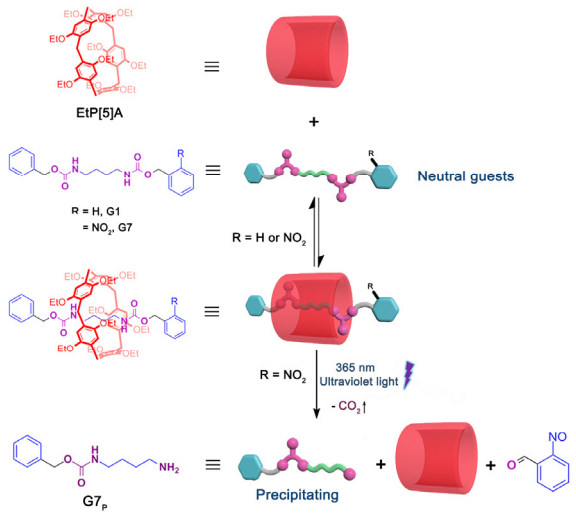
Novel neutral guest molecules, G1-G7, are studied for their host-guest complexation with per-ethylated pillar[5]arene (EtP[5]A). Among them, G1 and G7, dibenzyl tetramethylene bis-carbamate derivatives, are found to achieve a novel stable pseudo[2]rotaxane with EtP[5]A, respectively, and G7⊂EtP[5]A shows a photoresponsive property.

Supramolecular chemistry[1] has become an intersectional frontier field where chemistry, physics, materials science, and life science are combined together. One of the goals of the supramolecular chemistry is to build complex, highly ordered, and specific functional molecular machines, which can be applied for the translation of information, storage, processing, and scheduling, like most of molecular machines found in biological nature.[2]

Pseudorotaxanes, as a typical kind of molecular machine, have attracted considerable interest in the fields of supramolecular chemistry and materials chemistry in the past decades. As an interlocked architecture,[3] pseudorotaxanes constructed by π···π stacking, hydrogen bonding, hydrophilic-hydrophobic, host-guest, or metal-ligand binding interactions have been extensively investigated. Not only their special topological structures but also their mechanical, biological, and electronic functions can be achieved with their self-assemblies.[4]

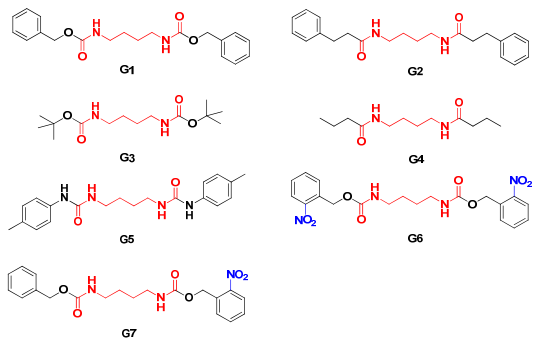
Pillararene, as a new type of macrocyclic host molecule discovered by Ogoshi[5] and Cao,[6] can participate in the formation of various pillararene-based pseudorotaxanes very well. Pillararene-based pseudo[2]rotaxanes could be achieved by pillararenes with three different types of guest molecules: (I) electropositive guests,[5, 7] (II) neutral guests,[8] and (III) electronegative guests.[9] Among these reported pseudo[2]roxtaxanes, electropositive and electronegative guest-based ones have been extensively studied, such as paraquat,[7a, 7c] ammonium salts,[7g] sodium 1-octanesulfonate,[9a] alkyl dicarboxylates,[9b, 9c] L-lysine, and L-arginine.[9d] However, for the neutral guest-based pseudo[2]roxtaxanes, there are only a few examples reported. For instance, Huang reported a pseudo[2]rotaxane formation between homopillar[5]arene and *n*-hexane,[8b] and Li studied neutral bis(imidazole) guests to form pseudo[2]roxtaxanes based on alkyl-substituted pillararens.[8a, 10] Therefore, the investigation of pillararene-based pseudo[2]roxtaxanes constructed from novel neutral guests is still necessary for the development of molecular machines.

Recently, we have reported the construction of a pillar[5]arene-based pseudo[1]rotaxane, which showed dynamic behaviors among three stations based on the synergy of its urea and amide moieties.[11] In addition, we also reported[8g] the formation of a new linear supramolecular polypseudorotaxane constructed from a bifunctional ureidopyrimidinone pillar[5]arene as the wheel and a linear alkyl diamine as the axle, where the neutral 1,4-butanediamine could thread into and stay in the pillar[5]arene cavity. Therefore, the tetramethylene bis-amide moiety, where there are four methylene groups between two amide units, was selected as the major new-designed skeleton of neutral guests reported in this paper for the investigation of their host-guest chemistry with per-ethylated pillar[5]arene (**EtP[5]A**). It was found that **G1** and **G7** could thread into the cavity of **EtP[5]A** in chloroform to achieve a novel stable pseudo[2]rotaxane (Scheme 1), respectively, and **G2-G4** and **G6** (Scheme 2) showed weak or no host-guest binding affinity with **EtP[5]A**. Particularly, **G7**, where one extra nitro group was introduced into the ortho position of one benzyl group compared with **G1**, could form a UV-responsive pseudo[2]rotaxane with **EtP[5]A** due to the photocleavage property of *o*-nitrobenzyl carbamate of **G7** under UV light (Scheme 1).



Scheme 1 Chemical structures of **EtP[5]A**, **G1**/**G7**, **G7**$_P$ and the graphical representation of the construction of pseudo[2]rotaxanes

Initially, we designed various neutral guests **G1-G5** with the major skeleton of tetramethylene bis-amide moiety (Scheme 2), where different sizes of phenyl, *t*-butyl, or *n*-propyl groups were introduced into the ends of guests for the investigation of their steric effect, and plus, one extra oxygen or nitrogen atom was introduced into each of amide groups to achieve a carbamate or urea group for the investigation of its potential extra hydrogen bondings brought by heteroatoms. **G1-G5** were synthesized from the starting material 1, 4-butanediamine (Scheme S1-S5, ESI†), and their structures were characterized by ^{1}H NMR, ^{13}C NMR, and ESI-MS. The host molecule **EtP[5]A** was prepared according to the literature.[8a]



Scheme 2 Structures of the new-designed neutral guests **G1-G7**

Subsequently, the host-guest complexation of **G1-G5** guests with **EtP[5]A** was investigated by ^{1}H NMR titration experiments, respectively. As shown in Fig. 1, it was clearly observed that after mixing equimolar host **EtP[5]A** and guest **G1**, each set of proton signals of both **EtP[5]A** host and **G1** guest were split into two sets of proton signals, respectively, where for **G1** guest one set of proton signals kept unchanged and the other set of proton signals shifted upfield, and for **EtP[5]A** host one set of proton signals kept unchanged and the other set of proton signals shifted downfield, indicating a typical slow exchange host-guest complexation on the proton NMR time scale. This means that there are four sets of proton signals during the complexation process of **EtP[5]A** and **G1**, one of which came from uncomplexed **EtP[5]A**, one of which came from uncomplexed **G1**, and two of which, in fact, came from the same set of proton

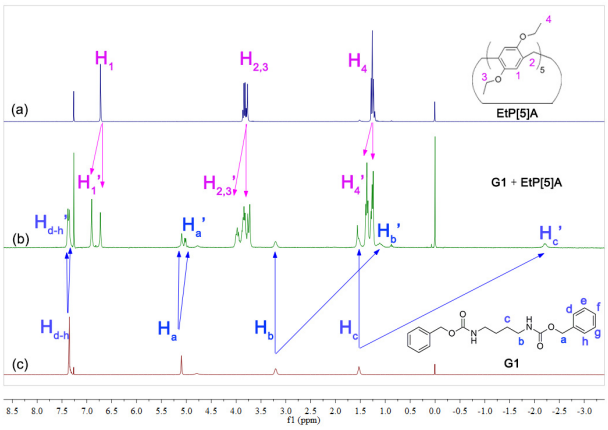


Fig. 1 ^{1}H NMR spectra (300 MHz, $CDCl_3$, 298 K): (a) **EtP[5]A** only (2.5 mM); (b) the mixture of **G1**(2.5 mM) and **EtP[5]A** (2.5 mM); (c) **G1** only (2.5 mM)

signals of **G1⊂EtP[5]A** complex (Fig. 1b). Typically, as shown in Fig. 1b, it was found that one set of H_b and H_c signals of **G1** greatly shifted from 3.21 ppm and 1.56 ppm to 1.08 ppm and −2.22 ppm, respectively, due to the shielding effect of the cavity of **EtP[5]A**, which strongly suggested that **G1** threaded into the cavity of **EtP[5]A** to form a stable pseudo[2]rotaxane. Plus, one set of H_1 signal of **EtP[5]A** remarkably shifted from 6.71 ppm to 6.90 ppm, supporting the formation of **G1⊂EtP[5]A** as well. The polar solvent, methanol-d_4, was then added into the mixture of **G1** and **EtP[5]A** in chloroform-*d*, and the ^{1}H NMR spectrum showed that the independent proton signals of free **G1** and free **EtP[5]A** were clearly observed, respectively, indicating that the hydrogen bondings could play a key role in the formation of **G1⊂EtP[5]A** (Fig. S16d, ESI†). Next, the host-guest complexation of **G1** and **EtP[5]A** was further confirmed by 2D NOSEY spectrum (Fig. 2), where the correlations were observed between tetramethylene protons (H_b' and H_c') of **G1** and the aromatic protons (H_1') of **EtP[5]A** as well as the bridging methylene protons (H_2') of **EtP[5]A**. Based on the integrations of uncomplexed and complexed proton peaks (Fig. 1b), the binding stoichiometry of **EtP[5]A** with **G1** was determined to be 1 : 1, and the association constant K_a of **G1⊂EtP[5]A** was calculated to be (1274 ± 5) M^{-1} (Fig. S16, ESI†).

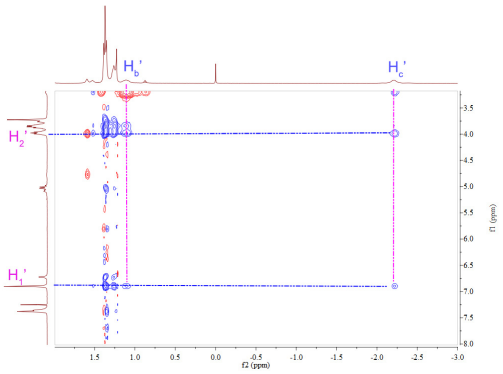


Fig. 2 2D NOSEY analysis of equimolar mixture **G1⊂EtP[5]A** in $CDCl_3$ (20 mM, 400 MHz, 298 K)

In **G2** case, the similar splitting patterns of proton signals of ^{1}H NMR spectra from the mixture of **G2** and **EtP[5]A** were observed as **G1**, but its binding constant was calculated to be (71.5 ± 2.5) M^{-1}, which was much lower than that of **G1⊂EtP[5]A**, indicating much weaker host-guest complexation of **G2** and **EtP[5]A** (Fig. S17, ESI†). This result implied that the extra oxygen atom in **G1** could possibly form another C-H ⋯ O hydrogen bond to strengthen its host-guest complexation with **EtP[5]A**. Furthermore, in order to investigate the effect of other heteroatom compared with oxygen, **G5**, in which the oxygen atom was replaced by the nitrogen atom, was synthesized for the study of its host-guest complexation with **EtP[5]A**, but unfortunately, **G5** was not soluble in chloroform-*d* and it was only partially soluble in DMSO-d_6. Therefore, the study of host-guest complexation of **G5** and **EtP[5]A** in chloroform-*d* cannot be achieved. In **G3** and **G4** cases, no obvious chemical shift change was observed for proton signals of **G3**, **G4**, and **EtP[5]A** upon addition of equimolar **G3** or **G4** into **EtP[5]A** in chloroform-*d* (Fig. S18 and S19, ESI†). This result suggested that compared with **G1**, **G3** that has a big *t*-butyl end-functional group

possibly prevented itself from threading into the cavity of **EtP[5]A**, and compared with **G2, G4** that has a small *n*-propyl end-functional group possibly prevented itself from stably staying in the cavity of **EtP[5]A** even if it could possibly thread into the cavity of **EtP[5]A**, which agreed well with the reported literature.[7c, 7f, 8a] We speculate that the size of phenyl group in **G1** is just fine to not only make itself pass through the cavity of **EtP[5]A** but also stabilize the resulting pseudo[2]rotaxane to prevent **G1** from easily taking off the cavity of **EtP[5]A**. All of above results indicated that the size of end-functional groups of guest **G1-G4** and the oxygen atom connecting with benzyl group of the carbamate of **G1** would greatly influence their host-guest interaction with **EtP[5]A**. Consequently, among **G1-G4**, **G1** that has the appropriate size of phenyl end-functional groups as well as carbamate units showed the best binding affinity with **EtP[5]A** in chloroform-*d* to obtain a stable pseudo[2]rotaxane.

In recently years, chemists have been trying to construct various photoresponsive supramolecular systems, due to the eco-friendly and mild reaction conditions of photoresponsive reactions, which were widely used in cell detection,[12] drug delivery system,[13] and copolymer polymersome.[14] Among them, especially for the photoresponsive pseudorotaxanes, the azobenzene group[15] was often used as a reversible switch based on its different configuration irradiated by light. As is well known, *o*-nitrobenzyloxycarbonyl group[12-13, 16] was used as a highly sensitive photocleavage group, whose structure is very similar as **G1**, therefore, one or two NO_2 groups were introduced into the benzyl group of **G1** to achieve two new neutral guests, symmetrical **G6** and unsymmetrical **G7** (Scheme 2), which could possibly complex with **EtP[5]A** as **G1** did. And similarly as **G1**, the host-guest complexation of **G6** or **G7** with **EtP[5]A** was also studied by ^{1}H NMR experiments. Upon addition of **EtP[5]A** into **G6** solution in chloroform-*d*, no chemical shift change was observed, which could be the reason that the size of the two *o*-nitrophenyl end-functional groups of **G6** was too bigger to thread into the cavity of **EtP[5]A**. However, in **G7** case where only one NO_2 group was introduced into one of benzyl group to obtain unsymmetrical guest **G7**, the pseudo[2]rotaxane could be well constructed from **EtP[5]A** and **G7**, which was confirmed by ^{1}H NMR experiments. As shown in ^{1}H NMR spectra (Fig. 3), which were similar as **G1** case, three sets of proton signals were clearly observed, and the proton signals of H_b and H_c of **G7** shifted upfield from 3.21 ppm and 1.56 ppm to 1.07 ppm and − 2.22 ppm (Fig. 3), respectively, and one set of H_1 signal of **EtP[5]A** remarkably shifted from 6.72 ppm to 6.91 ppm, both of which strongly implied the formation of **G7⊂EtP[5]A**. It means that although *o*-nitrobenzyl group at one end of **G7** was too big to thread into the cavity of **EtP[5]A**, the other unsubstituted benzyl group at the other end of **G7** was still a proper size of end-functional group like **G1** to pass through the cavity of **EtP[5]A** forming a stable pseudo[2]rotaxane. And then the stoichiometry of **G7** and **EtP[5]A** was determined to be 1 : 1, and its association constant K_a was calculated to be (856 ± 5) M^{-1}, which is a little smaller than that of **G1⊂EtP[5]A** (Fig. S21, ESI†).

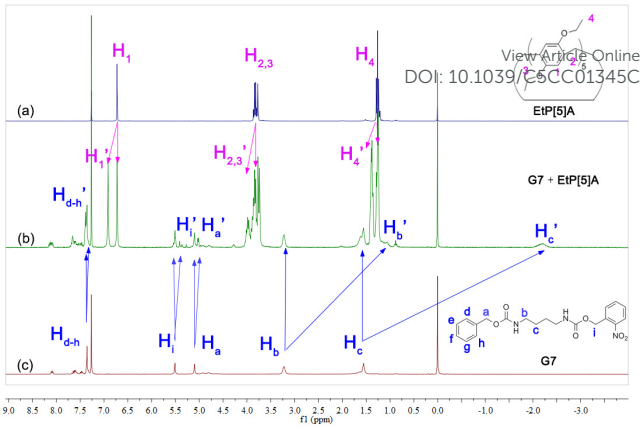


Fig. 3 ^{1}H NMR spectra (300 MHz, $CDCl_3$, 298 K) of (a) **EtP[5]A** only (2.5 mM); (b) the mixture of **G7**(2.5 mM) and **EtP[5]A** (2.5 mM); (c) **G7** only (2.5 mM)

Eventually, the UV-responsiveness of **G7⊂EtP[5]A** was tested in chloroform-*d*. When equvimolar **G7** (2.5 mM) and **EtP[5]A** (2.5 mM) was mixed in the chloroform-*d*, the solution was almost colourless (Fig. S23a, ESI†). After exposed in 365 nm ultraviolet light for 1.5 hours, the solution colour dramatically changed into yellow (Fig. S23b, ESI†) and plenty of precipitates from the chloroform-*d* were observed at the same time. These plenty of precipitates that were caused by their low solubility in chloroform were filtered out and identified by ^{1}H NMR and ESI-MS to be *N*-carbobenzoxy-1,4-diaminobutane, $\mathbf{G7_P}$, which is the photocleavage product of **G7** (Scheme 1), agreeing well with the reported literature.[16] The UV-responsiveness of **G7⊂EtP[5]A** was also monitored by ^{1}H NMR experiments in chloroform-*d*. Comparing with ^{1}H NMR spectra before and after the exposure of 365 nm ultraviolet light (Fig. S23, ESI†), it was found that the proton peaks of ^{1}H NMR spectrum became broad, but the typical proton signals H_c', H_a', and H_i' of pseudo[2]rotaxane and the typical proton signal H_i of uncomplexed **G7** all disappeared after UV light exposure. All of the solution colour change, precipitates, and ^{1}H NMR spectra results indicated the photocleavage of **G7⊂EtP[5]A** pseudo[2]rotaxane due to the photoresponsiveness of *o*-nitrobenzyloxycarbonyl group of **G7**.

Conclusions

In summary, we have studied the host-guest chemistry of a few novel neutral guests **G1-G7** with **EtP[5]A** by ^{1}H NMR and 2D NOESY NMR methods. The experimental results demonstrate that the size of end-functional groups and the oxygen atom connecting with benzyl group of the carbamate of guests both affected their host-guest interactions with **EtP[5]A**. Therefore, **G1** and **G7** that have the proper size of phenyl end-functional groups as well as two carbamate groups were good guests for binding **EtP[5]A** to form stable pseudo[2]rotaxanes, especially for **G7** to form a photoresponsive pseudo[2]rotaxane with **EtP[5]A**. The present study afforded the different examples of pillar[5]arene-based pseudo[2]rotaxanes constructed from neutral guests, especially with photoresponsiveness, and provided a novel and simple way to build various pseudo[2]rotaxanes.

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Notes and references

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† Electronic Supplementary Information (ESI) available: Experimental details, ^{1}H NMR, ^{13}C NMR, 2D NOESY analysis.

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1. (a) J. M. Lehn, *Angew. Chem., Int. Ed. Engl.*, 1988, **27**, 89; (b) C. J. Pedersen, *Angew. Chem., Int. Ed. Engl.*, 1988, **27**, 1021; (c) X. Yan, D. Xu, X. Chi, J. Chen, S. Dong, X. Ding, Y. Yu and F. Huang, *Adv. Mater.*, 2012, **24**, 362; (d) M. Zhang, D. Xu, X. Yan, J. Chen, S. Dong, B. Zheng and F. Huang, *Angew. Chem. Int. Ed.*, 2012, **51**, 7011.
2. (a) L. L. Zhu, M. Q. Lu, Q. W. Zhang, D. H. Qu and H. Tian, *Macromolecules*, 2011, **44**, 4092; (b) V. Balzani, A. Credi, F. M. Raymo and J. F. Stoddart, *Angew. Chem. Int. Ed.*, 2000, **39**, 3349; (c) Q. Wang, Y. Chen and Y. Liu, *Polym. Chem.*, 2013, **4**, 4192.
3. (a) D. B. Amabilino and J. F. Stoddart, *Chem. Rev.*, 1995, **95**, 2725; (b) F. M. Raymo and J. F. Stoddart, *Chem. Rev.*, 1999, **99**, 1643; (c) X. Ma and H. Tian, *Chem. Soc. Rev.*, 2010, **39**, 70; (d) R. S. Forgan, J. P. Sauvage and J. F. Stoddart, *Chem. Rev.*, 2011, **111**, 5434; (e) J. Rotzler and M. Mayor, *Chem. Soc. Rev.*, 2013, **42**, 44.
4. (a) D. M. Walba, *Tetrahedron*, 1985, **41**, 3161; (b) H. L. Frisch and E. Wasserman, *J. Am. Chem. Soc.*, 1961, **83**, 3789; (c) V. Balzani, M. Gomez-Lopez and J. F. Stoddart, *Acc. Chem. Res.*, 1998, **31**, 405; (d) E. R. Kay, D. A. Leigh and F. Zerbetto, *Angew. Chem. Int. Ed.*, 2007, **46**, 72.
5. T. Ogoshi, S. Kanai, S. Fujinami, T. A. Yamagishi and Y. Nakamoto, *J. Am. Chem. Soc.*, 2008, **130**, 5022.
6. D. R. Cao, Y. H. Kou, J. Q. Liang, Z. Z. Chen, L. Y. Wang and H. Meier, *Angew. Chem. Int. Ed.*, 2009, **48**, 9721.
7. (a) T. Ogoshi, M. Hashizume, T. A. Yamagishi and Y. Nakamoto, *Chem. Commun.*, 2010, **46**, 3708; (b) T. Ogoshi, H. Kayama, D. Yamafuji, T. Aoki and T. Yamagishi, *Chem. Sci.*, 2012, **3**, 3221; (c) C. J. Li, Q. Q. Xu, J. Li, F. N. Yao and X. S. Jia, *Org. Biomol. Chem.*, 2010, **8**, 1568; (d) G. C. Yu, Z. B. Zhang, J. M. He, Z. Abliz and F. H. Huang, *Eur. J. Org. Chem.*, 2012, 5902; (e) S. Sun, X. Y. Hu, D. Z. Chen, J. B. Shi, Y. P. Dong, C. Lin, Y. Pan and L. Y. Wang, *Polym. Chem.*, 2013, **4**, 2224; (f) C. J. Li, L. Zhao, J. A. Li, X. Ding, S. H. Chen, Q. L. Zhang, Y. H. Yu and X. S. Jia, *Chem. Commun.*, 2010, **46**, 9016; (g) M. E. Belowich, C. Valente, R. A. Smaldone, D. C. Friedman, J. Thiel, L. Cronin and J. F. Stoddart, *J. Am. Chem. Soc.*, 2012, **134**, 5243.
8. (a) C. J. Li, S. H. Chen, J. Li, K. Han, M. Xu, B. J. Hu, Y. H. Yu and X. S. Jia, *Chem. Commun.*, 2011, **47**, 11294; (b) Z. B. Zhang, B. Y. Xia, C. Y. Han, Y. H. Yu and F. H. Huang, *Org. Lett.*, 2010, **12**, 3285; (c) K. Han, Y. Y. Zhang, J. Li, Y. H. Yu, X. S. Jia and C. J. Li, *Eur. J. Org. Chem.*, 2013, 2057; (d) H. M. Deng, X. Y. Shu, X. S. Hu, J. Li, X. S. Jia and C. J. Li, *Tetrahedron Lett.*, 2012, **53**, 4609; (e) T. Ogoshi, K. Demachi, K. Kitajima and T. Yamagishi, *Chem. Commun.*, 2011, **47**, 10290; (f) L. Z. Liu, L. Y. Wang, C. C. Liu, Z. Y. Fu, H. Meier and D. R. Cao, *J. Org. Chem.*, 2012, **77**, 9413; (g) X. Y. Hu, X. Wu, S. I. Wang, D. Z. Chen, W. Xia, C. Lin, Y. Pan and L. Y. Wang, *Polym. Chem.*, 2013, **4**, 4292; (h) L. Y. Gao, C. Y. Han, B. Zheng, S. Y. Dong and F. H. Huang, *Chem. Commun.*, 2013, **49**, 472; (i) Y. J. Ma, M. Xue, Z. B. Zhang, X. D. Chi and F. H. Huang, *Tetrahedron*, 2013, **69**, 4532; (j) Z. Zhang, Y. Luo, J. Chen, S. Dong, Y. Yu, Z. Ma and F. Huang, *Angew. Chem. Int. Ed.*, 2011, **50**, 1397.
9. (a) Y. J. Ma, X. F. Ji, F. Xiang, X. D. Chi, C. Y. Han, J. M. He, Z. Abliz, W. X. Chen and F. H. Huang, *Chem. Commun.*, 2011, **47**, 12340; (b) P. F. Wei, X. Z. Yan, J. Y. Li, Y. J. Ma and F. H. Huang, *Chem. Commun.*, 2013, **49**, 1070; (c) Q. P. Duan, W. Xia, X. Y. Hu, M. F. Ni, J. L. Jiang, C. Lin, Y. Pan and L. Y. Wang, *Chem. Commun.*, 2012, **48**, 8532; (d) C. J. Li, J. W. Ma, L. Zhao, Y. Y. Zhang, Y. H. Yu, X. Y. Shu, J. Li and X. S. Jia, *Chem. Commun.*, 2013, **49**, 1924.
10. C. J. Li, *Chem. Commun.*, 2014, **50**, 12420.
11. Y. F. Guan, P. Y. Liu, C. Deng, M. F. Ni, S. H. Xiong, C. Lin, X. Y. Hu, J. Ma and L. Y. Wang, *Org. Biomol. Chem.*, 2014, **12**, 1079.
12. (a) J. Zhao, S. Lin, Y. Huang, J. Zhao and P. R. Chen, *J. Am. Chem. Soc.*, 2013, **135**, 7410; (b) W. Li, J. Wang, J. Ren and X. Qu, *J. Am. Chem. Soc.*, 2014, **136**, 2248.
13. J. Yang, G. Yu, D. Xia and F. Huang, *Chem. Commun.*, 2014, **50**, 3993.
14. X. Wang, G. Liu, J. Hu, G. Zhang and S. Liu, *Angew. Chem. Int. Ed.*, 2014, **53**, 3138.
15. (a) V. Fasano, M. Baroncini, M. Moffa, D. Iandolo, A. Camposeo, A. Credi and D. Pisignano, *J. Am. Chem. Soc.*, 2014, **136**, 14245; (b) K.-J. Chang, Y.-J. An, H. Uh and K.-S. Jeong, *J. Org. Chem.*, 2004, **69**, 6556; (c) G. Yu, C. Han, Z. Zhang, J. Chen, X. Yan, B. Zheng, S. Liu and F. Huang, *J. Am. Chem. Soc.*, 2012, **134**, 8711.
16. C. Daengngam, S. B. Thorpe, X. Guo, S. V. Stoianov, W. L. Santos, J. R. Morris and H. D. Robinson, *J. Phys. Chem. C*, 2013, **117**, 14165.