Synthesis and Characterization of a New Pillar[5]arene-based [1]Rotaxane

Huasheng Tian, Chunyu Wang, Po-Han Lin, Kamel Meguellati

PII: S0040-4039(18)30976-6
DOI: https://doi.org/10.1016/j.tetlet.2018.08.004
Reference: TETL 50179

To appear in: *Tetrahedron Letters*

Received Date: 13 June 2018
Revised Date: 29 July 2018
Accepted Date: 2 August 2018

Please cite this article as: Tian, H., Wang, C., Lin, P-H., Meguellati, K., Synthesis and Characterization of a New Pillar[5]arene-based [1]Rotaxane, *Tetrahedron Letters* (2018), doi: https://doi.org/10.1016/j.tetlet.2018.08.004

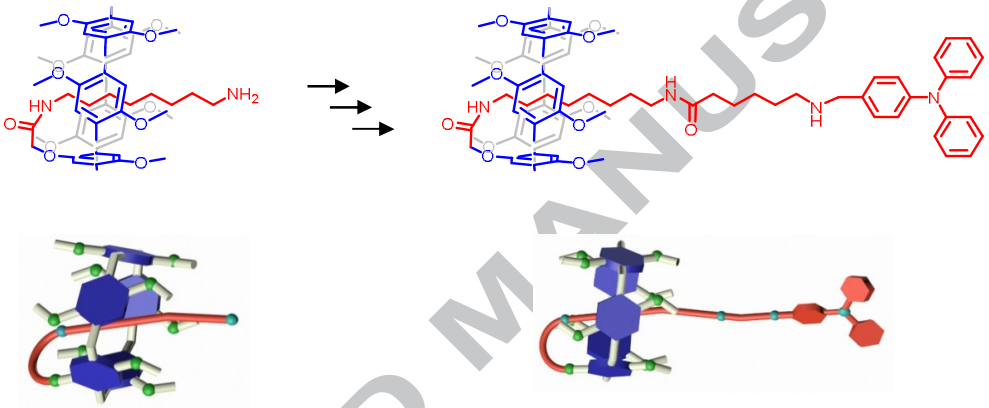
Graphical Abstract

Synthesis and Characterization of a New Pillar[5]arene-based [1]Rotaxane

Huasheng Tian,[a, 1] Chunyu Wang,[b, 1] Po-Han Lin,[a] Kamel Meguellati[a*]

[a]*International Joint Research Laboratory of Nano-Micro Architecture Chemistry (NMAC), College of Chemistry, Jilin University, 2699 Qianjin Street, Changchun 130012, P. R. China. E-mail: kamel_m@jlu.edu.cn*

[b]*State Key Laboratory of Supramolecular Structure and Materials, Jilin University, 2699 Qianjin Street, Changchun 130012, P. R. China.*



Pseudo[1]rotaxane **[1]Rotaxane**

Tetrahedron Letters
journal homepage: www.elsevier.com

Synthesis and Characterization of a New Pillar[5]arene-based [1]Rotaxane

Huasheng Tian, [a, 1] Chunyu Wang, [b, 1] Po-Han Lin, [a] Kamel Meguellati [a*]

[a] *International Joint Research Laboratory of Nano-Micro Architecture Chemistry (NMAC), College of Chemistry, Jilin University, 2699 Qianjin Street, Changchun 130012, P. R. China.*
[b] *State Key Laboratory of Supramolecular Structure and Materials, Jilin University, 2699 Qianjin Street, Changchun 130012, P. R. China.*

ARTICLE INFO

Article history:
Received
Received in revised form
Accepted
Available online

Keywords:
Pillar[5]arene
Pseudo[1]rotaxane
[1]rotaxane
Mechanically interlocked molecule

ABSTRACT

In this study, we reported the synthesis of three kinds of mono-functional pillar[5]arene derivatives **PRI**, **PRII** and **R** and their structures were studied by 1D and 2D NMR spectra and mass spectra. The 2D NMR spectra including ^{1}H-^{13}C HSQC, ^{1}H-^{1}H COSY and NOESY spectra indicated that **PRI** and **PRII** are both stable self-included pseudo[1]rotaxanes in $CDCl_3$. These original structures are promising compounds for the design of pillar[5]-based [1]rotaxane. And the results showed that **R** could exist stable in $CDCl_3$ and DMSO because of the coordination of N-H···O hydrogen bonding interaction and C-H···π interaction.

1. Introduction

Mechanically interlocked molecules (MIMs),[1,2] such as rotaxanes[3,4] catenanes[5] and knots,[6] have been an attractive field for chemists in the last two decades because of their typical topological structures and their applications in molecular machines,[7] organocatalysis,[8] self-assemblies,[9,10] controlled drug release[11] and molecular recognition,[12] *etc*. Among the mechanically interlocked molecules, rotaxanes, composed of a dumbbell-shaped axle and a threaded macrocycle, were very promising due to their special structures, diverse topological behavior (from [1]rotaxanes[13] to poly[*n*]rotaxanes[14]) and their broad applications in nanometer functional materials and molecular machines. The common synthetic strategies for rotaxanes include ''threading-followed-by-stoppering'', "slippage", "clipping", ''threading-followed-by-swelling'' and template-directed methods.[15] [1]Rotaxanes, whose axles were threaded by own wheels and connected by the covalent bond, are new members and occupy an important position in mechanically interlocked molecules. Tian *et al*. reported a symmetric [1]rotaxane combined with a cobalt(III) ion bridged by Schiff base units based on an azobenzene-modified β-cyclodextrin.[16] while Qu *et al*. reported a bistable ferrocene-based [1]rotaxane and studied its switching property in different electrochemical states.[17] However, the synthetic strategies with high yield and efficient applications have been poorly reported.

Pillar[n]arenes[18] are a new promising kind of macrocycle constituted by five 1,4-dialkoxybenzene units linked together by methylene bridges at the 2- and 5-positions. It was firstly reported by T. Ogoshi in 2008, and have played a promising role in material science,[19-24] nanotechnology[25-30] and biology.[31-34] Because of its symmetric pillar-shape structures, its easy modification of the terminal rims and the electron-rich cavities, pillar[5]arenes are becoming an emerging macrocyclic host for the construction of MIMs, such as daisy chains,[35] pseudo[n]rotaxanes,[36] [n]catenanes[37,38] and [n]rotaxane.[39] However, pillar[5]arenes-based [1]rotaxanes have been poorly reported. The common synthetic strategies were the construction of mono-functional pillar[5]arenes with a side chain that can be self-included due to cationic guest or hydrogen bond donor to form a dynamic threading and dethreading structure in different solvents with different polarity and ended by stoppers. T. Ogoshi *et al.* first reported that mono-guest-functionalized pillar[5]arene could form self-inclusion complex in $CDCl_3$ and the guest could dethread from the cavity in acetone.[40] Wang *et al*. reported an urea-modified pillar[5]arene that has a special self-inclusion behavior even in polar solvent.[41] All of these mono-functionalized pillar[5]arenes could form stable pseudo[1]rotaxanes in weak polar solvents, which provided the possibility to construct pillar[5]-based [1]rotaxane. Fortunately, Yang *et al*. reported a mono-functionalized pillar[5]arene bearing an imidazolium moiety that formed a stable pseudo[1]rotaxane, and [1]rotaxane which was synthesized through photo thiol-ene reaction.[42] Xue *et al*. reported a pillar[5]arene-based [1]rotaxane in high yield through the condensation reaction between a primary amine group and a carboxylic acid group, which created a new strategy to obtain a pillar[5]arene-based [1]rotaxane.[43]

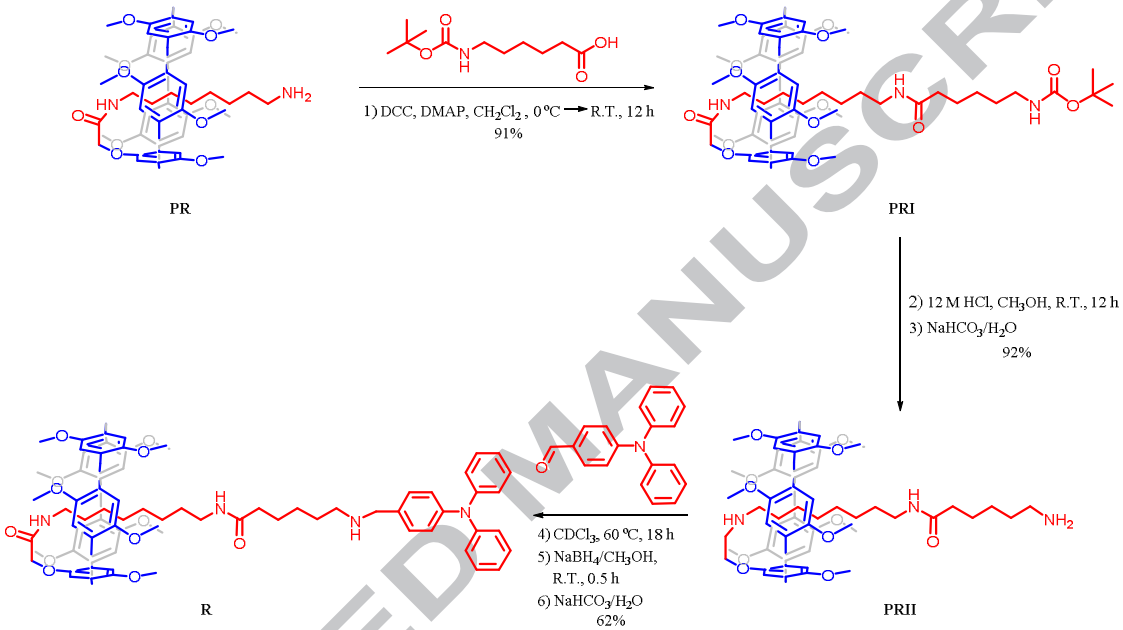
* Corresponding author. International Joint Research Laboratory of Nano-Micro Architecture Chemistry (NMAC), College of Chemistry, Jilin University, 2699 Qianjin Street, Changchun 130012, P. R. China.
E-mail: kamel_m@jlu.edu.cn

[1] Contributed equally to this work.

However, different efficient synthetic routes remain to be explored in the future.

Triphenylamine is a compound where a nitrogen is linked to three phenyl rings in a propeller-like structure. Because of its super conjugation, electronic propertie and easy modification, it has been widely used in photoelectric materials usually as hole transporting materials and nanomaterials[44] as a medium for cell-imaging, drug delivery and ion detection. We used it as a good stopper for the formation of a [1]rotaxane and as a good stimuli-responsive chromophore.

From the previous report[45], we know that mono-amide functionalized pillar[5]arene derivatives pseudo[1]rotaxane (**PR**) displayed an excellent self-inclusion structure in dilute or concentrate solution. So it was a potential candidate for the construction of (pseudo)[1]rotaxane. Herein, we report three kinds of pillar[5]arene-based mono-functionalized derivatives **PRI**, **PRII** and **R**. Studies including 1D NMR, 2D COSY NMR, 2D NOESY NMR and HRMS(ESI) spectra showed that **PRI** and **PRII** have an excellent self-inclusion ability even at high concentration in $CDCl_3$. [1]rotaxane **R** was synthesized by imine-reduction reaction in high yield and ^{1}H NMR, ^{13}C NMR, 2D-NMR spectras were studied in $CDCl_3$ and DMSO-d_6 as well HRMS(ESI), indicating that [1]rotaxane **R** is a very stable structure which maybe come from the N-H···O hydrogen bonds and C-H···π interaction between the pillar[5]arene and the axle.



Scheme 1 The synthetic procedures of related compounds.

2. Results and discussions

Our group has adopted a amide formation to get the self-inclusion pseudo[1]rotaxane **PR** in high yield.[45] We investigated the stability of (pseudo)[1]rotaxane by tuning the length of the axle. Firstly, **PRI** was synthesized efficiently from condensation reaction between the mono-amide-functionalized pillar[5]arene **PR** and 6-((tert-butoxycarbonyl)amino)hexanoic acid at room temperature, then an acidic deprotection of **PRI** was carried out to prepare **PRII**. Finally, the [1]rotaxane **R** was synthesized in $CDCl_3$ in high yield through Borch reduction reaction from **PRII** and 4-(diphenylamino)benzaldehyde (**Scheme 1**). ^{1}H NMR, ^{13}C NMR, 2D NMR and HRMS(ESI) were conducted to characterize the corresponding derivatives.

The ^{1}H NMR spectrum of **PRI** clearly indicated that some characteristic signals of the self-inclusion appeared below 0 ppm (**Fig. S16**), which showed that some protons in the axle were shielded by the cavity of pillar[5]arene. The ^{1}H-^{13}C HSQC spectrum (**Fig. S18**) and partial 2D ^{1}H-^{1}H COSY spectrum (**Fig. S19** and **Fig. S20**) of **PRI** indicated that the methylene peaks of $H_{2\text{-}5}$ upfield significantly, which displayed that $H_{2\text{-}5}$ may exist in the cavity of pillar[5]arene. From the 2D NOESY spectrum, we found a correlation between the protons $H_{2\text{-}6}$ of the axle and the aromatic protons of the pillar[5]arene of **PRI** proving the presence of a self-included structure (**Fig. S21**). Moreover, the chemical shift values of ^{1}H NMR spectra of **PRI** at various concentrations are almost in the same lines, which demonstrated that the self-inclusion structure of **PRI** is concentration-independent in $CDCl_3$ (**Fig. S35**).

Some characteristic protons found below 0 ppm were also observed in the ^{1}H NMR spectrum of **PRII** (**Fig. S23**), HSQC spectrum and partial 2D COSY spectrum (**Fig. 1** and **Fig. S26**) showed that significant upfield shifts of protons $H_{2\text{-}5}$ which suggested that those protons are significantly shielded by pillar[5]arene and existed in the cavity of pillar[5]arene. Moreover, some cross-peaks between protons H_2, H_3, H_4 and H_5 of the axle and the aromatic protons of pillar[5]arene were found in the 2D NOESY spectrum of **PRII** (**Fig. S27**), which indicated that the axle was threaded in the cavity of pillar[5]arene and **PRII** possesses a self-included structure. Because the terminal group ($-NH_2$) can be protonated in the process, the concentration-related ^{1}H NMR experiments was carried out to explore whether the interlocked structure could collapse (**Fig. S36**). These results showed that there was no obvious modification at different concentrations, which indicated that **PRII** is a self-inclusion structure. The above results clearly confirmed the formation of a stable pseudo[1]rotaxane. By comparison of the ^{1}H NMR spectra of **PRI** with **PRII**, there were

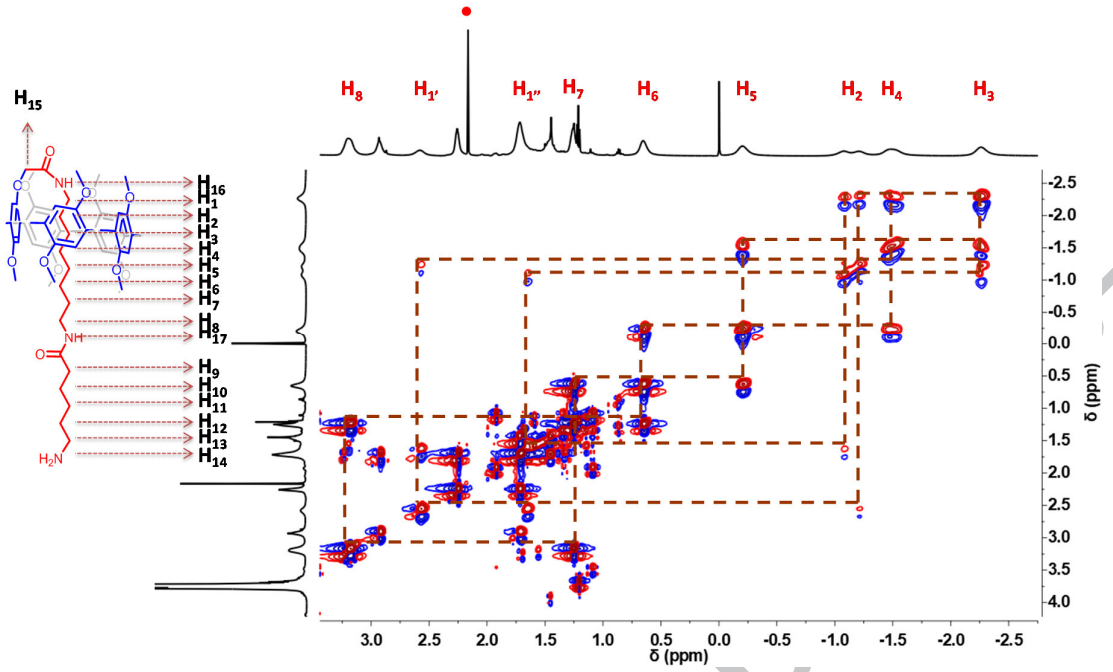


Fig. 1 Partial 2D NOESY NMR spectrum (600 MHz, 298K) of **PRII** in $CDCl_3$. • unassigned signal.

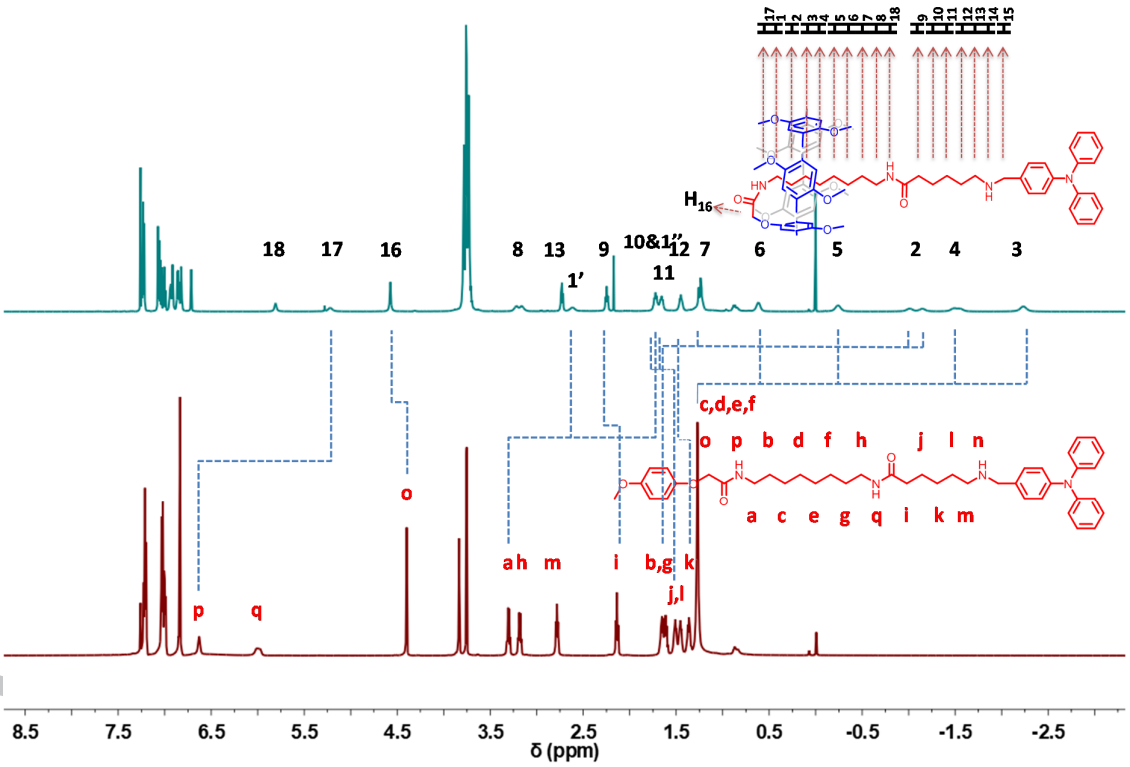


Fig. 2 Comparison of ^{1}H NMR (600 MHz, 298K) spectra of **R** and **6** in $CDCl_3$.

no obvious changes in the chemical shifts of $H_{2\text{-}5}$ of the axle, which showed that the buried part of axle in the cavity of pillar[5]arene can exist in high concentration. The results of which probably due to the strong N-H···O hydrogen bonds and C-H···π interaction between the pillar[5]arene and the axle.

[1]Rotaxane **R** was prepared from **PRII** and 4-(diphenylamino) benzaldehyde by an imine-reduction reaction in high yield. ^{1}H NMR spectrum, HSQC spectrum and 2D COSY spectrum showed H_2, H_3, H_4 and H_5 were significantly shielded by pillar[5]arene (**Fig. 2**, **Fig. S31**, **Fig. S32** and **Fig. S33**). The cross-peaks between $H_{2\text{-}6}$ and the aromatic protons (or proton of –CONH group) were also observed in the 2D NOESY spectrum (**Fig. 3**) indicating a self-included structure.

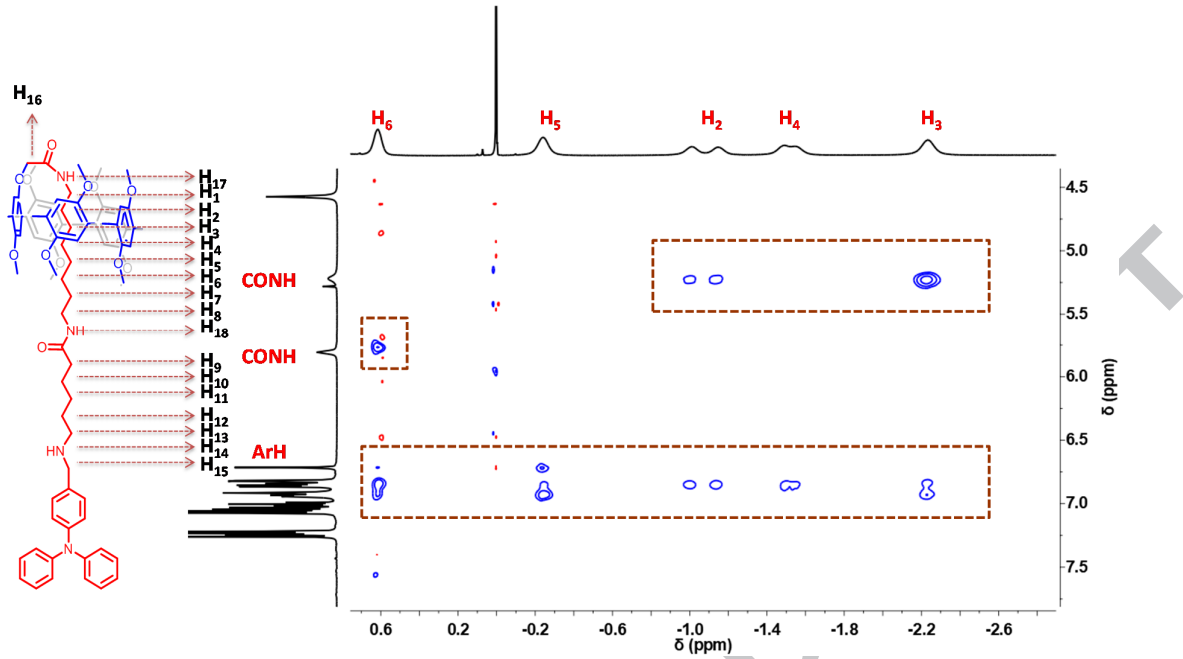


Fig. 3 Partial 2D NOESY NMR spectrum (600 MHz, 298K) of compound **R** in $CDCl_3$.

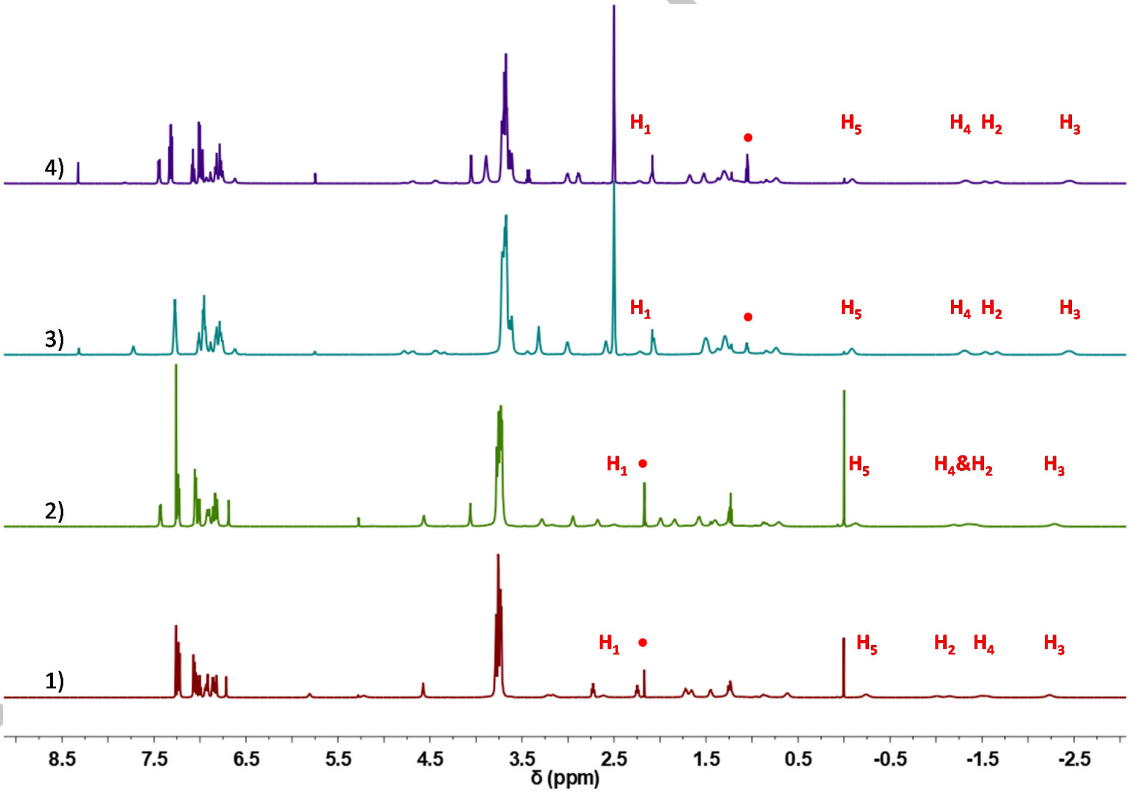


Fig. 4 ^{1}H NMR (600 MHz) spectra of **R** in different conditions: 1) $CDCl_3$, 2) $CDCl_3$ + DCl, 3) DMSO, 4) DMSO + DCl.

As reported, pillar[5]arene usually plays a pivotal role in macrocyclic host because of the electron-rich cavity, and the secondary amine which is a good electron donor can be easily protonated by an acid and making it an electron poor species. According to the studies of host-guest interaction of pillar[n]arene, we know that $CDCl_3$ is an excellent solvent to increase the host and guest interaction and DMSO is a better solvent to decrease the host and guest interaction, so we chose $CDCl_3$ and DMSO as the solvents of studies to explore whether the host-guest interaction could be tuned by changing the polarities of solvents and by adding an acid to enhance the host – guest interaction.

The positions of protons $H_{2\text{-}5}$ appeared below 0 ppm in the two solvents of studies and the results indicated that these protons still locate in the cavity of pillar[5]arene in $CDCl_3$ or DMSO; On the other hand, we also performed ^{1}H NMR titration of **R** in $CDCl_3$ (or DMSO) by adding excess of deuterated hydrochloric acid to check that if the [1]rotaxane is pH dependent. From the comparison of $CDCl_3$ and $CDCl_3$ + DCl and the comparison of DMSO and DMSO + DCl (**Fig. 4**), we concluded that these conditions are not enough to make the macrocycle stayed in the same position independently of the protonation of the ammonium $R^{'}NHR^{+}$ from the axle. All of the above results showed that the self-included compound **R** is very stable in this system and no obvious response to pH and different polarities of solvents were observed, which may be due to the strong N-H···O and C-H···π interaction between the axle and pillar[5]arene, which kept **R** in the minimum level of energy.

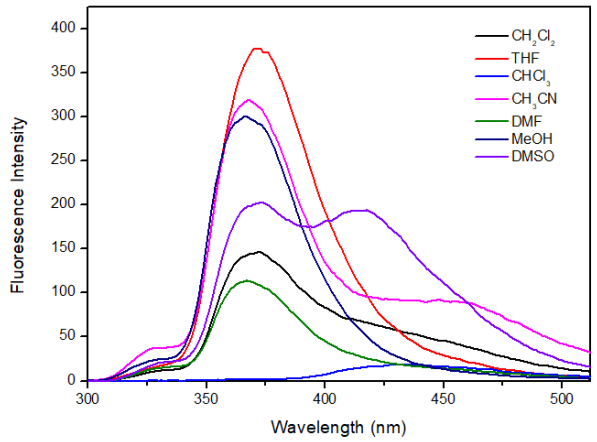


Fig. 5 Fluorescent spectra of a) **R** ([**R**] = 1×10^{-4} M).

Because of the excellent optical property of the triphenylamine chromophore, the fluorescent property of **R** in different polar solvents was studied (**Fig. 5**). According to the fluorescence spectra of compound **R**, the fluorescence intensity decreased with the increase of the polarity of the solvent, which comes from the aggregation-induced emission (AIE) property of triphenylamine occurring in these solvents. And the fluorescence-quenching appeared only in $CHCl_3$ maybe due to the solvation of triphenylamine by $CHCl_3$. It also indicated that the pillar[5]arene stayed far from the chromophore.

3. Conclusion

In conclusion, three different kinds of pillar[5]arene derivatives **PRI**, **PRII** and **R** were successfully synthesized. The ^{1}H NMR spectra, 2D HSQC, 2D COSY, 2D NOESY and ESI-MS certified that the presence of self-inclusion for **PRI**, **PRII** and **R**. **R** is almost not sensible to the polarity of the solvent and the pH. The above results confirmed that they existed in excellent stable forms, which may be due to the strong N-H··· O bond and C-H···π interactions between the amide group and pillar[5]arene. These kinds of stable pseudo[1]rotaxane and [1]rotaxane have great potential for the development novel functional molecular machines in the near future.

4. Experimental section

*4.1. 6-((tert-butoxycarbonyl)amino)hexanoic acid (**1**)*

To a solution of 6-aminohexanoic acid (1.31 g, 10.0 mmol) and triethylamine (2.8 mL, 20.0 mmol) in acetone-water (1:1, 20 mL), di-tert-butyl dicarbonate ($(Boc)_2O$, 2.5 mL, 11.0 mmol) was added and the reaction mixture was stirred for 4 hours at room temperature. After completion of the reaction, the solution was concentrated under vacuum and the residual aqueous suspension was acidified with 1 M HCl to pH 4–5. The solution was extracted with CH_2Cl_2, and the combined organic phases were washed with brine, dried with anhydrous Na_2SO_4, and the solvent was removed by rotary evaporation to give the compound **1** (2.25 g, 97%) as a white solid under 4 °C and as a colorless oil at room temperature. ^{1}H NMR (300 MHz, $CDCl_3$) δ 4.57 (s, CON*H*, 1H), 3.10 (d, NHCH_2, J=3.11, 2H), 2.34 (t, COCH_2, J=2.34, 2H), 1.64 (m, NHCH$_2$CH_2, J=1.64, 2H), 1.43 (m, CH_2&CH_3, 13H). ^{13}C NMR (75 MHz, $CDCl_3$) δ 179.28, 156.42, 79.48, 40.65, 34.26, 29.97, 28.69,26.50, 24.65.

*4.2. 4- (diphenylamino) benzaldehyde (**2**)*

3.00 mL of DMF was cooled to 0 °C in ice bath then 2.95 mL of $POCl_3$ was added dropwise. After stirring for 40 minutes at 0 °C, the solution was warmed up to room temperature then 250 mg of triphenylamine was added and the reaction mixture was heated at 45 °C for 14 hours. After cooling down to room temperature, the reaction mixture was poured into 15.0 mL of ice and neutralized with a solution of 1.0 M NaOH. Products were extracted with CH_2Cl_2. Combined organic layers were washed with brine, dried with Na_2SO_4 and concentrated to give a crude mixture, which was purified by silica gel column chromatography (EtOAc:hexane = 1:30) to give the compound **2** (244.10 mg, 89%) as a yellowish solid. ^{1}H NMR (300 MHz, DMSO-d_6) δ: 9.77 (s, C*H*O, 1H), 7.72 (d, J = 8.8 Hz, 2H), 7.42 (t, J = 7.9 Hz, 4H), 7.30 – 7.14 (m, 6H), 6.88 (d, J = 8.8 Hz, 2H); ^{13}C NMR (75 MHz, DMSO-d_6) δ 190.54, 145.53, 131.27, 130.01, 128.56, 126.38, 125.45, 118.14, 89

*4.3. Compound **PRI***

To a solution of compound **PR** (230.00 mg, 0.25 mmol) and 6-((tert-butoxycarbonyl)amino)hexanoic acid (57.79 mg, 0.25 mmol) dissolved in anhydrous CH_2Cl_2 (2.5 mL), was added dropwise at 0 °C a solution of DCC (77.37 mg, 0.38 mmol) and DMAP (3.05 mg, 0.025 mmol) which were dissolved in anhydrous CH_2Cl_2 (2.5 mL) then the reaction mixture was stirred for 12 hours at room temperature. After completion of the reaction, the white precipitate was filtered off and the organic layer was concentrated by rotary evaporator. The pure compound **PRI** (260.6 mg, 91%) was obtained by silica gel column chromatography (CH_2Cl_2:CH_3OH = 1:60) as a white powder. m.p. 129.6 °C; ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.03 – 6.69 (m, Ar*H*, 10H), 5.79 (s, CON*H*, 1H), 5.23 (s, CON*H*, 1H), 4.57 (br,t-BuOCON*H*&ArOCH_2, 3H), 3.96 – 3.56 (m, ArCH_2Ar&ArOCH_3, 37H), 3.18 (d, NHCH_2, J = 26.3 Hz, 4H), 2.63 (s, CONHCH_2, 1H), 2.21 (s, COCH_2, 2H), 1.70 (br, CONHCH_2&CH_2, 2H), 1.45 (s, CH_2&OC(CH_3)$_3$, 13H), 1.25 (s, CH_2, 4H), 0.63 (s, CH_2, 2H), -0.23 (s, CH_2, 2H), -1.07 (d, J = 70.3 Hz, CH_2, 2H), -1.47 (s, CH_2, 2H), -2.22 (s, CH_2, 2H). ^{13}C NMR (150 MHz, $CDCl_3$) δ 172.87, 167.72, 156.32, 152.16, 150.96, 150.70, 150.56, 150.40, 147.64, 129.55, 129.39, 128.94, 128.71, 128.63, 128.48, 128.17, 127.74, 114.68, 114.48, 114.06, 113.09, 112.73, 66.38, 56.70, 5.43, 56.05, 55.99, 55.82, 55.75, 55.47, 40.70, 40.18, 38.31, 37.00, 30.52, 30.42, 29.57, 29.22, 28.98, 28.75, 28.37, 27.74, 27.12, 25.72, 24.06; MS (m/z): HRMS (ESI) calculated for $[M\text{-BocOOC+2H}]^{2+}$ $C_{60}H_{81}N_3O_{12}^{2+}$, 517.7905; found 517.7947.

*4.4. Compound **PRII***

To a solution of compound **PRI** (340.10 mg, 0.3 mmol) in MeOH (10.9 mL), 12 M HCl (1.4 mL) was added dropwise at room temperature. After stirring for 12 hours at room

temperature, the pH of the mixture was adjusted to 8~9 with an aqueous solution of saturated $NaHCO_3$, then the solution was extracted with CH_2Cl_2 (3×10 mL) and the organic layers were combined and evaporated by rotary evaporation to get pure **PRII** (310.1 mg, 92%). m.p., 123.1 °C; ^{1}H NMR (600 MHz, $CDCl_3$) δ 6.98 – 6.67 (m, Ar*H*, 10H), 6.00 (s, CON*H*, 1H), 5.18 (s, CON*H*, 1H), 4.56 (s, ArOCH_2, 1H), 3.75 (td, ArCH_2Ar&ArOCH_3, J = 13.2, 8.8 Hz, 37H), 3.19 (d, NHCH_2, J = 11.6 Hz, 2H), 2.93 (s, NH_2CH_2, 2H), 2.58 (s, CONHCH_2, 1H), 2.26 (s, COCH_2, 2H), 1.72 (s, CONHCH_2&CH_2, 5H), 1.45 (s, CH_2, 2H), 1.25 (s, CH_2, 2H), 0.66(s, CH_2, 2H), -0.19 (s, CH_2, 2H), -1.14 (d, CH_2, J = 80.1 Hz, 2H), -1.48 (d, CH_2, J = 24.1 Hz, 2H), -2.24 (s, CH_2, 2H); ^{13}C NMR (150 MHz, $CDCl_3$) δ 173.02, 167.66, 151.14, 150.97, 150.73, 150.65, 150.53, 1550.39, 147.63, 129.56, 129.39, 128.94, 128.70, 128.59, 128.46, 128.16, 127.68, 127.40, 1114.68, 114.51, 114.04, 113.13, 112.74, 66.32, 56.73, 56.44, 56.10, 55.99, 55.80, 55.45, 40.84, 40.27, 38.30, 36.69, 30.47, 29.59, 29.23, 28.99, 28.73, 28.48, 27.83, 26.54, 25.51, 24.01; MS (m/z): HRMS (ESI) calculated for $[M+2H]^{2+}$ $C_{60}H_{81}N_3O_{12}^{2+}$, 517.7905; found 517.7950.

*4.5. Compound **R***

A solution of compound **PRII** (51.68 mg, 0.05 mmol) and compound **2** (13.66 mg, 0.05 mmol) in $CDCl_3$ (0.5 mL) was stirred for 18 hours at 60 □ then the reddish brown solution was cooled to room temperature. Then $NaBH_4$ (1.90 mg, 0.05 mmol) in 0.5 mL CH_3OH was added dropwise to the previous solution. After stirring for 0.5 hour at room temperature, 20 μL of deionized water was added to quench the reaction. After completion of the reaction, the solvent was removed by rotary evaporator and the pure product **R** (39.90 mg, 62%) was obtained by silica gel column chromatography (CH_2Cl_2:MeOH = 30:1). m.p. 96.9 °C; ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.25 – 6.69 (m, Ar*H*, 24H), 5.81 (s, N*H*COCH$_2$O Ar, 1H), 5.22 (s, -CON*H*, 1H), 4.57 (s, OCH_2, 2H), 3.81 – 3.68 (m, -OCH_3, 37H), 3.19 (d, J = 34.8 Hz, CONHCH_2, 2H), 2.73 (t, J = 7.3 Hz, CONHCH_2, 2H), 2.62 (s, CONHCH_2,1H), 2.25 (t, J = 7.5 Hz, COCH$_2$, 2H), 1.76 – 1.70 (m, CONHCH_2&CH_2, 3H), 1.69 – 1.63 (m, CH_2, 2H), 1.49 – 1.42 (m, CH_2, 2H), 1.24 (dd, J = 13.0, 6.0 Hz, CH_2, 4H), 0.62 (s, CH_2, 2H), -0.24 (s, CH_2, 2H), -1.08 (d, J = 79.3 Hz, CH_2, 2H), -1.52 (d, J = 32.4 Hz, CH_2, 2H), -2.24 (s, CH_2, 2H). ^{13}C NMR (150 MHz, $CDCl_3$) δ 172.95, 167.70, 154.83, 151.17, 151.00, 150.74, 150.67, 150.55, 150.40, 148.13, 147.60, 147.19, 130.08, 129.52, 128.98, 128.72, 128.61, 128.49, 128.17, 127.74, 127.40, 124.98, 124.42, 123.92, 122.99, 114.77, 114.54, 114.11, 113.14, 112.86, 112.70, 77.36, 66.33, 56.77, 56.50, 56.08, 56.02, 55.83, 55.76, 55.64, 55.44, 53.81, 49.50, 40.22, 38.30, 37.07, 30.55, 30.46, 29.93, 29.59, 29.25, 28.99, 28.76, 28.39, 27.81, 27.44, 27.10, 25.99, 23.98; MS (m/z): HRMS (ESI) calculated for $[M+2H]^{2+}$ $C_{79}H_{96}N_4O_{12}^{2+}$, 646.3507; found 646.3548; calculated for $[M+5H]^{5+}$ $C_{79}H_{99}N_4O_{12}^{5+}$,259.1446, found 258.1294.

*3.6.N-(8-aminooctyl)-2-(4-methoxyphenoxy)acetamide (**3**)*

To a solution of ethyl 2-(4-methoxyphenoxy)acetate (840.00 mg, 4.00 mmol) dissolved in ethanol (10.0 mL), 1,8-diaminooctane (1.73 g, 12.00 mmol) was added. After the mixture was heated at reflux for 12 hours, the solvent was removed by rotary evaporator. The crude product was purified by column chromatography (SiO_2, DCM:CH_3OH = 10:1) to give a white power (899.50 mg, 73 %). ^{1}H NMR (300 MHz, $CDCl_3$) δ 6.85 (s, Ar*H*, 4H), 6.64 – 6.51 (s, CON*H*, 1H), 4.43 (s, CONHCH_2, 2H), 3.77 (s, OCH_3, 3H), 3.32 (dd, CONHCH_2, J = 13.6, 6.8 Hz, 2H), 2.67 (t, NH_2CH_2, J = 6.9 Hz, 2H), 1.61 – 1.49 (m, CONHCH$_2$CH_2, 2H), 1.44 (d, NH_2CH$_2$CH_2, J = 6.5 Hz, 2H), 1.38 (s, NH_2, 2H), 1.29 (s, CH_2, 8H). ^{13}C NMR (75 MHz, $CDCl_3$) δ 168.62, 155.01, 151.68, 115.96, 115.14, 68.50, 55.99, 39.30, 33.43, 29.84, 29.62, 29.50, 27.08.

*3.7.tert-butyl (6-((8-(2-(4methoxyphenoxy)acetamido)octyl) amino) -6-oxohexyl) carbamate (**4**)*

To a solution of compound **3** (308.30 mg, 1.00 mmol) and 6-((tert-butoxycarbonyl)amino)hexanoic acid (231.20 mg, 1.00 mmol) in anhydrous CH_2Cl_2 (5 mL), DCC (309.50 mg, 1.50 mmol) and DMAP (12.20 mg, 0.10 mmol) dissolved in anhydrous CH_2Cl_2 (5 mL) were added dropwise at room temperature and the mixture was stirred for 16 hours at room temperature. After completion of the reaction, the white precipitate was filtered off and the solvent was removed by rotary evaporation. The crude product was purified by column chromatography (SiO_2, DCM:MeOH = 30:1) to get the compound **4** (285.00 mg, 55%) as a white power. m.p. 90.0 □; ^{1}H NNR (300 MHz, $CDCl_3$) δ 6.83 (s, Ar*H*, 4H), 6.61 (s, OCH$_2$CON*H*, 1H), 5.64 (s, CON*H*, 1H), 4.62 (s, $(CH_3)_3$COCON*H* 1H), 4.41 (s, ArOCH_2, 2H), 3.75 (s, ArOCH_3, 3H), 3.30 (dd, J = 13.3, 6.6 Hz, CONHCH_2, 2H), 3.20 (dd, J = 13.0, 6.5 Hz, CONHCH_2, 2H), 3.08 (dd, J = 11.8, 5.6 Hz, CONHCH_2, 2H), 2.14 (t, J = 7.4 Hz, COCH_2, 2H), 1.62 (dt, J = 15.4, 7.8 Hz,CONHCH$_2$CH_2, 2H), 1.50 – 1.38 (m, t-but-*H*&CH_2, 13H), 1.35 – 1.21 (m, CH_2, 12H). ^{13}C NMR (75 MHz, $CDCl_3$) δ 173.03, 172.95, 168.64, 155.05, 151.72, 116.00, 115.18, 77.78, 77.36, 76.93, 68.55, 56.00, 39.73, 39.26, 36.90, 30.10, 29.90, 29.78, 29.37, 27.08, 27.00, 26.71, 25.65. MS (m/z): HRMS (ESI) calculated for $[M+H]^+$ $C_{28}H_{48}N_3O_6^+$, 522.3538; found 522.3561; m/z calculated for $[M-CO_2-C_4H_8]^+$ $C_{23}H_{40}N_3O_4^+$, 422.3013; found 422.3046.

*3.8.6-amino-N-(8-(2-(4-methoxyphenoxy)acetamido)octyl) hexanamide (**5**)*

To a solution of compound **4** (52.14 mg, 0.10 mmol) in anhydrous CH_2Cl_2 (0.4 mL), TFA (0.1 mL) was added dropwise. The reaction mixture was stirred at room temperature for 0.5 hour and the solvent was removed by rotary evaporator. The crude product was recrystallized by diethyl ether to get the pure compound **5** (28 mg, 66%) as a white power. m.p. 87.1□; ^{1}H NMR (300 MHz, DMSO-d_6) δ 8.01 (t, J = 6.0 Hz, OCH$_2$CON*H*, 1H), 7.74 (t, J = 5.6 Hz, CON*H*, 1H), 7.64 (s, NH_2, 2H), 6.88 (d, J = 4.0 Hz, Ar*H*, 4H), 4.37 (s, ArOCH_2, 2H), 3.69 (s, OCH_3, 3H), 3.10 (dd, J = 13.4, 6.7 Hz, CONHCH_2, 2H), 3.00 (dd, J = 13.0, 6.6 Hz, CONHCH_2, 2H), 2.75 (dt, J = 12.0, 6.1 Hz, CONHCH_2, 2H), 2.04 (t, J = 7.3 Hz, NHCH_2, 2H), 1.57 – 1.44 (m, COCH_2, 2H), 1.43 – 1.31 (m, CH_2, 4H), 1.29 – 1.15 (m, CH_2, 10H). ^{13}C NMR (75 MHz, DMSO-d_6) δ 172.58, 168.58, 116.63, 115.47, 68.67, 56.29, 40.45, 36.06, 30.10, 30.02, 29.64, 27.76, 27.34, 27.23, 26.44, 25.73. MS (m/z): HRMS (ESI) calculated for $[M+H]^+$ $C_{23}H_{40}N_3O_4^+$, 422.3013; found 422.3043.

*3.9.6-((4-(diphenylamino)benzyl)amino)-N-(8-(2-(4-methoxyphen oxy)acetamido) octyl)hexanamide (**6**)*

To a solution of compound **5** (50.00 mg, 0.12 mmol) in anhydrous $CDCl_3$ (1.2 mL), 4-(diphenylamino)benzaldehyde (32.77 mg, 0.12 mmol) was added. The reaction mixture was stirred at 60 □ for 10 hours and the solvent was removed by rotary evaporation. The mixture was dissolved in $CHCl_3$ (0.5 mL) and CH_3OH (0.5mL), then $NaBH_4$ (4.54 mg, 0.12 mmol) were added and the reaction was stirred at room temperature for 10 min. After that, $NaHCO_3$ aqueous solution (20.0 μL) was added to quench the reaction and the solvent was removed by rotary evaporation. The crude product was purified by column chromatography (SiO_2, DCM:MeOH = 10:1) to get the product **6** (18.60 mg, 23%) as a yellowish power. m.p. 107.6 □; R_f (DCM:MeOH = 10:1) 0.50; ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.21

(t, J = 8.0 Hz, Ar*H*, 6H), 7.07 – 6.98 (m, Ar*H*, 8H), 6.84 (s, Ar*H*, 4H), 6.63 (s, CON*H*, 1H), 5.99 (d, J = 19.8 Hz, CON*H*, 1H), 4.40 (s, ArOCH_2, 2H), 3.83 (s, ArCH_2, 2H), 3.75 (d, J = 1.8 Hz, ArOCH_3, 3H), 3.30 (dd, J = 13.3, 6.6 Hz, CONHCH_2, 2H), 3.18 (dd, J = 12.7, 6.1 Hz, CONHCH_2, 2H), 2.78 (t, J = 7.4 Hz, NHCH_2, 2H), 2.14 (t, J = 7.4 Hz, COCH_2, 2H), 1.69 – 1.58 (m, CH_2, 2H), 1.55 – 1.49 (m, CH_2, 2H), 1.48 – 1.43 (m, CH_2, 2H), 1.36 (dt, J = 14.8, 7.6 Hz, CH_2, 2H), 1.27 (s, CH_2,8H). ^{13}C NMR (150 MHz, $CDCl_3$) δ 173.13, 168.71, 155.02, 151.66, 148.29, 147.67, 130.46, 129.60, 124.89, 123.51, 123.35, 115.98, 115.15, 77.36, 68.45, 55.98, 52.23, 47.79, 39.75, 39.26, 36.36, 29.78, 29.35, 27.41, 27.06, 26.98, 26.50, 25.32. MS (m/z): HRMS (ESI) calculated for $[M+H]^+$ $C_{42}H_{55}N_4O_4^+$, 679.4218; found 679.4254; m/z calculated for $[NPh_3CH_2]^+$ $C_{19}H_{16}N^+$, 258.1277; found 258.1298; calculated for $[M\text{-}NPh_3CH_2]^+$ $C_{23}H_{40}N_3O_4^+$, 422.3013; found 422.3029.

Acknowledgments

We thank NMAC and the college of chemistry at Jilin University for financial support on this work. We thank Prof Frederic Coutrot for his intellectual input and comments. The authors declare no conflict of interest.

References and notes

1. Stoddart, J. F. *Angew Chem Int Ed Engl.* **2017,** *56*, 11094-11125.
2. Chang, J.-C.; Tseng, S.-H.; Lai, C.-C.; Liu, Y.-H.; Peng, S.-M.; Chiu, S.-H. *Nature Chemistry.* **2016,** *9*, 128-134.
3. Leigh, D. A.; Marcos, V.; Nalbantoglu, T.; Vitorica-Yrezabal, I. J.; Yasar, F. T.; Zhu, X. *J Am Chem Soc.* **2017,** *139*, 7104-7109.
4. Altmann, P. J.; Pothig, A. *Angew Chem Int Ed Engl.* **2017,** *56*, 15733-15736.
5. Wu, Q.; Rauscher, P. M.; Lang, X.; Wojtecki, R. J.; de Pablo, J. J.; Hore, M. J. A.; Rowan, S. J. *Science.* **2017,** *358*, 1434-1439.
6. Ayme, J. F.; Beves, J. E.; Campbell, C. J.; Leigh, D. A. *Angew Chem Int Ed Engl.* **2014,** *53*, 7823-7.
7. Pezzato, C.; Cheng, C.; Stoddart, J. F.; Astumian, R. D. *Chem Soc Rev.* **2017,** *46*, 5491-5507.
8. Mitra, R.; Zhu, H.; Grimme, S.; Niemeyer, J. *Angew Chem Int Ed Engl.* **2017,** *56*, 11456-11459.
9. Aeschi, Y.; Drayss-Orth, S.; Valášek, M.; Raps, F.; Häussinger, D.; Mayor, M. *Eur J Org Chem.* **2017,** *2017*, 4091-4103.
10. Da Silva Rodrigues, R.; Mullen, K. M. *ChemPlusChem.* **2017,** *82*, 814-825.
11. Xu, T.; Li, J.; Cao, J.; Gao, W.; Li, L.; He, B. *Carbohydr Polym.* **2017,** *174*, 789-797.
12. Zheng, B.; Wang, F.; Dong, S.; Huang, F. *Chem Soc Rev.* **2012,** *41*, 1621-36.
13. Hosomi, T.; Harada, R.; Masai, H.; Fujihara, T.; Tsuji, Y.; Terao, J. *Chem Commun.* **2018,** *54*, 2487-2490.
14. Shukla, T.; Arumugaperumal, R.; Raghunath, P.; Lin, M.-C.; Lin, C.-M.; Lin, H.-C. *Sens Actuat B Chem.* **2017,** *243*, 84-95.
15. Chiu, C.-W.; Lai, C.-C.; Chiu, S.-H. *J Am Chem Soc.* **2007,** *129*, 3500-3501.
16. Gao, C.; Ma, X.; Zhang, Q.; Wang, Q.; Qu, D.; Tian, H. *Org Biomol Chem.* **2011,** *9*, 1126-32.
17. Li, H.; Zhang, H.; Zhang, Q.; Zhang, Q.-W.; Qu, D.-H. *Org Lett.* **2012,** *14*, 5900-5903.
18. Ogoshi, T.; Yamagishi, T. A.; Nakamoto, Y. *Chem Rev.* **2016,** *116*, 7937-8002.
19. Yao, Y.; Xue, M.; Zhang, Z.; Zhang, M.; Wang, Y.; Huang, F. *Chem Sci.* **2013,** *4*, 3667.
20. Sun, S.; Hu, X.-Y.; Chen, D.; Shi, J.; Dong, Y.; Lin, C.; Pan, Y.; Wang, L. *Polymer Chemistry.* **2013,** *4*, 2224.
21. Xia, W.; Ni, M.; Yao, C.; Wang, X.; Chen, D.; Lin, C.; Hu, X.-Y.; Wang, L. *Macromolecules.* **2015,** *48*, 4403-4409.
22. Zhang, H.; Nguyen, K. T.; Ma, X.; Yan, H.; Guo, J.; Zhu, L.; Zhao, Y. *Org Biomol Chem.* **2013,** *11*, 2070-4.
23. Zhang, H.; Strutt, N. L.; Stoll, R. S.; Li, H.; Zhu, Z.; Stoddart, J. F. *Chem Commun.* **2011,** *47*, 11420-2.
24. Zhang, H.; Zhao, Y. *Chemistry.* **2013,** *19*, 16862-79.
25. Li, H.; Chen, D.-X.; Sun, Y.-L.; Zheng, Y. B.; Tan, L.-L.; Weiss, P. S.; Yang, Y.-W. *J Am Chem Soc.* **2013,** *135*, 1570-1576.
26. Montes-Garcia, V.; Fernandez-Lopez, C.; Gomez, B.; Perez-Juste, I.; Garcia-Rio, L.; Liz-Marzan, L. M.; Perez-Juste, J.; Pastoriza-Santos, I. *Chemistry.* **2014,** *20*, 8404-9.
27. Zhang, H.; Liu, Z.; Zhao, Y. *Chem Soc Rev.* **2018**, *47*, 5491-5528.
28. Zhang, H.; Zhao, Y. In *Pillararenes*; The Royal Society of Chemistry, 2016; pp. 208-228.
29. Yao, Y.; Wang, Y.; Huang, F. *Chem Sci.* **2014,** *5*, 4312-4316.
30. 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.
31. Zhang, H.; Ma, X.; Nguyen, K. T.; Zhao, Y. *ACS Nano.* **2013,** *7*, 7853-7863.
32. Yao, Y.; Zhou, Y.; Dai, J.; Yue, S.; Xue, M. *Chem Commun.* **2014,** *50*, 869-71.
33. Zhang, H.; Ma, X.; Nguyen, K. T.; Zeng, Y.; Tai, S.; Zhao, Y. *ChemPlusChem.* **2014,** *79*, 462-469.
34. Park, C.; Jeong, E. S.; Lee, K. J.; Moon, H. R.; Kim, K. T. *Chem Asian J.* **2014,** *9*, 2761-4.
35. Zhang, Z.; Han, C.; Yu, G.; Huang, F. *Chem Sci.* **2012,** *3*, 3026-3031.
36. Ogoshi, T.; Nishida, Y.; Yamagishi, T.-a.; Nakamoto, Y. *Macromolecules.* **2010,** *43*, 3145-3147.
37. Kitajima, K.; Ogoshi, T.; Yamagishi, T. A. *Chem Commun.* **2014,** *50*, 2925-7.
38. Ogoshi, T.; Akutsu, T.; Yamafuji, D.; Aoki, T.; Yamagishi, T. A. *Angew Chem Int Ed Engl.* **2013,** *52*, 8111-5.
39. Hou, X.; Ke, C.; Cheng, C.; Song, N.; Blackburn, A. K.; Sarjeant, A. A.; Botros, Y. Y.; Yang, Y. W.; Stoddart, J. F. *Chem Commun.* **2014,** *50*, 6196-9.
40. Ogoshi, T.; Demachi, K.; Kitajima, K.; Yamagishi, T. A. *Chem Commun.* **2011,** *47*, 7164-6.
41. Guan, Y.; Liu, P.; Deng, C.; Ni, M.; Xiong, S.; Lin, C.; Hu, X. Y.; Ma, J.; Wang, L. *Org Biomol Chem.* **2014,** *12*, 1079-89.
42. 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.
43. Xia, B.; Xue, M. *Chem Commu.* **2014,** *50*, 1021-3.
44. Wei, Y.; Wang, L.; Huang, J.; Zhao, J.; Yan, Y. *ACS Applied Nano Materials.* **2018,** *1*, 1819-1827.
45. 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.

1. Amide formation as an efficient method to construct very stable pillar[5]arene-based pseudo[1]rotaxane.
2. Preparation of [1]rotaxane by reductive amination in high yield.
3. Introduction of triphenylamine as a chromophore sensible to different solvents.
4. Fabrication of a robust [1]rotaxane stable independently of the pH or solvent.