RSC Advances

ROYAL SOCIETY OF CHEMISTRY

www.rsc.org/advances

Sugar-functionalized water-soluble pillar[5]arene and its host–guest interaction with fullerene

Hui Li,[a] Qi Chen,*[a] Christian Schönbeck,[a,b] Bao-Hang Han*[a]

[a] *National Center for Nanoscience and Technology, Beijing 100190, China.*

Tel: +86 10 8254 5576; E-mail: hanbh@nanoctr.cn

[b] *Department of Chemistry, University of Copenhagen, Universitetsparken 5, 2100 Copenhagen, Denmark.*

Abstract

Pillar[5]arenes have attracted much attention as a new member of macrocycles for their unique symmetrical pillar architecture. Pillar[5]arenes are mostly soluble in organic solvents and slightly soluble in water, thus their application in aqueous media has been limited as a result. Thus, it is necessary to design water-soluble pillar[5]arene derivatives. Herein, by the introduction of neutral sugar moieties at both upper and lower rims *via* click reaction, a neutral water-soluble pillar[5]arene (**P5AG**) was prepared and well characterized. Furthermore, the host–guest interaction between **P5AG** and fullerene was investigated in both organic medium and aqueous solution. The host–guest complexation was confirmed by fluorescence, nuclear magnetic resonance, ultraviolet–visible, and Raman spectroscopy.

Keywords: pillar[5]arene; sugar; fullerene; water-soluble; host–guest interaction

Introduction

Since first reported as a new class of macrocyclic host in 2008,[1] the pillarenes have attracted considerable attention owing to their unique structure and intriguing host–guest binding behavior. Compared with the traditional macrocyclic hosts, pillarenes have highly rigid and symmetrical structure. The pillar-like conformation facilitates selective binding toward various guest molecules. They are also easier to be functionalized in several ways.

Despite a great amount of work already dedicated to pillarenes, these molecules continue to fascinate researchers in many different fields such as molecular recognition,[2] sensing and detection,[3] delivery systems,[4] liquid crystals,[5] and dispersion of carbon materials.[6] Among all these situations, complexation behaviors pillarenes towards different guest molecules have been extensively studied. With the electron-rich cavity, pillarenes are especially good at binding the electron-deficient guest molecules and some neutral molecules, such as viologen derivatives,[7,8] (bis)-imidazolium cations,[9] *n*-octyltrimethyl ammonium hexafluorophosphate,[10] alkanediamines,[11] and neutral bis(imidazole) derivatives.[12] It is worth noting that the studies on host–guest properties of pillar[5]arenes are always carried out in organic media owing to their poor solubility in aqueous media. Therefore, it is necessary to design water-soluble pillar[5]arene derivatives. A water-soluble pillar[5]arene with negatively charged carboxylate groups functionalized at both rims was reported,[7] and its binding behavior towards cationic viologen salts was studied in water. a pillar[5]arene decaamine was prepared and its encapsulation of linear diacids in neutral, alkaline, and acidic conditions were further investigated.[13] Cationic pillar[5]arenes containing trimethylammonium groups were reported to strongly bind sodium 1-octanesulfonate in aqueous media, mainly driven by hydrophobic and electrostatic interactions.[14]

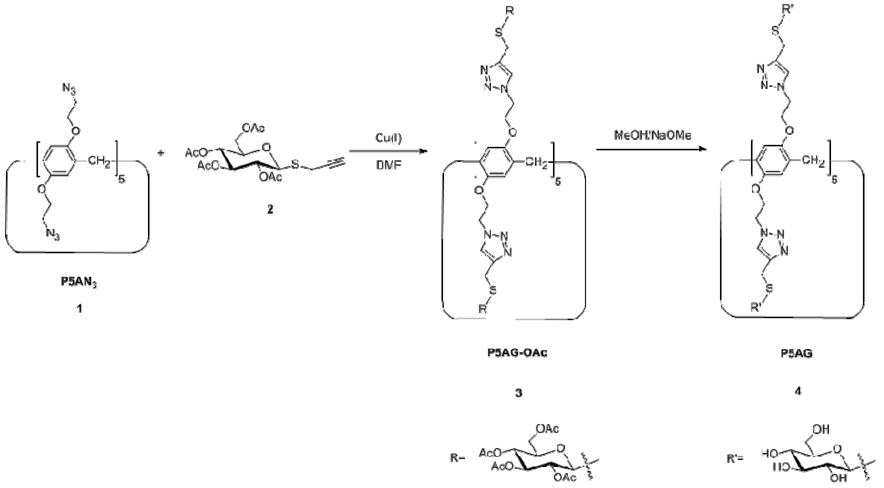
Fullerene, a condensed ring aromatic compound with extended π-conjugated systems, has cage-like structure and is 0.7 nm in diameter. Several studies have shown that fullerene has unique biological properties both *in vitro* and *in vivo*.[15] Its applications have been gradually extended to various research fields, such as pharmaceutical science and biological field.[15] However, the low solubility of fullerene in aqueous media significantly hampers its biological application. To overcome the natural repulsion of fullerenes and water, strategies including preparation of water-soluble supramolecular complexes with macrocyclic hosts such as cyclodextrin,[16] calixarene derivatives,[17] or cyclotriveratrylene (CTV) derivatives[18] have been developed. These macrocycles can form complex with C_{60} in aqueous media.Water-soluble glycoconjugated CTV hosts prepared by introducing neutral sugar moieties into CTV platform can bind C_{60} with good binding constants.[18b,18c] The supramolecular chemistry of pillarene and fullerene is still rarely studed. Herein, by the introduction of neutral sugar moieties at both upper and lower rims *via* click reaction, a neutral water-soluble pillar[5]arene (**P5AG**) was prepared, and the host–guest interaction between **P5AG** and C_{60} was investigated in both aqueous solution and co-organic solvent.

Experimental section

Materials and charactization

All chemical reagents are commercially available and used as received unless otherwise stated. Pillar[5]arene derivative **1** (Scheme 1) and alkyne-functionalized sugar derivative **2** (Scheme 1) were prepared according to reporting methods. [7,13] Ultrapure water (18.2 MΩ cm) was purified with a Millipore purification system (Milli-Q water, Merck Millipore, Germany).

Proton nuclear magnetic resonance (^{1}H NMR) and carbon nuclear magnetic resonance (^{13}C NMR) spectra were acquired with a Bruker DMX400 spectrometer (Bruker, Germany). Mass spectra were measured using a Microflex LRF MALDI-TOF mass spectrometer (Bruker Daltonics, USA). Ultraviolet−visible (UV−vis) spectra were recorded with a Lamda 950 UV−vis−NIR spectrophotometer (Perkin−Elmer Instruments Co. Ltd., USA) and quartz cells with 1 cm path length. The fluorescence spectra were measured in a conventional cell with 1 cm path length using an LS55 spectrophotometer (Perkin−Elmer Instruments Co. Ltd., USA) at room temperature. Raman spectra were recorded with a Renishaw inVia Raman spectrometer (Renishaw, UK) by dropping the sample solutions onto a slide glass (after air drying) or putting C_{60} powder directly on a slide glass.



Scheme 1. Synthesis Route to **P5AG**

Synthesis of P5AG-OAc

The synthesis of **P5AG-OAc** is outlined in Scheme 1. To attach sugar groups via the click reaction, an intermediate azide substituted pillar[5]arene **1** was prepared from bromoethoxy group substituted pillar[5]arene through azido reaction. Then compound **1** (0.0455 g, 0.035 mmol) and glucose derivative **2** (0.1477 g, 0.367 mmol) were dissolved in DMF (1 mL) under nitrogen atmosphere. Ascorbic acid (6.93 mg, 0.036 mmol) and $CuSO_4$ $5H_2O$ (4.37 mg, 0.018 mmol) were added to the mixture as catalyst. The reaction mixture was refluxed overnight at 60 ºC and then poured into pure water. The resulted precipitate was collected by filtration after washing with water for three times. After recrystallization in acetone and ether co-solvent, the pale yellow solid **3** was obtained (0.145 g, yield: 78%). ^{1}H NMR ($CDCl_3$) δ(ppm) 7.81 (s, 10H), 6.57 (d, *J* = 6.8 Hz, 10H), 5.24–5.18 (m, 10H), 5.12–5.03 (m, 20H), 4.72–4.63 (m, 30H), 4.26–3.90 (m, 50H), 3.72 (s, 10H), 3.27 (s, 10H), 3.12–3.38 (m, 10H), 2.04–1.97 (m, 120H). ^{13}C NMR ($CDCl_3$) 171.4, 170.8, 170.2, 150.3, 145.5, 129.5, 123.7, 116.8, 83.7, 83.6, 76.6, 74.6, 70.7, 69.1, 68.2, 66.6, 62.7, 59.1, 51.1, 31.7; MALDI-TOF-MS calcd. for $C_{225}H_{280}N_{30}O_{100}S_{10}$, 5324.95 (*m*/*z*), found 5324.96. Melting point: 132.2–134.8 ºC.

Synthesis of P5AG

A solution of sodium methoxide (1.0 M) in methanol was added to a solution of **P5AG-OAc** (60 mg, 0.011 mmol) in methanol–dichloromethane (2:1, 12 mL) drop-wise until the pH value reached to 11. The reaction mixture was stirred at room temperature for 6 h. After neutralization, the resulted suspension was filtered and washed with dichloromethane and petroleum ether for three times to give **4** (0.037 g, yield: 93%). ^{1}H NMR (DMSO-d_6) δ (ppm) 8.18 (s, 10H), 6.71 (s, 10H), 5.08–4.69 (m, 40H), 4.58–4.38 (m, 20H), 4.36–4.08 (m, 20H), 4.02 (d, J = 14.0 Hz, 10H), 3.91 (d, J = 13.6 Hz, 10H), 3.70 (d, J = 11.2 Hz, 20H), 3.17 (s, 20H), 3.14 (s, 20H), 3.09 (s, 20H). ^{13}C NMR (DMSO-d_6) δ (ppm) 154.7, 150.7, 134.4, 129.3, 90.3, 87.0, 84.1, 79.1, 76.1, 73.3, 67.3, 62.0, 60.9, 55.8, 54.6, 29.1. MALDI-TOF-MS calcd. For $C_{145}H_{200}N_{30}O_{60}S_{10}$, 3643.95 (*m*/*z*), found 3643.97. Melting point: 148.5–150.9 ºC.

Spectrofluorometric titration of P5AG–C_{60} complexation in toluene–DMSO

A solution of **P5AG** was prepared in toluene–DMSO (1:1, v/v). Aliquots of C_{60} in the same solvent were added to the solution. The final concentration of **P5AG** was 5×10^{-6} M, and the final concentration of C_{60} ranged from 0 to 50.0×10^{-6} M. After each addition, the sample was allowed to equilibrate for hours prior to recording a spectrum. Additions of C_{60} were continued until no significant change in the fluorescence signal was observed. The excitation wavelength was 280 nm and the emission scan ranged from 290 to 520 nm.

Preparation of P5AG–C_{60} complexes in aqueous solution

The aqueous solutions of sugar-bearing **P5AG–C_{60}** complexes were prepared by stirring an aqueous solution of **P5AG** (5.0×10^{-5} M) containing C_{60} solid (>99%) for days. After centrifugation, clear aqueous solutions containing sugar-bearing **P5AG**–C_{60} complexes were obtained for further studies.

Computational details

An molecular dynamics (MD) simulation of a 1:1 complex in a 60×60×60 $Å^3$ periodic TIP3P water box was run by the NAMD code[19] using CHARMM force field parameters.[20,21,22,23] The details are included in the ESI. Simulations were run for 50 nanoseconds (ns) with a two femtosecond timestep in the NPT ensemble at 298 K and 1.013 bar. The van der Waals interactions were cut off at 12 Å with a switching function starting at 10 Å.

Results and discussion

A sugar-bearing pillar[5]arene derivative was designed by introducing ten glucose moieties into pillarene structure. Cu(I)-catalyzed azide "click" ligation between azido-substituted pillarene and alkyl-functionalized sugar derivatives is chosen to introduce ten sugar groups into pillar[5]arene structure, on account of its highly efficient ligation and mild reaction condition. Formation of the triazole ring was confirmed by the chemical shift nearly at 7.81 ppm in the ^{1}H NMR spectrum and the peaks nearly at 123.7 and 145.5 ppm on the ^{13}C NMR spectrum of the corresponding desired intermediate **P5AG-OAc**. After removing all the acetyl groups with MeONa/MeOH, the desired water-soluble **P5AG** was obtained quantitively and further confirmed by ^{1}H NMR, ^{13}C NMR, and mass spectrum. The disappearance of the peak of Ac ($\delta = 2.04$ ppm) after final efficient global deprotection suggests the successful preparation of **P5AG** compared with ^{1}H NMR spectrum of the protected precursor. The protected sugar-bearing pillar[5]arene is readily soluble in common organic solvents such as methylene chloride, chloroform, and tetrahydrofuran, but insoluble in methanol, ethanol, and water. The solubility of the resulting **P5AG** is different from its precursor, exhibiting a good solubility in DMF, DMSO, toluene−DMSO (1:1, v/v), and water.

The photophysical properties of the complexes generated from interaction of **P5AG** with C_{60} were investigated. **P5AG** possesses a distinct photoluminescence, an emission maximum peak at 323 nm in toluene−DMSO (1:1, v/v) solution appears when excited at 280 nm. The fluorescence in the region from 340 to 390 nm is probably due to the formation of ground-state dimer as a result of the interactions between the benzene rings upon excitation[24] or excimeric emission caused by the interaction between the phenyl groups.[25] Introducing the bulky sugar substituents by the click reaction not only inhibits the rotation of the units, but also extends arms of ten benzene rings thus making it possible to exhibit better host–guest behavior. The fluorescence may be ascribed to the enhanced planar conformation of benzene rings of pillar[5]arene derived from spatial effect of bulky branch chains.

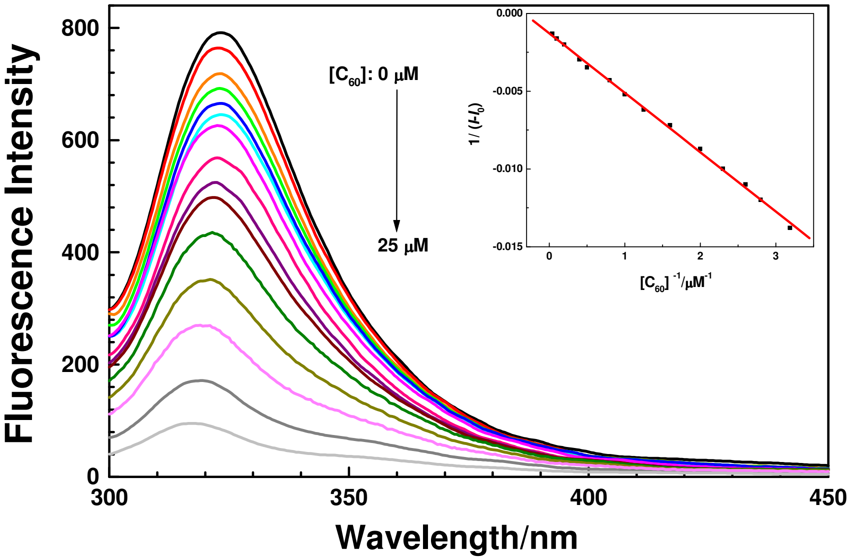


Fig. 1 Fluorescence spectra of **P5AG** (5.0×10^{-6} M) in the absence and presence of various concentrations of C_{60} in the toluene–DMSO solution at room temperature (λ_{ex}=280 nm). The concentrations of C_{60} ($\times10^{-6}$ M) are 0, 0.313, 0.357, 0.384, 0.435, 0.500, 0.625, 0.800, 1.000, 1.250, 2.000, 2.500, 5.000, 10.000 and 25.000, respectively. The inset is the plot of ΔI vs $[C_{60}]^{-1}$.

The complexing properties of sugar-substituted **P5AG** with extended arms towards C_{60} were further verified by photoluminescence and Raman spectroscopy.[26] The fluorescence spectroscopy is widely used as a tool to investigate the complexion between macrocycles and small guest molecules for its sensitivity, convenience, and cost-effectiveness. Both sugar-bearing **P5AG** and C_{60} are readily soluble in toluene–DMSO co-solvent (1:1, v/v) at low concentrations. Host–guest interaction between sugar-bearing **P5AG** and C_{60} was studied by spectrofluorometric titrations[27,28] in the co-solvent at 25 °C. The emission spectrum from C_{60} solution is broad and between 650 and 725 nm in toluene.[29] Furthermore, the fluorescence emission of highly purified samples of C_{60} at room temperature has been found to be very weak.[30] The fluorescence emission of **P5AG** dissolved in toluene–DMSO (1:1, v/v) ranged from 340 to 390 nm, and no peak for C_{60} can be observed. Upon successive addition of the fullerene (0–25 μM) to the host solutions, a continuous fluorescence quenching was observed in the fluorescence spectra of sugar-bearing **P5AG**. The fluorescence intensity of **P5AG** gradually decreased and was significantly quenched when concentration of C_{60} was up to 10 μM (Fig. 1). Furthremore, fluorescence intensity of **P5AG** was finally quenched by 88% when concentration of C_{60} was up to 25.0 μM. The quenching might be attributed to the change in the extended cavity of the host with sugar moieties modified on ten arms of pillar[5]arene. Ground-state C_{60} possesses remarkable electron acceptor properties and is capable of accommodating as many as six electrons in solution.[31] When sugar-bearing pillar[5]arene interacts with C_{60}, there may exsits photo-induced intermolecular electron transfers between sugar-bearing pillar[5]arene host and C_{60} thus leading to fluorescence quenching of sugar-bearing host. The extended spatial structure of **P5AG** with ten sugar moieties can accommodate C_{60} to some extent, so the photo-induced intermolecular electron transferring tends to take place. On the basis of linear fitting of the plot of $[C_{60}]^{-1}$ vs ΔI and the hypothesis that the complex can be formed by host and C_{60} with 1:1 ratio at a low concentration, the calculated association constants K_a of host **P5AG** with C_{60} in toluene–DMSO solution was 1.75×10^5 M^{-1} at 298 K (R^2=0.9991).

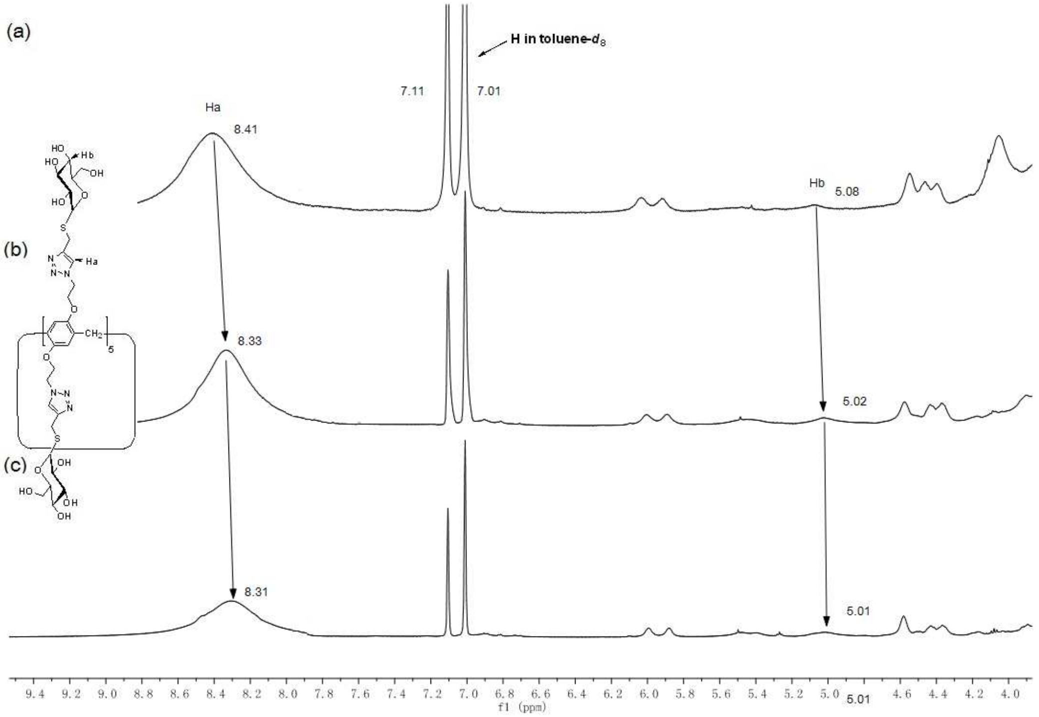


Fig. 2 Partial ^{1}H NMR spectra (400 MHz, toluene-d_8–DMSO-d_6 (1:1, v/v), 25 ºC) of (a) **P5AG**, (b) **P5AG**+1 eq. C_{60}, (c) **P5AG**+2 eq. C_{60}. [**P5AG**]= 4.0 μM.

In order to further characterize and confirm the host–guest interaction between **P5AG** and C_{60} in toluene-d_8–DMSO-d_6 (1:1, v/v) co-solvent, ^{1}H NMR spectroscopy (Fig. 2) was employed. The solubility of C_{60} in toluene is very limited at room temperature, reported by Ruoff.[32] In order to maitain a proper proportion of host and guest and get well-dissolved mixture to characterize, we prepared the host solution with a concentration of 4.0 μM. Two peaks that appear at 7.01 and 7.11 ppm should be assigned to toluene-d_8. As shown in Fig. 2, in the presence of about 1 equiv. of C_{60}, the signals of **P5AG**'s triazole proton (H_a) and part of sugar protons (H_b) exhibited a very slight upfield shift ($\Delta\delta < -0.1$ ppm) compared to the free **P5AG**. As 2 equiv. of C_{60} were added, the correspongding protons of **P5AG** showed broadening effects and a bit larger upfield shift ($\Delta\delta$=−0.1 ppm) compared to the free **P5AG**. Although only slight chemical shift changes were observed in the complexation systems probably owing to poor solubility of C_{60} in the solvent, the NMR experiments can give us some proof about interaction between **P5AG** host and C_{60}.

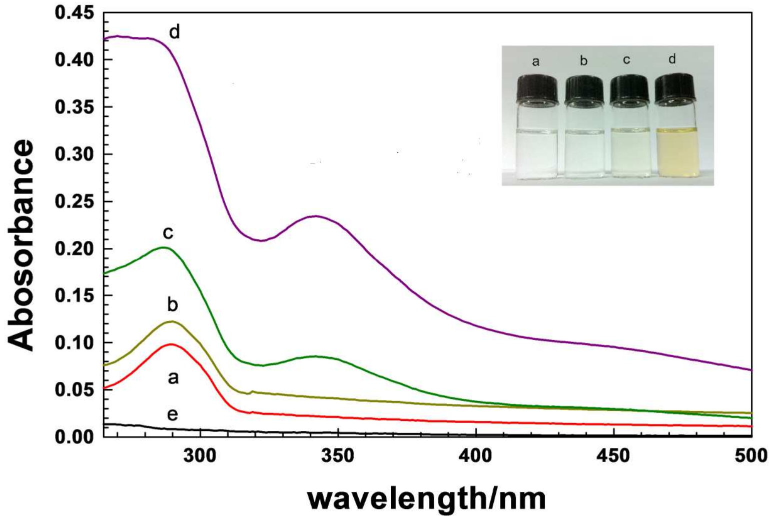


Fig. 3 Absorption spectra of aqueous **P5AG** (a) and **P5AG–C_{60}** solutions (b, c, d. concentration of **P5AG** is 5.0×10^{-5} M), and C_{60} in water (e). Inset shows the photographs of aqueous **P5AG** and **P5AG–C_{60}** solutions corresponding to the traces. (a, **P5AG**; b, **P5AG+C_{60}** 70h; c, **P5AG+C_{60}** 2 weeks; d, **P5AG+C_{60}** 3 weeks).

The host–guest interaction of sugar-bearing pillar[5]arene host and C_{60} was also investigated in aqueous solution. Formation of the complex facilitates the dispersion of fullerene in aqueous media. The water-soluble supramolecular complex between pillar[5]arene-based host and fullerenes was prepared simply by stirring an aqueous solution of **P5AG** (5.0×10^{-5} M) containing C_{60} solid (>99%) for days. Fig. 3 shows the UV-Vis absorption spectra of C_{60}, **P5AG**, and **P5AG–C_{60}** complex, respectively, in aqueous solution. C_{60} is insoluble in water as we known, therefore no absorption intensity was observed. However, after interacting with pillar[5]arene host for days, a new absorption peak at around 342 nm which assigned to characteristic signal peak of C_{60} in UV–vis region was observed, and its intensity gradually increased. The interaction of sugar-bearing **P5AG** hosts with C_{60} can also be visually monitored by a color change of the corresponding solutions. As shown in the inset of Fig. 3, the aqueous solution of **P5AG** is almost colorless, upon addition of C_{60}, the color of aqueous **P5AG–C$_{60}$** solution gradually changes into yellow after stirring for days. The color changes of the solution suggest that **P5AG** can interact with C_{60} in aqueous solution and form a water-soluble complex. Although there is also possibility that the C_{60} aggregates might contribute to the peak of 342 nm,[33] we did not observe any absorption of C_{60} in the control experiment in pure water.

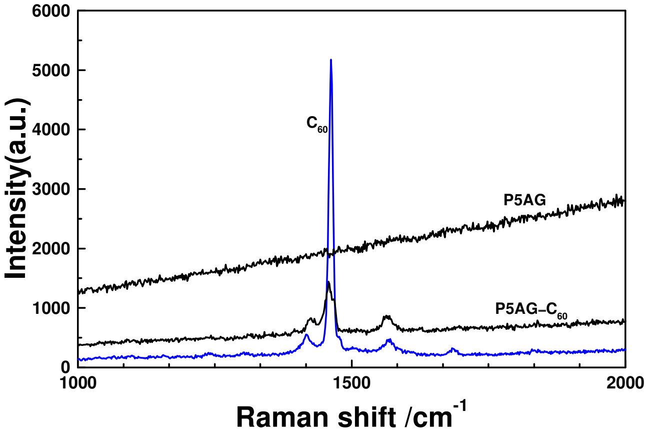


Fig. 4 Raman spectra of **P5AG–C$_{60}$**, **P5AG** and C_{60}.

Equilateral pentagonal **P5AG** cavity with sugar–triazole cluster structure can not only provide an internal cavity capable of encapsulating the hydrophobic C_{60}

guest considering the size-fit concept, but also prevent the aggregation in an aqueous solution owing to the fullerene−fullerene interaction. Multiple hydroxyl groups of sugar moieties make the supramolecular complexes water-soluble. The hydrophobic triazole groups and ten-membered ring skeleton of sugars can increase the hydrophobic and van der Waals interactions between the inner surface of sugar-bearing **P5AG** hosts and C_{60}. These major driving forces are important in forming the supramolecular complexes. Further study with Raman spectra can also prove the existence of C_{60} in aqueous solution. The featured peak at 1470 cm^{-1} was assigned to the totally symmetric pentagonal pinch mode of C_{60} in **P5AG–C_{60}** sample, while no corresponding peak was found in **P5AG** (Fig. 4).[34]

Molecular dynamics simulations of complex in water

Molecular dynamics simulations of a 1:1 complex were conducted to investigate possible binding conformations. During the first 35 nanoseconds (ns), C_{60} stays close to its initial position in front of the cavity opening of the pillarene. It moves somewhat back and forth but stays encapsulated by the sidechains, as showed in Fig. 5a. The sidechains are relatively mobile and alternate between interacting with the C_{60} molecule and being immersed in the water, but all of the time, three or four sidechains are in direct contact with the C_{60} and form a basket that keeps C_{60} in place in front of the cavity opening. Both the triazole and glucose moieties interact with C_{60}, but it never moves so close to the pillarene cavity that is in direct contact with the ester oxygen and the two methylene groups that connect the central pillarene structure to the triazole ring. Shortly after 35 ns of simulation, C_{60} moves from this binding conformation to a new binding conformation on the side of the central pillarene structure, where it is in direct contact with one of the phenyl groups (Fig. 5b). This change in binding conformation takes less than 5 ns. Gradually, several sidechains from both rims of the pillarene start interacting with the C_{60}, thereby forming a basket that restricts it to this binding conformation for the remaining simulation time (up to 50 ns). Two additional 25 ns simulations with different initial velocities support the observed binding conformations.

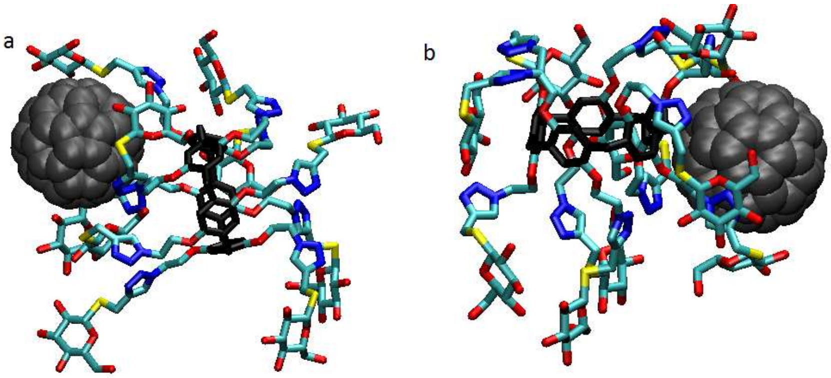


Fig. 5 Snapshot from MD simulation. (a) C_{60} moves around in front of the cavity opening of the pillarene. Three or four ones of the sidechains form a basket that keeps C_{60} in place. (b) C_{60} sticks to the side of the central pillarene structure and is in direct contact with the phenyl groups as well as the various parts of the sidechains. The atoms of the central pillarene structure are shown in black, oxygens are red, nitrogen is blue, carbons are cyan, and sulfur is yellow. Hydrogens are not shown.

The identification of these two distinct binding conformations opens up for the following consequences. First, when a single C_{60} binds **P5AG**, there is plenty of room for another, or maybe several other C_{60} molecules, to bind **P5AG** and therefore form higher-order complexes. The formation of higher-order complexes is of course concentration dependent, being favored by high concentrations of C_{60}. Second, the C_{60} molecules are not surrounded by the host molecules and more than half of the C_{60} surface is still exposed to water. It does not seem unreasonable that these surfaces engage in hydrophobic interactions with other C_{60} or **P5AG** molecules, thereby forming extended structures in the form of clusters.

Conclusions

A sugar-functionalized water-soluble pillar[5]arene derivative (**P5AG**) modified with ten glucose moieties via click reaction has been successfully synthesized in a high yield. **P5AG** exhibits a distinct photoluminescence, thus can be used to conveniently detect their interaction with C_{60} through spectrofluorometric titration. **P5AG** can bind C_{60} to form supramolecular complexes in toluene−DMSO co-solvent. As a result of the extended arms on both rims of pillar[5]arene, the instinct cavity is enlarged. C_{60} can interact with host molecules owing to van der Waals force and hydrophobic interaction. The supramolecular complexation between **P5AG** and C_{60} was investigated in both organic solvent and aqueous solution, and also confirmed by fluorescence, ^{1}H NMR, UV−vis, and Raman spectra. Molecular dynamics simulations of complexes reveal two distinct binding conformations in which C_{60} is located either in front of the cavity opening or at the side of the central pillarene structure. In both conformations the arms of the pillarene interact with C_{60} to form binding pockets. The association constant K_a of host **P5AG** with C_{60} was 1.75×10^5 M^{-1} in organic solvent, calculated on the hypothesis that supramolecular complex was formed with 1:1 molar ratio at 298 K. The host–guest interaction between sugar-bearing **P5AG** and C_{60} in aqueous solution will boost the potential biological application of C_{60}.

Acknowledgements

The financial support of the National Science Foundation of China (Grant no. 21374024 and 61261130092), the Ministry of Science and Technology of China (Grant no. 2014CB932200 and 2011CB932500) is acknowledged. The authors also acknowledge the financial support from the Danish-Chinese Center for Molecular Nanoelectronics funded by the Danish National Research Foundation and the Danish Agency for Science, Technology and Innovation.

Notes and references

† Electronic Supplementary Information (ESI) available: Computational details; ^{1}H NMR, ^{13}C NMR and MS spectra of the key compounds.

1 T. Ogoshi, S. Kanai, S. Fujinami, T. A. Yamagishi and Y. Nakamoto, *Para*-bridged symmetrical pillar[5]arenes: their lewis acid catalyzed synthesis and host–guest property. *J. Am. Chem. Soc.*, 2008, **130** (15), 5022–5023.

2 (a) C. Han, F. Ma, Z. Zhang, B. Xia, Y. Yu and F. Huang, DIBPillar[n]arenes (n=5, 6): Syntheses, X-ray crystal structures, and complexation with n-Octyltriethyl ammonium hexafluorophosphate. *Org. Lett.*, 2010, **12** (19), 4360–4363. (b) G. Yu, C. Han, Z. Zhang, J. Chen, X. Yan, B. Zheng, S. Liu and F. Huang, Pillar[6]arene-based

photoresponsive host–Guest complexation. *J. Am. Chem. Soc.*, 2012, **134** (20), 8711–8717. (c) M. Xue, Y. Yang, X. Chi, Z. Zhang and F. Huang, Pillararenes, a new class of macrocycles for supramolecular chemistry. *Acc. Chem. Res.*, 2012, **45** (8), 1294–1308. (d) X. Shu, S. Chen, J. Li, Z. Chen, L. Weng, X. Jia and C. Li, Highly effective binding of neutral dinitriles by simple pillar[5]arenes. *Chem. Commun.*, 2012, **48** (24), 2967–2969. (e) W. Chen, Y. Zhang, J. Li, X. Lou, Y. Yu, X. Jia and C. Li, Synthesis of a cationic water-soluble pillar[6]arene and its effective complexation towards naphthalenesulfonate guests. *Chem. Commun.*, 2013, **49** (72), 7956–7958.

3 (a) N. L. Strutt, R. S. Forgan, J. M. Spruell, Y. Y Botros and J. F. Stoddart, Monofunctionalized pillar[5]arene as a host for alkanediamines. *J Am Chem Soc*, 2011, **133** (15), 5668–5671. (b) T. Adiri, D. Marciano and Y. Cohen, Potential ^{129}Xe-NMR biosensors based on secondary and tertiary complexes of a water-soluble pillar[5]arene derivative. *Chem Commun*, 2013, **49** (63), 7082–7084. (c) S. Sun, X. Y. Hu, D. Chen, J. Shi, Y. Dong, C. Lin, Y. Pan and L. Wang, Pillar[5]arene-based side-chain polypseudorotaxanes as an anion-responsive fluorescent sensor. *Polym Chem*, 2013, **4** (7), 2224–2229. (d) S. Sun, J. B. Shi, Y. P. Dong, C. Lin, X. Y. Hu and L. Y. Wang, A pillar[5]arene-based side-chain pseudorotaxanes and polypseudorotaxanes as novel fluorescent sensors for the selective detection of halogen ions. *Chin Chem Lett*, 2013, **24** (9), 987–992. (e) Y. Yao, X. Chi, Y. Zhou and F. Huang. A bola-type supra-amphiphile constructed from a water-soluble pillar[5]arene and a rod-coil molecule for dual fluorescent sensing, *Chem Sci*, 2014, **5** (7), 2778–2782. (f) P. Wang, X. Yan and F. Huang, Host-guest complexation induced emission: a pillar[6]arene-based complex with intense fluorescence in dilute solution. *Chem Commun*, 2014, **50** (39), 5017–5019. (g) R. R. Kothur, J. Hall, B. A. Patel, C. L.

Leong, M. G. Boutellec and P. J. Cragg, A low pH sensor from an esterified pillar[5]arene. *Chem Commum*, 2014, **50** (7), 852–854.

4 (a) Q. Duan, Y. Cao, Y. Li, X. Hu, T. Xiao, C. Lin, Y. Pan and L. Wang, pH-responsive supramolecular vesicles based on water-soluble pillar[6]arene and ferrocene derivative for drug delivery. *J Am Chem Soc*, 2013, **135** (28), 10542–10549. (b) Y. L. Sun, Y. W. Yang, D. X. Chen, G. Wang, Y. Zhou, C. Y Wang and J. F. Stoddart, Mechanized silica nanoparticles based on pillar[5]arenes for on-command cargo release. *Small*, 2013, **9** (19), 3224–3229.

5 (a) I. Nierengarten, S. Guerra, M. Holler, J. F. Nierengarten and R. Deschenaux, Building liquid crystals from the 5-fold symmetrical pillar[5]arene core. *Chem Commun*, 2012, **48** (65), 8072–8074. (b) I. Nierengarten, S. Guerra, M. Holler, L. Karmazin-Brelot, J. Barberá, R. Deschenaux and J. F. Nierengarten, Macrocyclic effects in the meso morphic properties of liquid-crystalline pillar[5]- and pillar[6]arenes. *Eur J Org Chem*, 2013, (18), 3675–3684.

6 (a) G. Yu, M. Xue, Z. Zhang, J. Li, C. Han and F. Huang, A water-soluble pillar[6]arene: synthesis, host-guest chemistry, and its application in dispersion of multiwalled carbon nanotubes in water. *J Am Chem Soc*, 2012, **134** (32), 13248–13251. (b) J. Yang, G. Yu, D. Xia and F. Huang, A pillar[6]arene-based UV-responsive supra-amphiphile: synthesis, self-assembly, and application in dispersion of multiwalled carbon nanotubes in water. *Chem Commum*, 2014, **50** (30), 3993–3995.

7 T. Ogoshi, M. Hashizume, T. A. Yamagishi and Y. Nakamoto, Synthesis, conformational and host–guest properties of water-Soluble pillar[5]arene. *Chem. Commun.*, 2010, **46** (21), 3708–3710.

8 T. Ogoshi, D. Yamafuji, T. Aoki and T. A. Yamagishi, Photoreversible Transformation between Seconds and Hours Time-Scale: Threading of pillar[5]arene onto the azobenzene-end of a viologen derivative. *J. Org. Chem.*, 2011, **76** (22), 9497–9503.

9 C. Li, L. Zhao, J. Li, X. Ding, S. Chen, Q. Zhang, Y. Yu and X. Jia, Self-assembly of [2]pseudorotaxanes based on pillar[5]arene and bis(imidazolium) cations. *Chem. Commun.*, 2010, **46** (47), 9016–9018.

10 Z. Zhang, Y. Luo, B. Xia, C. Han, Y. Yu, X. Chen and F. Huang, Four constitutional isomers of BMpillar[5]arene: synthesis, crystal structures and complexation with N-Octyltrimethyl ammonium hexafluorophosphate. *Chem. Commun.*, 2011, **47** (8), 2417–2419.

11 N. L. Strutt, R. S. Forgan, J. M. Spruell, Y. Y. Botros and J. F. Stoddart, Monofunctionalized pillar[5]arene as a host for alkanediamines. *J. Am. Chem. Soc.*, 2011, **133** (15), 5668–5671.

12 C. Li, S. Chen, J. Li, K. Han, M. Xu, B. Hu, Y. Yu and X. Jia, Novel neutral guest recognition and interpenetrated complex formation from pillar[5]arenes. *Chem. Commun.*, 2011, **47** (40), 11294–11296.

13 X.-B. Hu, L. Chen, W. Si, Y. Yu and J.-L Hou, Pillar[5]arene decaamine: synthesis, encapsulation of very long linear diacids and formation of ion pair-stopped [2]rotaxanes. *Chem. Commun.*, 2011, **47** (16), 4694–4696.

14 Y. Ma, X. Ji, F. Xiang, X. Chi, C. Han, J. He, Z. Abliz, W. Chen and F. Huang, cationic water-soluble pillar[5]arene: synthesis and host–guest complexation with sodium 1-octanesulfonate. *Chem. Commun.*, 2011, **47** (45), 12340–12342.

15 M. Prato and T. D. Ros, Medicinal chemistry with fullerenes and fullerene derivatives. *Chem. Commun.*, 1999, (8), 663–669.

16 (a) C. N. Murthy and K. E Geckeler, The Water-soluble β-cyclodextrin–[60]fullerene complex. *Chem. Commun.*, 2001, (13), 1194–1195. (b) S. Takekuma, H. Takekuma, T. Matsumoto and Z. Yoshida, A highly efficient generation of cyclodextrin-bicapped C_{60} in aqueous solution. *Tetrahedron Lett.*, 2000, **41** (25), 4909–4912.

17 A. Ikeda, T. Hatano, M. Kawaguchi, H. Suenaga and S. Shinkai, Water-soluble [60]fullerene-cationic homooxacalix[3]arene complex which is applicable to the photocleavage of DNA. *Chem. Commun.*, 1999, (15), 1403–1404.

18 (a) Y. Rio and J. F. Nierengarten, water soluble supramolecular cyclotriveratrylene–[60] fullerene complexes with potential for biological applications. *Tetrahedron Lett*., 2002, **43** (24), 4321–4324. (b) F. Yang, Q. Chen, Q.-Y. Cheng, C.-G. Yan and B.-H. Han, Sugar-functionalized water-soluble cyclotriveratrylene derivatives: preparation and their interaction with fullerene. *J. Org. Chem.*, 2012, **77** (2), 971–976. (c) L.-J. Feng, H. Li, Q. Chen and B.-H. Han, Cationic cyclotriveratrylene-based glycoconjugate and its interaction with fullerene. *RSC Adv.*, 2013, **3** (19), 6985–6990.

19 J. C. Phillips, R. Braun, W. Wang, J. Gumbart, E. Tajkhorshid, E. Villa, C. Chipot, R. D. Skeel, L. Kalé and K. Schulten, Scalable molecular dynamics with NAMD. *J. Comput. Chem.*, 2005, **26** (16), 1781–1802.

20 K. Vanommeslaeghe, E. Hatcher, C. Acharya, S. Kundu, S. Zhong, J. Shim, E. Darian, O. Guvench, P. Lopes, I. Vorobyov and A. D. Mackerell, CHARMM general force field: A force field for drug-like molecules compatible with the CHARMM all-atom additive biological force fields. *J. Comput. Chem.*, 2010, **31** (4), 671–690.

21 K. Vanommeslaeghe and A. D MacKerell, Automation of the CHARMM general force field (CGenFF) I: bond perception and atom typing. *J. Chem. Inf. Model.*, 2012,

52 (12), 3144–3154.

22 K. Vanommeslaeghe, E. P. Raman and A. D MacKerell, Automation of the CHARMM general force field (CGenFF) II: sssignment of bonded parameters and partial atomic charges. *J. Chem. Inf. Model.*, 2012, **52** (12), 3155–3168.

23 O. Guvench, S. N. Greene, G. Kamath, J. W. Brady, R. M. Venable, R. W. Pastor and A. D. Mackerell, Additive empirical force field for hexopyranose monosaccharides. *J. Comput. Chem.*, 2008, **29** (15), 2543–2564.

24 H. Itagaki, Y. Inagaki and N. Kobayashi, Microenvironments in poly(ethylene terephthalate) film revealed by means of fluorescence measurements. *Polymer*, 1996, **37** (16), 3553–3558.

25 C. W. Frank, D. J. Henker and J. W. Thomas, Photophysical studies of amorphous orientation in poly(ethylene terephthalate) films. *Polymer*, 1988, **29** (3), 437–447.

26 J. L. Atwood, J. W. Steed, P. C. Junk, C. L. Raston, M. J. Barnes and R. S. Burkhalter, Ball and socket nanostructures: new supramolecular chemistry based on cyclotriveratrylene. *J. Am. Chem. Soc.*, 1994, **116** (22), 10346–10347.

27 Y. Liu, B.-H. Han, S.-X. Sun, T. Wada and Y. Inoue, Molecular recognition study on supramolecular systems. 20. molecular recognition and enantioselectivity of aliphatic alcohols by tryptophan-modified β-cyclodextrin. *J. Org. Chem.*, 1999, **64** (5), 1487–1493.

28 Y. Liu, B.-H. Han and Y.-T. Chen, Molecular recognition and complexation thermodynamics of dye guest molecules by modified cyclodextrins and calixarenesuffonates. *J. Phys. Chem. B*, 2002, **106** (18), 4678–4687.

29 D. Kim and M. Lee, Observation of fluorescence emission from solutions of C_{60} and C_{70} and measurement of their excited-state lifetimes. *J. Am. Chem.* Soc., 1992,

114 (11), 4429–4430.

30 D. J. van den Heuvel, G. J. B. van den Berg, E. J. J. Groenen and J. Schmidt, Lowest excited singlet state of C_{60}: a vibronic analysis of the fluorescence. *J. Phys. Chem.*, 1995, **99** (30), 11644–11649.

31 D. M. Guldi, M. Maggini, G. Scorrano and M. Prato, Intramolecular electron transfer in fullerene/ferrocene based donor-bridge-acceptor dyads. *J. Am. Chem. Soc.*, 1997, **119** (5), 974–980.

32 R. S. Ruoff, R. Malhotra, D. L. Huestis, D. S. Tse, and D. C. Lorents, Anomalous solubility behavior of fullerene C_{60}. *Nature*, 1993, **362** (6416), 140–141.

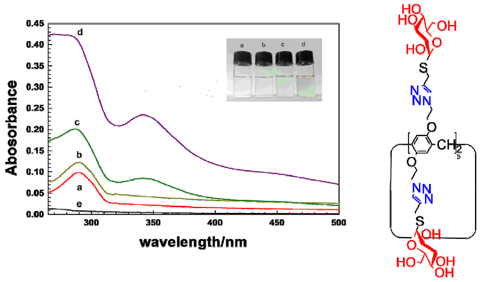
33 A. D. Bokare and A. Patnaik, C_{60} aggregate structure and geometry in nonpolar o-xylene. *J. Phys. Chem.* B, 2005, **109** (1), 87–92.

34 M. Moskovits, K. L. Akers, C. Douketis and T. L. Haslett, Raman spectroscopy of C_{60} solid films: A Tale of Two Spectra. *J. Phys. Chem.*, 1994, **98** (42), 10824–10831.

Graphical and textual abstract

Sugar-functionalized water-soluble pillar[5]arene and its host–guest interaction with fullerene

Hui Li,[a] Qi Chen,[*,a] Christian Schönbeck,[a,b] Bao-Hang Han[*,a]



The host–guest interaction between a neutral water-soluble pillar[5]arene containing ten sugar moieties and C_{60} was investigated.