

ChemComm

Accepted Manuscript



This is an *Accepted Manuscript*, which has been through the Royal Society of Chemistry peer review process and has been accepted for publication.

Accepted Manuscripts are published online shortly after acceptance, before technical editing, formatting and proof reading. Using this free service, authors can make their results available to the community, in citable form, before we publish the edited article. We will replace this *Accepted Manuscript* with the edited and formatted *Advance Article* as soon as it is available.

You can find more information about *Accepted Manuscripts* in the [Information for Authors](#).

Please note that technical editing may introduce minor changes to the text and/or graphics, which may alter content. The journal's standard [Terms & Conditions](#) and the [Ethical guidelines](#) still apply. In no event shall the Royal Society of Chemistry be held responsible for any errors or omissions in this *Accepted Manuscript* or any consequences arising from the use of any information it contains.

A dual thermal and photo-switchable shrinking-swelling supramolecular peptide dendron gel

 Fan Xie,^a Long Qin^a and Minghua Liu^{*ab}

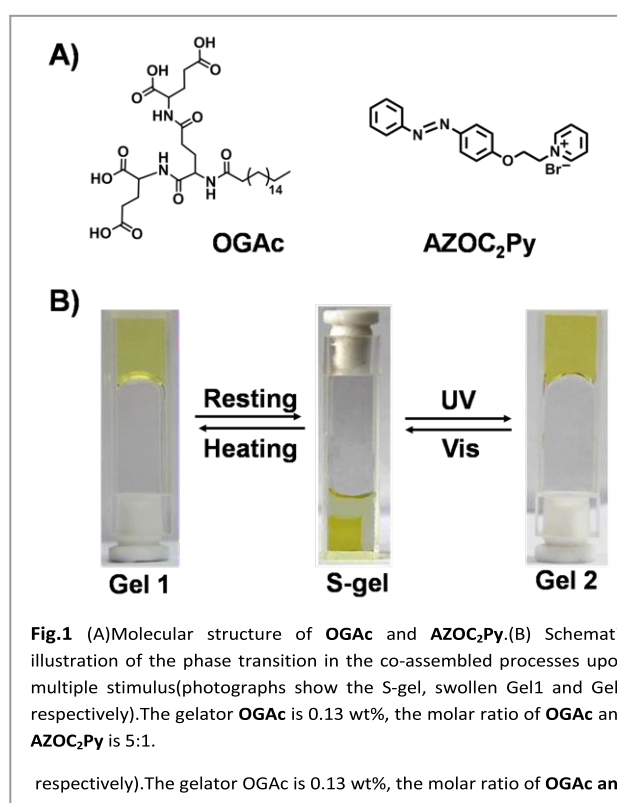
 Received 00th January 20xx,
 Accepted 00th January 20xx

DOI: 10.1039/x0xx00000x

www.rsc.org/

A supramolecular dendron gel was fabricated through the co-assembly of an L-glutamic acid terminated amphiphilic dendron and a positively charged azobenzene derivative, which showed a dual thermal and photo-switched reversible volume phase transition or shrinking/swelling.

Supramolecular gels, in which small molecules self-assembled into entangled nanostructures and immobilized the solvents, have been attracting continue interest due to their stimuli-responsiveness and many potential applications as smart materials.¹⁻⁵ Various stimuli such as the pH, metal ions, light and sound have been applied to the supramolecular gels and gel-to-sol or sol-to-gel transition were successfully realized. However, stimuli-responsive hydrogels materials with the macroscopic volume phase transition or shrinking/swelling property, which is very necessary in consideration the application in drug release,⁶⁻⁹ biosensing,¹⁰⁻¹¹ controlled microvalves,¹²⁻¹⁴ and self-healing¹⁵⁻¹⁸, has been scarcely realized in supramolecular gels due to the inherent non-covalent bond nature. Some only examples are reported. Hamachi et al.^{8,19} realized a thermal and pH-responsive supramolecular hydrogel by using glycosylated amino acetate as the gelator. We have developed a metal ion triggered peptide dendron gelator.²⁰ However, in all these systems, the triggers of the shrinking and swelling are greatly involved in the gel system. A more important and remote stimulus such as the light to cause the gel shrinkage or swelling have not been successful in supramolecular gel system. Here, combining the shrinkable merit of our dendron hydro-gelator and the photoactive azobenzene, we present a strategy to construct a reversible shrinking and swelling supramolecular gel system triggered by photoirradiation.



The hydrogel system composed of an amphiphilic dendron terminated with three L-glutamic acid groups (OGAC) and a positively charged azobenzene derivative, as shown in Fig. 1. When OGAc and AZOC₂Py were mixed in certain ratios, they formed a transparent hydrogel initially. When such hydrogel was kept at a room temperature of 20 °C, the gel underwent shrinkage to form shrinking gel (S-gel), during which water was expelled. Interestingly, when the S-gel was irradiated with UV light, the S-gel swollen and formed a gel again (Gel 2). The Gel 2 is very stable and will not change upon keeping at room temperature. However, if Gel 2 was subjected to a visible light, then the Gel 2 would change into S-gel again. Such shrinking and swelling between S-gel and Gel 2 can be reversibly switched by the alternative Vis/UV irradiation many times.

^a CAS Key Laboratory of Colloid, Interface and Chemical Thermodynamics, Institute of Chemistry, Chinese Academy of Sciences, Beijing, 100190, People's Republic of China.

^b Collaborative Innovation Centre of Chemical Science and Engineering, Tianjin, P. R. China.

E-mail: liumh@iccas.ac.cn; Tel: +86-10-82615803

†Electronic Supplementary Information (ESI) available: See DOI: 10.1039/x0xx00000x

addition, as the basic property of the gel, S-gel can be thermally changed to Gel 1 upon heating to solution and cooling down to room temperature. Therefore with this system, a dual thermal and photo-switchable shrinking/swelling gel can be realized. So far many researches have been devoted to the volume phase transition in polymer systems. Here, we present the first example of the photo-switchable shrinking/swelling gel in the supramolecular system.

The reversible change of the gel states and the corresponding shrinking/swelling process can be visualized or followed by the spectroscopy. Fig. 2A shows UV-Vis spectral change of different gels in comparison with that of the AZOC₂Py aqueous solution. In solution, the absorption peak of AZOC₂Py appeared at 350nm and 430nm, respectively. In the UV-Vis spectra of the Gel 1, which is as-prepared by cooling the mixed solution of OGAC and AZOC₂Py to room temperature, the peak maximum peak shows at 346 nm, which can be ascribed to the π - π^* of the *trans*-form azobenzene moiety in an aggregated state. Upon resting to form the shrinking gel (S-gel), the peak intensity increased and shifted further to 344 nm due to the expelling of water. When the shrinkage approached to equilibrium after nearly 12 hours, the shrinkage ratio was estimated to be 60% (ESI, Table 1). Upon irradiation of the S-gel by the UV light, the peak 344 nm decreased, while a new peak at 420 nm can be observed, which can be ascribed to the n - π^* transition of *cis*-form azobenzene.²¹ This indicated that upon UV irradiation, azobenzene experiences a *trans* to *cis*-form transformation and Gel 2 was composed mostly of the *cis*-form azobenzene. Upon irradiation with visible light, the Gel 2 changed into the S-gel and the corresponding UV-Vis spectra back to the same one.

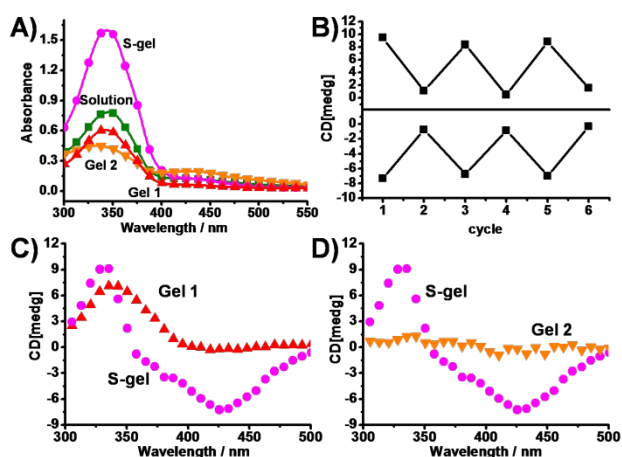


Fig. 2 UV-Vis (A) and CD (C, D) spectra of OGAc co-assembled with AZOC₂Py. Gel1 (Red, regular triangle), S-gel (Pink, circle), Gel 2 (Orange, inverted triangle). (B) CD intensity as a function of irradiation cycle (331nm, Top; 427nm, Bottom); UV light (150 W at 365 nm) and visible light (40 W compact fluorescent lamp, >400 nm).

OGAc gelator is chiral, we have also investigated the CD spectral changes during the shrinkage and swelling of the gel in Fig. 2C and D since CD spectra can provide much information on the molecular packing in the chiral supramolecular system.²² In the CD spectra, a positive CD signal at 337nm was

observed in Gel 1, indicating the molecular chirality of OGAc was transferred to the achiral AZOC₂Py moiety. For the shrunken gel, the strong exciton coupled Cotton effect was observed, which showed crossover at 357 nm, and positive and negative valley at 331nm and 427nm, respectively. When S-gel was subjected to the UV light stimuli, the *trans*-azobenzene transformed into the *cis*-form, the CD signals totally disappeared. This phenomenon is the same as those self-assembled chiral system where azobenzene was involved.²³ This is because *cis*-form of azobenzene is difficult to be packed well and the molecular chirality localized in the carbon atom could not be transferred to the whole system. Upon the visible light irradiation with Gel 2, the CD signals can reappear again, as shown in Fig. 2D. Such process can be repeated many times and the CD signals changed subsequently. Fig. 2B shows a plot of the intensity change of the CD signal for the co-assembly as a function of the exposure cycles. In one direction, the shrunken hydrogel was regulated by heating/cooling to obtain the swollen Gel 1 with the transition from exciton-split to positive CD signal. In another direction, the shrunken hydrogel could transform to swollen Gel 2 with the CD-silent signal. Thus, compared to those chiroptical switch manifesting reversible supra-molecular chirality between gel and sol,^{24, 25} a dual thermo- and photo-driven chiroptical switch was realized displaying reversible chirality change based on *trans*-*cis* isomerization of azobenzene and the assembling to disassembling process in the gel.

In order to further clarify the assembling structure and the packing during the shrinking/swollen process, AFM and TEM of the corresponding xerogels were investigated, as shown in Fig. 3 and Fig. S1.

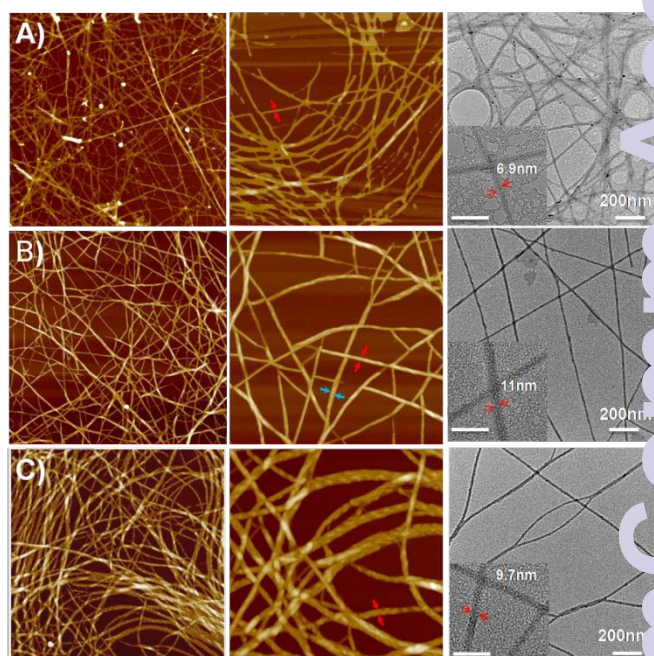


Fig. 3 AFM (left) and TEM (right) images of OGAc co-assembled with AZOC₂Py. (A) Gel 1, (B) S-gel, (C) Gel 2. The AFM images were 5 μ m \times 5 μ m and middle column images were 2 μ m \times 2 μ m (arrows with different colour represented different diameters). All the TEM images are 200nm \times 200nm and the inset images showed amplified structures in which the arrows indicated the diameters of nanofibers.

Long nanofibers were observed for the as-prepared gel. After shrunk, the fiber become thicker and straight (Fig. 3B). For the swelling Gel2, many helical structures are observed (Fig. 3C), which seemed to be due to the helical entanglement of the nanofiber. Such changes in the chiral structures reflected the slight different packing of the molecules in the gels.²⁶ AFM analysis indicated that these nanofibers fell in the range of several nanometers. TEM measurements, further confirmed the thickness of the nanofiber or nanohelix, which fell in the range of 6.9 -11 nm, in correspondence with the AFM measurements.

The X-ray diffraction of three xerogels were further investigated, as shown in Fig. S4. One diffraction peak were observed in all these xerogels, indicating the less ordered packing of the gelator molecules. The two theta values were observed at 2.08, 2.28 and 2.08, respectively. According to Braggs equation, the d-spacings were estimated to be 4.2, 3.9, 4.2 nm for the as-prepared, S-gel and Gel 2, respectively. Previously, we have reported that OGAc itself could self-assembly into a bilayer structure with a layer distance of 3.9 nm. From the similarity of the two systems, it can be suggested that a bilayer structure was essentially kept in the present gel. However, upon adding AZOC₂Py, both alkyl chain and the packing of the azobenzene seemed to be more tilted.

We have further investigated the FT-IR spectra of the xerogels, as shown in Fig. S5. It was found that upon shrinking, both the vibration bands assigned to COO⁻ at 1600 cm⁻¹ became more obvious, indicating the electrostatic interaction between AZOC₂Py and OGAc.

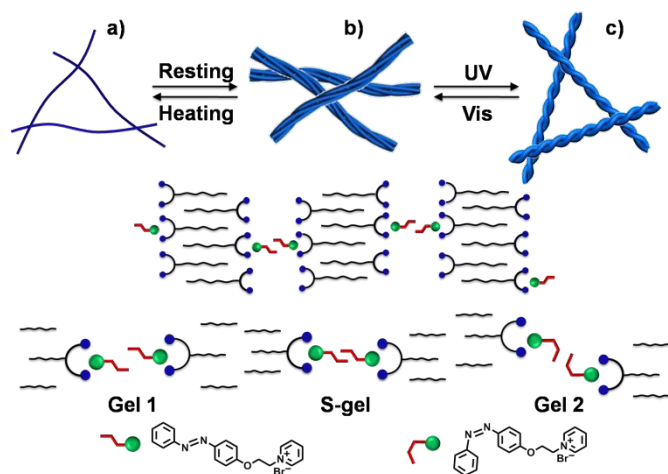


Fig. 4 Illustration of the hierarchical co-assembly of an amphiphilic dendron (OGAc) with azobenzene derivative (AZOC₂Py). Top: (a) Thin fibrils formed in fresh hydrogel. (b) thick fibrous bundles via strong π - π stacking upon shrinking of gel 1. (c) Helices obtained in swollen hydrogel after UV-photoirradiation. Bottom: the packing of the azobenzene and OGAc. OGAc formed a bilayer structure, in which azobenzene moiety was embedded. In the as-prepared gel, azobenzene moiety was separately existed due to less ratio (AZOC₂Py/OGAc, 1:5). During the gel shrinkage, the π - π stacking of the trans-azobenzene increased and the neighboring fiber assembled together. Upon trans-cis isomerization by UV light, the layer distance was slightly expanded. However, the whole gel structure was kept due to strong interaction between the OGAc gelators, thus causing the swollen of the gel rather than collapse.

Based on the above results, a possible mechanism for the gel shrinking and swelling can be proposed, as shown in Fig. 4. The amphiphilic gelator OGAc formed basically interdigitated bilayer units and the AZOC₂Py was attached at the headgroup of OGAc. Due to the additional AZOC₂Py in the headgroup the bilayer did not roll into the nanotube. Instead, they formed the nanofiber structures, which is from a multi-bilayer structure composed of OGAc/AZOC₂Py, as confirmed from AFM and TEM. For the as-prepared Gel 1, the AZOC₂Py distributed separately on the surface of each bilayer through the electrostatic interactions, as confirmed by the CD spectrum of Gel 1, in which only a positive CD signal was observed. Since the azobenzene moiety is hydrophobic and has a strong π - π stacking tendency, it aggregated when the Gel 1 is kept at room temperature. As a result, water molecules were expelled from the fiber and the gel shrunk. This can be verified from two points. An evidence is from the CD spectrum of the S-gel, in which a strong exciton couplet was observed due to the π - π stacking of the azobenzene moiety. The other evidence is the change of the layer distance, which was diminished upon shrinking. In addition, the slightly shift of the absorption maximum confirmed the aggregation of the azobenzene. All these suggested that the azobenzene moiety was aggregated during the gel shrinkage. Upon photoirradiation of the S-gel, there experienced a trans-cis isomerization for azobenzene. This process cause the volume change of the azobenzene moiety and the surrounding water was taken into the bilayer again and the S-gel swollen into Gel 2. If a visible light was applied to the Gel 2, the gel shrunk again due to the isomerization of azobenzene. Since the AZOC₂Py was attached to the headgroup of OGAc, during such change, the basic bilayer structures were not destroyed and the neighboring fibers were connected. Different from most of the gels containing azobenzene moiety,²³ the present gel showed swollen rather than collapse due to the strong interaction between the OGAc molecules. Thus, we obtained unambiguously a reversible shrinking/swelling supramolecular gel using alternative UV/Vis photo-irradiation.

It should be noted that Gel2 is different from Gel 1. Gels did not show any CD spectrum and the azobenzene moiety is in a cis form, while Gel 1 showed CD spectra and the azobenzene moiety is in a trans form. Only in a trans form the chirality of the molecules can be transferred to the whole nanostructure. Moreover, there is a reversible change between Gel 1 and S-gel upon thermal treatment since Gel 1 was formed by cooling the solution to room temperature.

Conclusions

We demonstrated a reversible shrinking / swelling behavior in the supramolecular gel upon photoirradiation and thermal switch. The gel was composed of an amphiphilic dendron and a positively charged azobenzene derivative. It was confirmed that the amphiphilic gelator and the azobenzene moiety formed a multi-bilayer structure through the electrostatic interaction. Upon resting of the as-prepared gel at room

temperature, the azobenzene moiety experienced a aggregation, which caused the shrinkage of the gel. Upon photoirradiation of the shrinking gel, a trans-cis isomerization occurred, which lead to the swollen of the shrunken gel. Such process can be repeated. As a result, using the combination of OGAC and azobenzene derivative, we obtained a dual thermal and photo-switchable shrinking-swelling supramolecular peptide dendron gel. The work provided a new strategy to develop photo switchable smart soft materials with volume phase transition.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (Nos 21473219, 91427302, and 2132106).

Notes and references

#Footnotes relating to the main text should appear here. These might include comments relevant to but not central to the matter under discussion, limited experimental and spectral data, and crystallographic data.

- 1 C. H. Ren, J.W. Zhang, M.S. Chen, and Z.M. Yang, *Chem. Soc. Rev.*, 2014, **43**, 7257-7266;
- 2 S. Dattaa, S. Bhattacharya, *Chem. Soc. Rev.*, 2015, **44**, 5596–5637;
- 3 L. Zhang, X.F. Wang, T.Y. Wang, and M.H. Liu, *Small*, 2015, **11**, 1025–1038;
- 4 P.F. Duan, H. Cao, L. Zhang, and M.H. Liu, *Soft Matter*, 2014, **10**, 5428–5448;
- 5 N. Kameta, M. Masudaa, and T. Shimizu, *Chem. Commun.*, 2015, **51**, 1104-11107;
- 6 J. Nanda, A. Biswas, A. Banerjee, *Soft Matter*, 2013, **9**, 4198–4208;
- 7 J.L. Shen, G.Y. Xu, X. Xin, L.W. Z.H. Song, H. Zhang, L. Tong, Z.W. Yang, *RSC Adv.*, 2015, **5**, 40173–40182;
- 8 H. Komatsu, S. Matsumoto, S. Tamaru, K. Kaneko, M. Ikeda, I. Hamachi, *J. Am. Chem. Soc.*, 2009, **131**, 5580–5585;
- 9 Y.F. Jiao, Y.F. Sun, B.S. Chang, D.R. Lu, W.L. Yang, *Chem. Eur. J.*, 2013, **19**, 15410-15420;
- 10 N. Kameta, M. Masudaa, and T. Shimizu, *Chem. Commun.*, 2015, **51**, 6816–6819;
- 11 M.M. Zhou, J.D. Xie, S.T. Yan, X.M. Jiang, T. Ye, W.T. Wu, *Macromolecules*, 2014, **47**, 6055–6066
- 12 E. Lee, H.J. Lee, S.II Yoo, J.W. Yoon, *ACS Appl. Mater. Interfaces*, 2014, **6**, 16949–16955;
- 13 C.H. Zhu, Y. Lu, J. Peng, J.F. Chen, S.H. Yu, *Adv. Funct. Mater.*, 2012, **22**, 4017–4022;
- 14 Y. Shiraki, K. Tsuruta, J.P. Morimoto, C. Ohba, A. Kawamura, R. Yoshida, R. Kawano, T. Uragami and T. Miyata, *Macromol. Rapid Commun.*, 2015, **36**, 515–519;
- 15 M. Nakahata, Y. Takashima, H. Yamaguchi and A. Harada, *Nat. Commun.*, 2011, **2**, 1-6;
- 16 T. Nakamura, Y. Takashima, A. Hashidzume, H. Yamaguchi and A. Harada, *Nat. Commun.*, 2014, **5**, 1-9;
- 17 S. Bhattacharjee, and S. Bhattacharya, *J. Mater. Chem. A*, 2014, **2**, 17889–17898;
- 18 M.T. He, J.B. Li, S. Tan, R.Z. Wang and Y. Zhang, *J. Am. Chem. Soc.*, 2013, **135**, 18718–18721;
- 19 S.L. Zhou, S. Matsumoto, H.D. Tian, H. Yamane, A. Ojida, S. Kiyonaka, I. Hamachi, *Chem. Eur. J.*, 2005, **11**, 1130 – 1136;
- 20 L. Qin, P.F. Duan, F. Xie, L. Zhang, M.H. Liu, *Chem. Commun.*, 2013, **49**, 10823–10825;
- 21 E. Lüddecke, H. Rau, *J. Am. Chem. Soc.*, 1982, **104**, 1616-1620;
- 22 M.H. Liu, L. Zhang and T.Y. Wang, *Chem. Rev.*, 2015, **115**, 7302-7397;
- 23 P.F. Duan, Y.G. Li, L.C.Li, J.G. Deng, and M.H. Liu, *J. Phys. Chem. B*, 2011, **115**, 3322–3329;
- 24 M. Mukai, M. Kogiso, M. Aoyagi, M. Asakawa, T. Shimizu, and H. Minamikawa, *Ploymer. J.*, 2012, **44**, 646-650;
- 25 J. Zheng, W.Q. Qiao, J.P. Gao, Z.Y. Wang and X.H. Wan, *Chem. Mater.*, 2008, **20**, 6163–6168;
- 26 A. Brizard, C. Aimé, T. Labrot, J. Huc, D. Berthier, F. Artzner, B. Desbat and R. Oda, *J. Am. Chem. Soc.*, 2007, **129**, 3754–3762;