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## COMMUNICATION

## Construction of supramolecular organogels and hydrogels from crown ether based unsymmetric bolaamphiphiles

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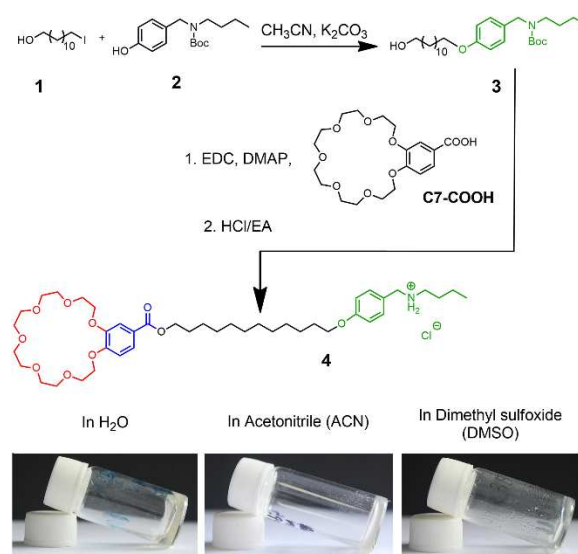
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**A bolaamphiphilic low molecular weight gelator based on crown ether, which could self-assemble into organogel and hydrogel, was prepared. The contribution of each part on the structure to the gelation property was investigated by designing a series of analogues. A simple framework (crown ether–hydrophobic linkage–ammonium salt) was proposed.**

Gels have been widely used in the preparation of cosmetics (like hyaluronic acid), contact lens, foodstuffs, and so on.<sup>1</sup> In the view of the development of gels, there are three types of gel systems distinguished by different kind of network-forming gelator: made of polymer gelator, prepared by low-molecular-weight gelator (LMWG), and self-assembled from polymer and surfactant or some other LMWG.<sup>2</sup> On the basis of supramolecular chemistry, organogels and hydrogels are usually constructed from LMWGs *via* reversible non-covalent interactions, such as hydrogen bonding,  $\pi$ - $\pi$  interactions, van der Waals forces, metal–ligand coordination, hydrophobic effects, *etc.*<sup>3</sup> Owing to inherent reversible nature of the non-covalent interactions, these supramolecular gels can respond to numerous external stimuli, like temperature, pH, light and redox, which have been gradually utilized as stimuli-responsive materials in frontier fields, such as drug delivery systems, tissue engineering systems, shape memory materials, *etc.*<sup>4</sup> Although a lot of low-molecular-weight organogelators and hydrogelators have been reported to date, examples of LMWGs which can exhibited as both organogelators and hydrogelators are still rare due to their different behaviors in organic solvents and water.<sup>5</sup> The gelation process of organogels involves the self-assembly of LMWGs to give polymer-like fibers and form a three-dimensional network, which lead to the immobilization of the organic solvent and finally formation of the gel. In the formation of hydrogels, the LMWGs are rendered insoluble due to the presence of chemical or physical crosslinks, which can be entanglements or crystallites to provide three-dimensional water-swollen network structures.<sup>2</sup> In consideration of the attracting and extensive applications of organogels and hydrogels, it is important and challenging to design a LMWG which can gelate both in organic medium and aqueous solution, which may pave a way in the simple construction of multifunctional adaptive materials in different mediums.

Crown ether is a kind of well-known supramolecular macrocyclic molecule and an important host molecule, which has been widely studied along with the development of supramolecular chemistry. Complexation of crown ethers with organic salts and other species possesses good selectivity, high efficiency and convenient responsiveness and crown ether-based host–guest recognition is capable of constructing different precise superstructures, like (pseudo)rotaxanes,<sup>6</sup> catenanes,<sup>7</sup> daisy chains,<sup>8</sup> and supramolecular polymers.<sup>9</sup> We relentless search for crown ether-based material and believe it will be a promising candidate for future application. Thus crown ether based gels will utilize the virtues of crown ethers and the gel matrix, which will expand the applications of gels in more fields, since supramolecular gels formed from crown ethers are countable to date. Herein, we report a series of crown ether appended unsymmetric bolaamphiphilic low-molecular-weight gelators, which can form gels both in organic medium and aqueous solutions, as organogelators and hydrogelators simultaneously.



**Scheme 1** Synthesis of monomer **4** and gels (organogels and hydrogel in different solvents) self-assembled from **4**.

We accidentally find the first crown ether appended unsymmetric bolaamphiphile **4** that can gelate in both organic medium and water. The synthetic route to the desired monomer **4** is quite straightforward (Scheme 1). Briefly, the acid derivative of the crown ether, **C7-COOH**, was coupled with *Boc*-protected derivatives **3**. After de-protection, the desired target compound **4** was obtained, which was confirmed by NMR and mass spectrometry. After a series of NMR tests, we found monomer **4** could gelate its acetonitrile solution, which was confirmed by stable-to-inversion method. Furthermore, rheological experiment was carried out to investigate this gel (Fig. S22, ESI†). The storage moduli ( $G'$ ) were larger than the loss moduli ( $G''$ ) in the experimental range, and the storage moduli  $G'$  are independent of the angular frequency  $\omega$ , thus indicating the formation of gel.<sup>10</sup> We realized it was a low-molecular-weight gelator. More interestingly, we found that monomer **4** could also form gel in dimethyl sulfoxide (DMSO) and hydrogel in water, which was the first hydrogel of this kind of gelators. Besides, simply by heating and cooling, gels prepared from acetonitrile, DMSO and water could realize sol-gel transition. These interesting properties inspired us to get insight into it.

Since molecular self-assembly has been extensively utilized in “bottom up” nanofabrication to obtain smart materials that can perform desired functions, it is of great importance that the constituent molecular blocks should be programmed to self-assemble, achieving the corresponding material properties. Thus, to get a better understanding of how to control the properties of the gels assembled from gelator **4** and lay the foundation for their further applications, it is necessary to probe and evaluate the detailed structure/property relationships of gelator **4**.

To elucidate the respective importance of the constituent molecular blocks, we cut the structure into three fragments and gradually assemble them. First, we aimed to investigate the role of B21C7 in the gelation process. We designed two analogues **5** and **6**. Analogue **5** was lack of the whole crown ether part, while in the analogue structure of **6**, B21C7 was replaced by a simple benzene ring (Fig. 1). Analogue **5** was soluble in acetonitrile, DMSO and water, though its solubility was poorer than that of monomer **4**. However, the solubility of analogue **6** was so poor that it could not dissolve in any of these solvents. By further efforts, we found that both of them could not form gels neither in organic solvents nor in water. As the result, we could see that the crown ether part (B21C7) helped to modify the solubility of the gelator in these solvents and promoted the hierarchical aggregation in the formation of organogels and hydrogel in different mediums.

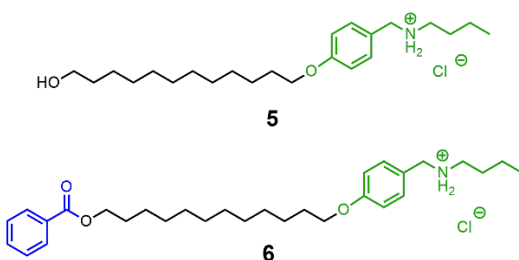


Fig. 1 Chemical structures of analogues **5** and **6**.

After we understood the importance of the crown ether end, we turned to explore the importance of the secondary ammonium salt and its counterion (chloride ion). First, we added base into a water solution of **4** to deprotonate the secondary ammonium. As a result, the neutral monomer precipitated from the solution. However, subsequently addition of acid to the resulting solution, the precipitate could dissolve again into water and the gelation could recur. Thus, we considered that the secondary ammonium salt worked as a

hydrophilic part in the structure to balance the solubility in water. After that, we carried on to study the part of the counterion performed in the gelation process.  $\text{NH}_4\text{PF}_6$  was added to an aqueous solution of monomer **4** to exchange the chloride ion into hexafluorophosphate, and white precipitate formed immediately. Although the precipitate could still be soluble in DMSO and acetonitrile, it could not form organogel. As reported before,<sup>11,8b</sup> when the chloride ion was exchanged to hexafluorophosphate, the secondary ammonium salt could thread into the cavity of B21C7 due to the loose ion-pair between secondary ammonium and hexafluorophosphate. Thus, the threaded structure interrupted the packing of molecules to form gels. Therefore, the intimate ion-pair between the secondary ammonium and chloride ion not only provided the water solubility of monomer **4**, but also preserved the arrangement and aggregation of gelator molecules to form gels.

Until now, we could find that both ends of molecule **4**, the crown ether unit and the secondary ammonium salt moiety, had remarkable influence in the gelation process. In view of the solubility of each unit of molecule **4** in organic medium and water, molecule **4** could be classified as a kind of bolaamphiphile, which contains a hydrophobic skeleton and two water-soluble groups on both ends.<sup>12</sup> As the hydrophobic spacer is an important part of bolaamphiphilic molecules, we changed the spacer of **4** to shorter alkyl chain and more hydrophilic chain to explore its importance, like analogues **7** and **8** (Fig. 2), respectively. The solutions of **7** or **8** kept flowing even at high concentration and could not form gels due to their good solubility. Therefore, the balance between the hydrophilic part and the hydrophobic part could also affect the gelation property of the monomer.

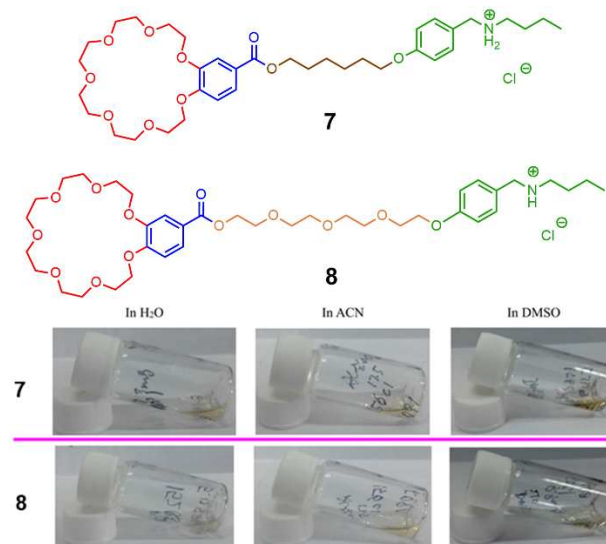
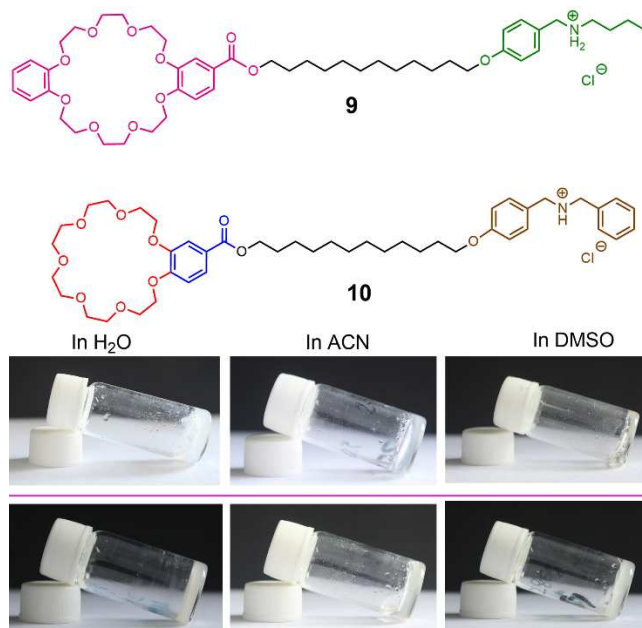


Fig. 2 Chemical structures of analogue **7** and **8** and corresponding solutions of them in different solvents.

As we could see, the long alkyl chain, the crown ether unit and the ammonium part all made contribution to the gelation property of the monomer **4**. The framework of this kind of gelator is clear: crown ether, long hydrophobic spacer and ammonium centre. Based on this framework, we further designed two new monomers (**9** and **10**, Fig. 3) to find out whether it was an efficient way to construct crown-ether-based gelators. Monomers **9** and **10** were composed of different crown ethers and ammonium salts. Monomer **9** carried a bigger crown ether instead, dibenzo-24-crown-8 (DB24C8), while monomer **10** had dibenzyl ammonium salt instead on the other end of the spacer.



**Fig. 3** Chemical structures of analogue **9** and **10** and gels formed from **9** (top) and **10** (bottom) in different solvents.

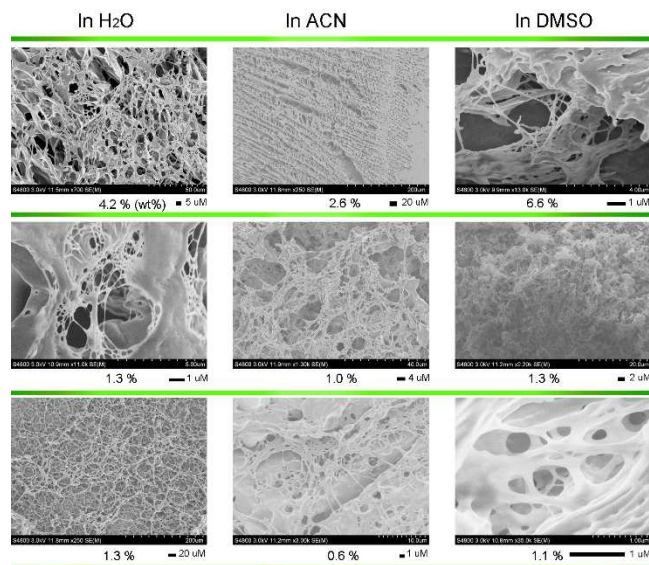
First of all, we dissolved monomer **9** and **10** in water, acetonitrile and DMSO respectively to find out whether they could form gels or not. Lived up to our expectations, both of them could form gels in these solvents. Further, we compared the critical gelation concentrations (CGC) of monomers **4**, **9** and **10** in water, acetonitrile and DMSO (Table 1), respectively. As shown by the CGC results, we could see that the three monomers exhibited quite different performances at room temperature. Monomer **9** and **10** showed lower CGC values than monomer **4** both in organic solvents and water, which means that they possessed better gelation properties. Moreover, in acetonitrile, monomer **10** gave the lowest CGC value, while in water and DMSO, monomer **9** showed the best gelation property. From these results, we considered that the framework discovered above could be used to successfully construct crown-ether-based organogels and hydrogels, and gelators with better properties could be obtained simply by modification of the motifs on the framework.

**Table 1.** Critical gelation concentration values (wt%)

	H <sub>2</sub> O	ACN	DMSO
<b>4</b>	3.3	4.3	3.7
<b>9</b>	0.8	1.2	1.4
<b>10</b>	1.4	0.6	2.0

To further investigate the formation of organogels and hydrogels by monomers **4**, **9** and **10**, xerogels were prepared by freeze-drying the corresponding gels and examined by scanning electron microscopy (SEM). As we could see from these images (Fig. 4), long fibers were formed and they further interconnected and entangled to construct a fibrous gel network. The formation of fibers revealed that these monomers tended to assemble together to fabricate hierarchical aggregates. These fibers further physically cross-linked and entangled to erect a three-dimensional fibrous

network. As the dense matrix gradually shaped, solvent molecules were entrapped, finally leading to the formation of gels both in organic medium and water.



**Fig. 4** SEM images of xerogels prepared from monomer **4** (top), **9** (middle) and **10** (bottom) in different solvents.

## Conclusions

In summary, we reported a bolaamphiphilic low molecular weight gelator **4** which could form gels both in organic medium and water. The contribution of each part on the unsymmetric bolaamphiphile **4** to the gelation property was carefully investigated by designing a series of analogues. By getting further understanding of the building motifs on gelator **4** and simple modification of this structure, two new gelators **9** and **10** with better gelation properties were successfully prepared. This simple framework (crown ether-hydrophobic linkage-ammonium salt) can be proposed as a new stratagem to facilitate the design and construction of new LWMGs, which can gelate in water and organic solvents. Crown ether appended structures can endow this kind of gelators with plenty of stimulus responsiveness for future construction of multifunctional adaptive materials in different mediums.

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## Notes and references

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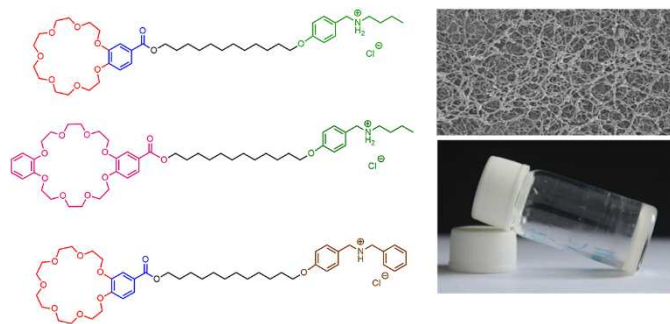
Electronic Supplementary Information (ESI) available: Synthesis, ESI-MS, NMR and other materials. See DOI: 10.1039/c000000x/

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