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ARTICLE TYPE

Key effect on the self-assembly mechanism of dendritic gelators: solubility parameters, generations and terminal effects

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Key effect on the self-assembling mechanism of dendritic gelators is researched by a comprehensive investigation of the gelation behavior of L-lysine dendritic gelators with different structures of three generations in 20 kinds of solvents. Solvents investigation, ^{1}H NMR, tube inversion method, DSC, rheology, FTIR and rheological measurement show that the reported dendritic gelators self-assemble through the main driving force of hydrogen bond and the second driving force of π–π stacking. So the key effect on the self-assembling mechanism is the factors that can influence the driving force of the self-assembling process. That's the reason that L-lysine dendritic gelators tend to gelate in solvents with low α and β parameter values which have less influence on the formation of hydrogen bond between gelators. Higher generation provides a much denser hydrogen bond density in the gelators, which make them have higher gelation ability. And benzyl terminal groups providing the second driving force of π–π stacking makes Bzl-Gly-Lys gelators have much stronger gelation ability. This research reports a comprehensive insight into the precise ways in which solubility parameters of the solvents, generations and terminal effects can influence the self-assembly and gelation of dendritic gelators. Gaining this type of fundamental understanding is essential if the key effect of this important class of self-assembly soft materials to be truly understood.

1. Introduction

Reversible self-assembling processes of supramolecular building blocks, including dendrons and dendrimers, in different solvents through non-covalent interactions to generate varieties of nanometre scale morphologies of gel-phase materials have attracted much interest, due to their importance of understanding the origin of driving force for the unique architectural feature to encourage intriguing new forms of gelation behavior as well as for developing efficient supramolecular gelators.[1-3] Dendritic supramolecules have well defined, three-dimensional branched architectures, and constitute a unique nanoscale toolkit, which achieve such reversible sol–gel phase transition by the means of the non-covalent nature of the interactions including ion–ion, dipole–dipole, hydrogen bonding, π–π stacking, van der Waals, host–guest, and ion coordination, and in so doing trap the solvent molecules in the supramolecular network to form supramolecular gels.[4] However, mechanisms governing the self-assembly of many supramolecular nanostructures, including supramolecular gels, are poorly understood.[5-7] A wide variety of research articles trying to understand the mechanism of self-assembling process from different point of views, majority of which bring up variety of structurally diverse molecules[8] and generations[9,10] to understand how the individual dendritic molecules are assembled into more complex arrays via non-covalent interactions and to explain the influence of gelator structure and generation on self-assembling processes[11-13]; and a few of which put their attempts on gaining a quantitative insight into the precise ways in which solvents influence self-assembly and gelation.[14-17] Even though from the already published results we can see that self-assembling process is influenced by the factors mentioned above, very few studies attempt to gain a much more comprehensive analysis of combining the influence factors including solubility parameters, structures and generations on the self-assembling mechanism, not to mention focusing on the gelators of dendrons that are independent types of supramolecules with individual dendritic branches that having special self-assembling behaviors because of the non-covalent interactions at the focal point and the multiple interaction between the multiple surface groups of dendrons and solvents.

In this paper, the influence of dendritic gelators' structure and generation, and solubility parameters of solvents on self-assembling processes is researched by comparing the gelation behavior of the first, second, third generation gelators **Bzl-Gly-Lys(G1)**, **Bzl-Gly-Lys(G2)** and **Bzl-Gly-Lys(G3)** that contain a focus group of benzyl, a link unit of glycine, a branching of L-lysine unit, and **HO-Gly-Lys(G1)**, **HO-Gly-Lys(G2)** and **HO-Gly-Lys(G3)** gelators that have a focus group of carboxyl obtained via hydrogenation reaction in 20 kinds of different solvents. The results show that the higher generation, the greater the strength of hydrogen bonding formed between the gelator molecules, the better of the thermal stability of the gel, and the higher the mechanical strength. ^{1}H NMR verifies that the main

driving force is the formation of hydrogen bond between gelators. Fluorescence spectra show that benzyl provides π-π stacking force in the self-assembling process of the gel. And the key effect on the self-assembling mechanism is the factors that can influence the driving force of the self-assembling process. That's the reason that L-lysine dendritic gelators tend to gelate in solvents with low α and β parameter values which have less influence on the formation of hydrogen bond between gelators. Higher generation provides a much denser hydrogen bond density in the gelators, which make them have higher gelation ability. And benzyl terminal groups providing the second driving force of π–π stacking that make Bzl-Gly-Lys gelators have much stronger gelation ability. This research attempts to gain a comprehensive insight into the precise ways in which solubility parameters of the solvents, generations and terminal effects of dendrons can influence self-assembly and gelation. Gaining this type of fundamental understanding is essential if the key effect of this important class of self-assembled soft materials to be truly understood.

2. Experiment

2.1 Materials

All the materials required in this reaction are commercial available. Glycine benzyl ester hydrochloride, (S)-2,6-Bis-tert-butoxycarbonylaminohexanoic acid (Boc-Lys(Boc)-OH), N-(3-dimethylaminopropyl)-N′-ethylcarbodiimide hydrochloride (EDCI), 1-hydroxybenzotriazole (HOBt), N-methyl morpholine (NMM), trifluoroacetic acid (TFA), platinum on carbon (10%), L-lysine methyl ester dihydrochloride, N,N,N′,N′-tetramethyl-O-(1H-benzotriazol-1-yl) uronium hexafluorophosphate (HBTU), and pyrene are supplied by Aladdin. Co., Ltd (Shanghai, China), and used as received. All the solvents used in the synthesis are analytical pure and used without further purification. Silica column chromatography is carried out using silica gel (200-300mesh) provided by Qingdao Haiyang Chemical. Co., Ltd (Qingdao, China). Thin layer chromatography is performed on commercially available glass backed silica plates.

2.2 Characterization

The structure of the product is determined by NMR (Bruker Avance III, 500MHz), ESI-TOF MS (Agilent 6210) and MALIDI-TOF MS (Bruker Autoflex III TOF/TOF) in linear mode with α-cyano-4-hydroxycinnamic acid as a matrix.

Rheological measurements are carried out on freshly prepared gels by using a controlled-stress rheometer (MCR302, Anton Paar, Austria). These gels are obtained by a heating-cooling process and sonication irradiation, respectively. Parallel-plate geometry of 25 mm diameter and 1 mm gap is employed throughout the dynamic oscillatory work. The tests are performed as followed: the sample is submitted to this parallel-plate very quickly to minimize solvent evaporation, and then increase the amplitude of oscillation up to certain apparent strain shear (keep a frequency of 1 rad s^{-1}) at 25□.

FESEM measurements are taken on a Hitachi S-4700 field emission scanning electron microscope (FESEM, Hitachi, Japan) for the morphological analysis. The samples are prepared as follows: the gel is formed in a glass vial by a heating-cooling process. And the prepared gels are severally allowed to dry under vacuum to a constant weight. Then the resulting xerogel is respectively coated with a thin layer of gold before investigation.

Fourier transform infrared (FTIR) spectra measurements are carried out on a Nicolet 6700. The gel samples are respectively listed on a surface of glass sheet and the solvent of the samples evaporated spontaneously at room temperature before measurement.

The thermal behaviors of samples are studied by a DSC instrument (Q-100, TA, USA) under dry nitrogen atmosphere. Both of the heating and cooling rates are 10 □/min.

Fluorescence spectrum is recorded using F-4600 fluorescence spectrophotometer (HITACHI Corp., Japan) with exciting wavelength at 335 nm.

Tube inversion method is operated in the following procedure. The gelator sample is mixed with certain solvents in a sealed test tube and the mixture is heated to certain temperature until the solid is completely dissolved. Then the solution is spontaneously cooled to room temperature in air, and finally the test tube is inversed to observe whether the solution inside could still flow. Gelation is considered to occur when a homogeneous "gel-like" material is obtained which exhibits no gravitational flow. The gel-sol transition temperature (T_{gel}) is measured with the ''tube inversion" method, in a water bath which is heated slowly.

Minimal gel concentration (MGC) is the lowest possible gelator concentration needed to form a stable gel in certain solvents at room temperature. It is tested as follows. A certain amount of gelators is put into a sealed test tube and the volume of a certain kinds of solvent is gradually increased until stable gels can not be obtained anymore. At this moment, the concentration of the solvent is recorded as MGC (mg/mL).

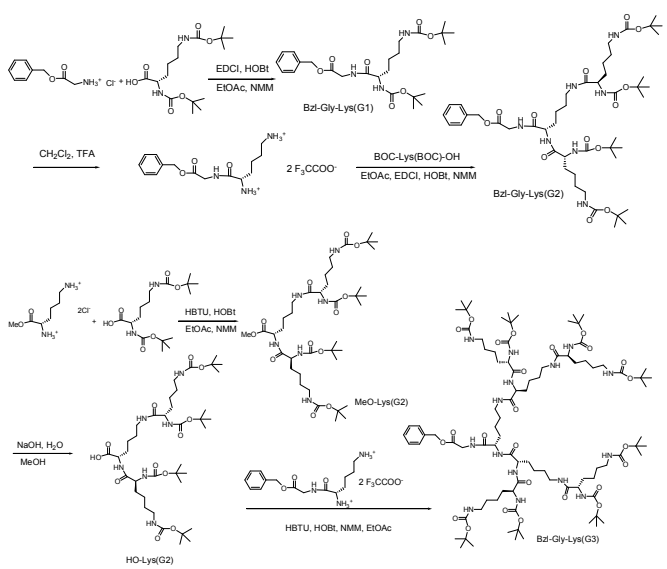
WAXD diffraction patterns of the samples are recorded in an X-ray diffractometer (X'Pert PRO, PANalytical, Holland) with Cu Kα radiation(λ=1.54 Å). It is operated at a voltage of 40 kV and a filament current of 35 mA. The spectra are recorded in the 2θ range of 5-40°, at the scanning rate of 4° /min.

2.3 Synthesis and characterization

Gelators with different genarations are synthesized as shown in scheme 1.

Bzl-Gly-Lys(G1) is synthesized as follows. 5.2 g (15.0 mmol) BOC-Lys(BOC)-OH is dissolved in 50 mL ethyl acetate, then 3.4 g (18.0 mmol) EDCI, 2.4 g (18.0 mmol) HOBt and 3.6 g (36.0 mmol) NMM are added in ice bath. After 30 min, 3.1 g (15.0 mmol) glycine benzyl ester hydrochloride is added. The reaction mixture is allowed to warm to room temperature and stirred at room temperature for 24 h, and then filtered to get yellow filtrate. The filtrate is then treated with $NaHCO_3$ aqueous saturated solution (50 mL×3) and $NaHSO_4$ aqueous saturated solution (8.0 g / 50 mL, 50 mL×3) 3 times, separately. After drying with anhydrous magnesium sulfate, the concentrated filtrate is purified by column chromatography (silica, ethyl acetate: petroleum ether = 3:2) to give a transparent dope with the yield of 5.9 g (80%). R_f =0.35 (ethyl acetate: petroleum ether = 3:2). ^{1}H NMR δH (500 MHz, $CDCl_3$): 7.38 (5H, s, C_6H_5), 5.20 (2H, s, $C_6H_5CH_2$), 4.20 (1H, q, C*H*), 4.16 (2H, d, $COCH_2$), 3.18 (2H, q, CH_2CH_2NH), 1.79 (2H, q, $CHCH_2CH_2$), 1.55 (2H, q, CH_2CH_2NH), 1.38 (18H, s, CH_3), 1.25 (2H, q, $CHCH_2CH_2$); 6.7, 4.6, 4.1 (3H, s, NH); ESI-MS (m/z, $[M+H]^+$): the calculated is 494.3 and the tested result is

also 494.3.



Scheme 1 Synthesis of gelators with different generations

Bzl-Gly-Lys(G2) is synthesized as follows. 1.0 g (4.1 mmol) **Bzl-Gly-Lys(G1)** is dissolved in 5 mL CH_2Cl_2, then 5 mL TFA is added and stirred at room temperature for 60 min for off-protecting BOC group. After the off-protecting reaction is finished, CH_2Cl_2 and TFA are removed by vacuum rotatory evaporator. The raw product is dissolved in 50 mL ethyl acetate after vacuum drying. Then 1.8 g (17.8 mmol) NMM and 3.4 g (9.7 mmol) BOC-Lys(BOC)-OH are added and stirred for 5 min. After that, 1.8 g (9.7 mmol) EDCI and 1.3 g (9.7 mmol) HOBt are added in ice bath and allowed to warm to room temperature and stirred at room temperature for 48 h. After that, the reaction mixture is filtered to get yellow filtrate. The filtrate is then treated with $NaHCO_3$ aqueous saturated solution (50mL×3) and $NaHSO_4$ aqueous saturated solution (8.0 g / 50 mL, 50mL×3). After drying with anhydrous magnesium sulfate, the concentrated filtrate is purified by column chromatography (silica, ethyl acetate) to give a transparent crystal with the yield of 1.2 g (60%). R_f =0.5 (ethyl acetate: petroleum ether= 3: 1). ^{1}H NMR δH (500 MHz, $CDCl_3$):^{1}H NMR δH (500 MHz, $CDCl_3$):7.42, 7.17, 7.06 (3H, br, CON*H*); 5.93, 5.57, 4.96, 4.79 (4H, br, N*H*BOC); 7.33-7.36 (5H, m, Ar*H*), 5.18 (2H, s, Ar-CH_2), 4.33-4.39 (2H, d, COCH_2NH); 4.05-4.12 (3H, m, COC*H*(R)NH); 3.00-3.10 (6H, m, CH_2NHCO); 1.23-1.79 (54H, m, CH_2, CH_3); ESI-MS (m/z, $[M+H]^+$): the calculated is 950.6 and the tested result is 950.6.

MeO-Lys(G2) is synthesized as follows. 3.5 g BOC-Lys(BOC)-OH (10.0 mmol) is dissolved in 10mL ethyl acetate, then 2.4 g (23.0 mmol) NMM, 3.8 g (10.0 mmol) TBTU and 1.5 g (11.0 mmol) HOBt are added and stirred for 5 min. After that, 1.0 g (4.3 mmol) L-lysine methyl ester dihydrochloride is added and the mixture is stirred for 16 h, and then filtered to get yellow filtrate. The filtrate is then treated with $NaHCO_3$ aqueous saturated solution (50 mL×3) and $NaHSO_4$ aqueous saturated solution (8.0 g / 50 mL, 50 mL×3). After drying with anhydrous magnesium sulfate, the concentrated filtrate is purified by column chromatography (silica, DCM: MeOH = 20:1) to give a white crystal with the yield of 6.5 g (80%). R_f =0.62 (DCM: MeOH = 20:1). ^{1}H NMR δH (500 MHz, $CDCl_3$, ppm): 7.42 (brs, 1H; CON*H*), 6.97 (brs, 1H; CON*H*), 5.94 (brs, 1H; N*H*Boc), 5.58 (brs, 1H ; N*H*Boc), 4.90 (brs, 1H; N*H*Boc), 4.75 (brs, 1H; N*H*Boc), 4.40(brm, 1H; OC*H*(R)NH), 4.32 (brm, 1 H; COC*H*(R)NH), 4.11 (brm, 1H; COC*H*(R)NH), 3.73 (s, 3H; CO_2CH_3), 3.12 (m, 6H ; CH_2NH), 1.84-1.31 (m, 54H; CH_2, CH_3). ESI-MS (m/z, $[M+H]^+$): the calculated is 839.5 and the tested result is also 839.5.

HO-Lys(G2) is synthesized as follows. 2.9 g (3.6 mmol) **MeO-Lys(G2)** is dissolved in 10 mL MeOH, then the mixture is added to sodium hydroxide aqueous (1 M, 0.4 g, 10.7 mmol, 3 eq) to react for 24 h in ice bath. MeOH is removed by vacuum rotatory evaporator. PH value of the mixture is adjusted to 3 with $NaHSO_4$ and then extracted with ethyl acetate. Then ethyl acetate is removed by vacuum rotatory evaporator to get white crystal with the yield of 2.8 g (96.5%).^{1}H NMR δH (500 MHz, $CDCl_3$, ppm): 7.42 (brs, 1H; CON*H*), 6.97 (brs, 1H; CON*H*), 5.94 (brs, 1H; N*H*Boc), 5.58 (brs, 1H ; N*H*Boc), 4.90 (brs, 1H; N*H*Boc), 4.75 (brs, 1H; N*H*Boc), 4.40 (brm, 1H; COC*H*(R)NH), 4.32 (brm, 1H; COC*H*(R)NH), 4.11 (brm, 1H; COC*H*(R)NH), 3.73 (s, 3H; CO_2CH_3), 3.12 (m, 6H ; CH_2NH), 1.84–1.31 (m, 54H; CH_2, CH_3). ESI-MS (m/z, $[M+H]^+$): the calculated is 825.5 and the tested result is 825.5.

Bzl-Gly-Lys(G3) is synthesized as follows. 1.0 g (2.0 mmol) **Bzl-Gly-Lys(G1)** is deprotected with BOC and dissolved in 10 mL ethyl acetate. The solvent is modulated to neutral with NMM and named mixture A. 4.6 g (5.7 mmol) **HO-Lys(G2)** is dissolved in 50mL ethyl acetate, then 2.4 g (5.7 mmol) HBTU, 0.9 g (5.7 mmol) HOBt and 1.2 g (11.5 mmol) NMM are added. Then mixture A is added and stirred at room temperature for 24 h, and then filtered to get yellow precipitate. This precipitate is dissolved in MeOH and purified by column chromatography (silica, DCM: MeOH=15:1) to give a transparent crystal with the yield of 3.2 g (85%). R_f=0.4 (DCM: MeOH=15:1). ESI-MS (m/z, $[M+H]^+$): the calculated of $C_{91}H_{160}N_{15}O_{25}$ $[M+H]^+$ is 1864.2 and the tested result is 1864.2.

HO-Gly-Lys(G2) is synthesized as follows. 1.0 g (1.1 mmol) **Bzl-Gly-Lys(G2)** is dissolved in 30mL MeOH, and 0.1 g 10% Pd/C catalyst is added. The pressure of H_2 is kept at 5 Bar for 5 h at room temperature. After the reaction finished, H_2 is removed and the catalyst is removed by filtration. White crystal is obtained by vacuum rotatory evaporator with the yield of 8.7 g (99%). ^{1}H NMR δH (500 MHz, DMSO-d6):12.56 (1H, br, COO*H*); 4.27 (2H, m, COCH_2NH); 3.69-3.87 (3H, COC*H*NH(R)); 8.21 (1H, t, $COCH_2NH$); 7.74 (2H, m, N*H*CO); 6.70-6.90 (4H, m, N*H*BOC); 2.87-2.99 (6H, m, CH_2CH_2NH); 1.09-1.63 (54H, m, CH_2, CH_3). ESI-MS (m/z, $[M+H]^+$): the calculated of $C_{40}H_{73}N_7O_{13}Na$ $[M+Na]^+$ is 1771.1 and the tested result is1770.7.

3 Results and discussion

3.1 Kamlet-Taft model to investigate the influence of solvent on gelation behaviors

The gelation ability of these three kinds of dendritic gelators, **Bzl-Gly-Lys(G1)**, **Bzl-Gly-Lys(G2)** and **Bzl-Gly-Lys(G3)**, is tested in 20 kinds of common organic solvents (Table 1). From the results listed in Table 1 we could say that, these dendritic gelators tended to from transparent gel (marked as TG) in aromatic

solvents and opacity gel (marked as OG) in esters solvents. And clear solutions (marked as S) are inclined to be obtained in alcohols, ketones and chloralkanes. But in alkanes including hexane and cyclohexane, these dendritic gelators could not dissolve.

Table 1 Gelation Behavior of Bzl-Gly-Lys in Different Solvents [a]

Solvent	**Bzl-Gly-Lys (G1)**	**Bzl-Gly-Lys (G2)**(MGC)	**Bzl-Gly-Lys (G3)** (MGC)
Toluene	S	TG (3.0)	TG (1.0)
Dimethyl-benzene	S	TG (3.0)	TG (1.0)
Chlorbenzene	S	TG (5.0)	TG (1.0)
Orthodichloro-enzene(DCB)	S	TG (5.0)	TG (1.5)
Styrene	S	TG (6.0)	TG (3.0)
Ethyl acetate	S	OG (20.0)	OG (3.0)
Butyl acetate	S	OG (10.0)	OG (1.5)
methyl methacrylate(MMA)	S	OG (20.0)	OG (1.5)
Dimethoxy-ethane (DME)	S	S	OG (3.0)
Acetone	S	S	OG (10.0)
Tetrahydrofuran(THF)	S	S	TG (20.0)
Dimethyl Formamide (DMF)	S	S	S
Dimethyl sulfoxide (DMSO)	S	S	S
n-hexane	Ins	Ins	Ins
Cyclohexane	Ins	PG	Ins
Chloroform	S	S	S
Dichloro-methane	S	S	OG (13.0)
Methanol	S	S	S
Ethanol	S	S	S
n-octyl alcohol	S	S	OG (8.0)

[a]Transparent gel (marked as TG), opacity gel (marked as OG), partial gelation (marked as PG) and clear solutions (marked as S). MGC values are with the unit of mg/mL.

Kamlet-Taft model is used to better understand the effect of solvent on gelation. All the Kamlet-Taft parameters are listed in Table 2, in which the value of α parameter represents the hydrogen bond donating ability, the value of β parameter represents the hydrogen bond accepting ability, and the value of π* parameter represents polarity of solvents.[18, 19] That is to say, the higher the value of the α/β/π* parameters, the stronger the hydrogen bond donating ability/ hydrogen bond accepting ability/ polarity of the solvents, separately. From the results in Table 1 and Table 2, we take **Bzl-Gly-Lys(G3)** as an example to discuss the effect of solvent on gelation. **Bzl-Gly-Lys(G3)** could form gels in the solvents with α=0, including aromatic solvents like toluene, dimethylbenzene, chlorobenzene, DCB, styrene and esters and ketones like ethyl acetate, butyl acetate, MMA, DME and acetone. And most of the aromatic solvents have small β parameter values (close to zero), so when gels formed in such solvents, the minimal gel concentration (MGC) is as low as 1 mg/mL (0.1% w/v), which indicating a really strong ability of **Bzl-Gly-Lys(G3)** to obtain gels in such kinds of solvents. In other solvents with a much larger β parameter value (0.4-0.6), accordingly, MGC value is subsequently heightened. The MGC value in ethyl acetate is 3 mg/mL, in acetone is 10 mg/mL and in THF is 20 mg/mL. This indicated that the gelation ability of gelators became weaker with the increase of β parameter values. **Bzl-Gly-Lys(G3)** could not gel in the solvents with β parameter values higher than a certain value (>0.60 in this case), such as in DMSO and DMF, and transparent solution is obtained as a result even the concentration increases to 20 mg/mL. In the situation that β = 0, **Bzl-Gly-Lys(G3)** could only gel in solvents with low α parameter value and had high MGC value, such as in dichloromethane (α = 0.30) with a MGC value as high as 13 mg/mL. When the solvent changes from dichloromethane (α=0.30) to chloroform (α=0.44), although these two kinds of solvents have similar structures, **Bzl-Gly-Lys(G3)** could not gelate in chloroform, indicating the gelation ability is sensitive to α parameter values of the solvents. However, π* (polarizability parameter values) had no significant influence on the gelation ability of **Bzl-Gly-Lys(G3)**. Whether in high π* value solvents like DCB (π*=0.8), or in medium π* value solvents like toluene (π*=0.54), ethyl acetate (π*=0.55), stable gels could all be obtained. But in the solvents with π*=0, like hexane and cyclohexane, **Bzl-Gly-Lys(G3)** could not dissolve even being heated to the boiling point. That could be explained with the similarity-intermiscibility theory that **Bzl-Gly-Lys(G3)** with polar groups in its structure could not dissolve in nonpolar solvents with π*=0.

Table 2 Kamlet-Taft parameters of Different Solvents[a]

Solvent	α	β	π*
Toluene	0.00	0.11	0.54
Dimethylbenzene	0.00	N/A	0.43
Chlorbenzene	0.00	0.07	0.71
DCB	0.00	0.03	0.80
Styrene	0.00	N/A	N/A
Ethyl acetate	0.00	0.45	0.55
Butyl acetate	0.00	N/A	0.46
MMA	0.00	N/A	N/A
DME	0.00	0.41	0.53
Acetone	0.08	0.48	0.71
THF	0.00	0.53	0.58
DMF	0.00	0.69	0.88
DMSO	0.00	0.76	1.00
n-hexane	0.00	0.00	-0.08
Cyclohexane	0.00	0.00	0.00
Chloroform	0.44	0.00	0.69
Dichloromethane	0.30	0.00	0.73
Methanol	0.93	0.62	0.60
Ethanol	0.83	0.77	0.54
n-octyl alcohol	N/A	N/A	N/A

[a]α parameter represented the ability of hydrogen bond donating ability, β parameter represented the ability of hydrogen bond accepting ability, and π* parameter represented polarizability of solvents. [18, 19]

In a word, hydrogen bond donating ability of the solvents increases with α parameter value and hydrogen bond accepting ability increases with β parameter value.[20] Both of these two abilities of the solvents have a competition with the self-assembly of gelators, and α parameter value has a more significant influence. The research of the relationship between solvents and gelators gives us an opportunity to predict the formation of gelation. For instance, if we have a solvent with α=0, β=0 and π*>0, we could basically deduce that such solvent could be

gelated by similar kinds of gelators with **Bzl-Gly-Lys(G3)**, and the MGC values should be quite low.

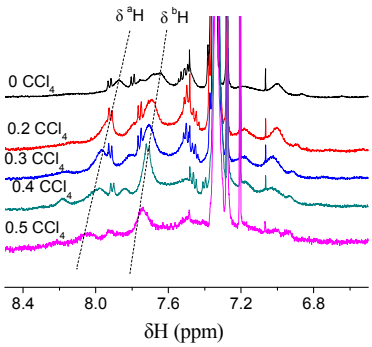


Figure 1 ^{1}H NMR spectra of **Bzl-Gly-Lys(G3)** in $CDCl_3$ and CCl_4 mixtures

3.2 Research of self-assembling process in molecular level by ^{1}H NMR

^{1}H NMR is used to study the influence of solvents in the self-assembling process of gelators in molecular level. Figure 1 is the ^{1}H NMR spectra of **Bzl-Gly-Lys(G3)** in $CDCl_3$ and CCl_4 mixtures.

From Figure1 we could find out that, the chemical shift of H in N-H bond moves to the lower field gradually with the increasing of the volume fraction of CCl_4. Take ^{a}H and ^{b}H for example, when the volume fraction of CCl_4 increases from 0 to 0.5, the chemical shift of ^{a}H moves to the lower field as much as 0.17 and ^{b}H moves 0.10, which indicates that the interaction between gelators increases with the increasing of the volume fraction of CCl_4. The D atoms in $CDCl_3$ molecules had hydrogen bond donating ability which could form hydrogen bond of C=O•••D-C with C=O in the gelators, which could weaken the hydrogen bonds between gelators. When the volume fraction of CCl_4 increases, the above weakening effects diminishes so that N-H band in gelators could contribute more in the formation of hydrogen bonds between gelators. The relationship of the chemical shift of H in N-H bond and the volume fraction of CCl_4 in the mixtures is shown in Figure S1 in supporting information. The result of ^{1}H NMR confirmed that hydrogen bonds are the driving force of the gel formation process for such kind of gelators. Actually, when the volume fraction of CCl_4 increases to 0.5, formation of gels can be observed clearly with naked eyes.

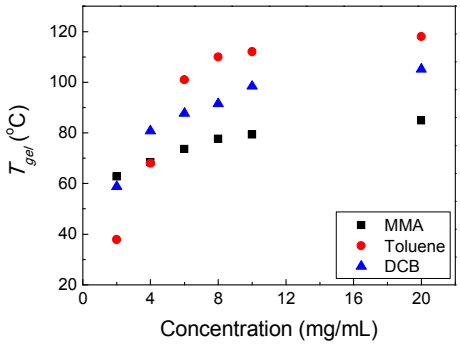


Figure 2 Gelation phase diagram of **Bzl-Gly-Lys(G3)** in MMA, DCB and toluene

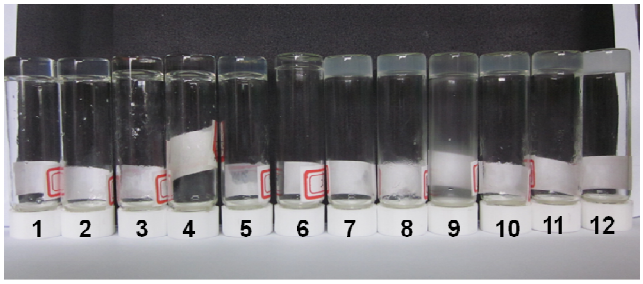


Figure 3 Digital pictures of gels in different solvents: 1-chlorobenzene, 2-DCB, 3-dimethylbenzene, 4-toulene, 5- styrene, 6-THF, 7-acetone, 8-ethyl acetate, 9- n-octyl alcohol, 10-MMA, 11- butyl acetate, 12-DME

3.3 Investigation of thermal stability of gels

Besides the MGC mentioned above, solvents could also influence the thermal stability of gels. Generally speaking, the lower MGC is, the better gels' thermal stability could be, which means T_{gel} of the gels could be higher at the same concentration. We also take **Bzl-Gly-Lys(G3)** as an example, whose gelation phase diagram in MMA, DCB and toluene are shown in Figure 2. The thermal stability of all the three gels increased with the increasing of concentration, but the order of the increasing speed of T_{gel} is toluene > DCB > MMA. When the concentration increased to 20 mg/mL, the T_{gel} in toluene is 118℃, in DCB is 105℃ and in MMA is 85℃. That is because MMA has a kind of hydrogen bond accepting ability, which weakens the hydrogen bond between gelators, so the gel's thermal stability in MMA is the lowest.

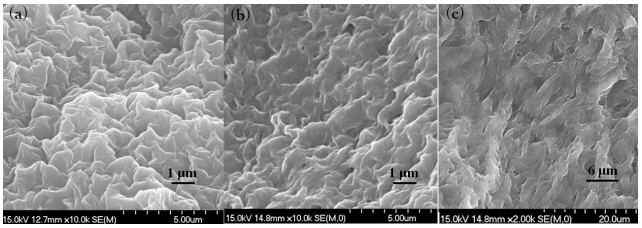


Figure 4 SEM images of **Bzl-Gly-Lys(G3)** xerogel obtained from(a)dimethylbenzene, (b)toluene and (c)MMA with gel concentration of 8 mg/mL

3.4 Morphology of the gel networks

From Figure 3 we can see gels in aromatic solvents has better transparency while in ketones, ethers and esters with different kinds of opacity. Scanning electron microscopy (SEM) is used to further investigate the scale and morphology of the gel networks. Figure 4 showed the SEM images of **Bzl-Gly-Lys(G3)** xerogel obtained from different solvents including dimethylbenzene, toluene and MMA with gel concentration of 8 mg/mL. Although similar morphologies like "fish scale" are found in all the three solvents, we could find that in dimethylbenzene and toluene, a much denser network with the scale of 500 nm ~ 1 μm is obtained to acquire stable gels in macrography, and the scale of the gel network is so small that it could not influence the transparency of the resultant gels, as shown in Figure 3-3 and Figure 3-4. However, the xerogel obtained in MMA solvent is relatively loose with a scale of 3 μm. And that is the reason why the gel

number 10 (in MMA) had reduced transparency compared to gel number 3 (in dimethylbenzene) and gel number 4 (in toluene) in Figure 3. Accordingly, such lower specific surface area reduces surface tension, as a result, **Bzl-Gly-Lys(G3)** has much lower gelation ability and thermal stability of the obtained gel in MMA than in dimethylbenzene and toluene as described above.

3.5 Generation influence on the gelation ability

The gelation ability of L-Lysine based dendritic gelators had a close link with the generation. The higher generation, the greater the strength of hydrogen bonding formed between the gelator molecules. But accordingly, the steric effect in the self-assembling process also increased and the gelation ability depended on the equilibrium of the two. From Table1 we could see that the first generation of L-Lysine based dendritic gelators, **Bzl-Gly-Lys(G1)** could not gelate in the tested solvents even the concentration up to 20 mg/mL. The second generation of **Bzl-Gly-Lys(G2)** could only gelate in aromatic and ester solvents. Besides the above solvents, the third generation of **Bzl-Gly-Lys (G3)** could also gelate in DME, THF, acetone, dichloromethane and n-caprylic alcohol, all of which had certain kinds of hydrogen bond competition abilities. MGC of the third generation is also lower than the second generation. So for such kind of L-Lysine based dendritic gelators, their gelation ability increased with the increasing of generation.

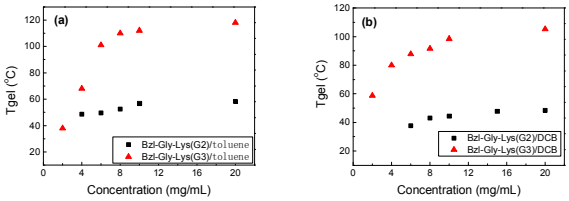


Figure 5 Gelation phase diagram of **Bzl-Gly-Lys(G2)** and **Bzl-Gly-Lys(G3)** in (a)toluene (b) DCB

Above conclusion could also be confirmed by the phase diagram of **Bzl-Gly-Lys(G2)** and **Bzl-Gly-Lys(G3)** in toluene and DCB, as shown in Figure 5. From Figure 5 we could also observe that the changes of T_{gel} of **Bzl-Gly-Lys(G2)** are not obvious with the increasing of concentration, while T_{gel} of **Bzl-Gly-Lys(G3)** had a steep increases at low concentration and always higher than T_{gel} of **Bzl-Gly-Lys(G2)**. When the concentration is 20 mg/mL, T_{gel} of **Bzl-Gly-Lys(G3)** is 60℃ higher than T_{gel} of **Bzl-Gly-Lys(G2)** in toluene, and 57℃ higher in DCB.

The FTIR spectra of the xerogels are shown in Figure 6. To have a clear comparison, **Bzl-Gly-Lys (G1)** is also dissolved in methylbenzene at a concentration of 20 mg/mL without gelation and dried to obtain the sample for FTIR test. The peak of N-H stretching vibration absorption (υ(N-H)) in amide A is red-shifted with the increasing of generation, as shown in Figure 6a, indicating the N-H bond changing from free state to association state gradually. In the mean while, as shown in Figure 6b, the peak of C=O stretching vibration absorption υ(C=O) in amide I is red-shifted and the peak shift of N-H in-plane bending vibration absorption δ(N-H) in amide Π is blue-shifted with the increasing of generation. The results of FTIR experiment show that the intense of hydrogen bond between gelators increases with the increasing of generations.

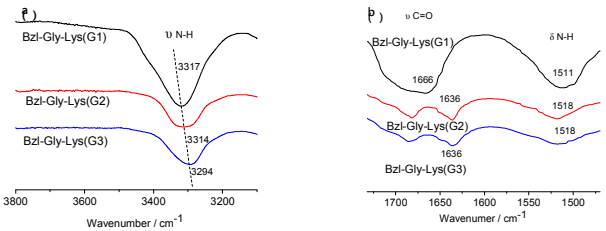


Figure 6 The FTIR spectra of L-Lysine based dendritic xerogels with the concentration of 20 mg/mL. (a) amide A; (b) amide I and amide Π

Rheological measurements are further taken to investigate the mechanical properties of the resultant gels with gelators in different generations. The dynamic frequency sweep between 0.1 and 100 rad/s (as shown in Figure 7) confirms that the gel with higher generation gelators has stronger mechanical properties, in which the gel with **Bzl-Gly-Lys (G3)** has a much higher storage modulus (G'=10000 Pa) than the gel with **Bzl-Gly-Lys (G2)** (G'=3000 Pa). And the G' value of each kind of gels is nearly 10 times higher than the G" value, indicating a kind of "elastic" gel is formed from the addition of **Bzl-Gly-Lys (G2)** or **Bzl-Gly-Lys (G3)** gelators. The elasticity of the gel is further evident from the fact that the G' and G" values are minimally sensitive to frequency, with a slight increase when increasing frequency, which indicated that the gel system formed a stable gel network.

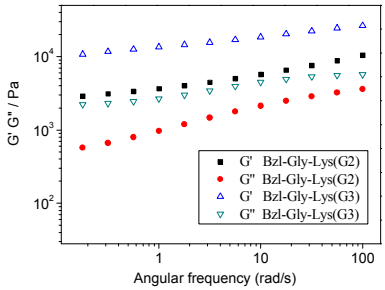


Figure 7. The relationship between the G' and G" value of Bzl-Gly-Lys (G2) or Bzl-Gly-Lys (G3) that is obtained from dynamic frequency sweep between 0.1 and 100 rad/s with 0.1% strain at 25°C (20 mg/mL)

3.6 Terminal effects on the gelation ability

The terminal group had a significant influence on the intermolecular reaction of gelators, so as to affect the self-assembly process. To understand such influence, we de-protect the benzyl group on the terminal through catalytic hydrogenation reaction and get gelators of **HO-Gly-Lys(G1)**, **HO-Gly-Lys(G2)** and **HO-Gly-Lys(G3)**, the scheme is shown in Scheme1. And their gelation abilities are listed in Table 3. Comparing the data in Table 3 and Table 1, we could find when terminal groups changed from benzyl group to carboxyl group, the gelation ability

of gelators decreased clearly. **Bzl-Gly-Lys(G2)**, as an example, could gelate in ester solvents whereas **HO-Gly-Lys(G2)** could not. And **Bzl-Gly-Lys(G3)** could gelate in THF, dichloromethane, n-caprylic alcohol but **HO-Gly-Lys(G3)** could not. That is because carboxyl group could form hydrogen bond with the solvents with certain α and β parameter value which reduced the interaction of gelators. That confirms terminal groups have significant influence on gelation process. In addition, in aromatic solvents with α and β parameter value close to zero, de-protected gelators have a much larger MGC value, which means their gelation ability is reduced. We can deduce that benzyl group on the terminal provided π-π stacking interaction besides protecting of carboxyl group.

Table 3 Gelation Behavior of HO-Gly-Lys in Different Solvents[a]

Solvent	HO-Gly-Lys (G1)	HO-Gly-Lys (G2)	HO-Gly-Lys (G3)
Toluene	S	PG	TG (8.0)
Dimethylbenzene	S	PG	TG (8.0)
Chlorbenzene	S	TG (15)	TG (6.5)
DCB	S	OG (10)	TG (6.5)
Styrene	S	OG (20)	TG (8.0)
Ethyl acetate	S	S	OG (8.0)
Butyl acetate	S	PG	OG (20.0)
MMA	S	S	OG (8.0)
DME	S	S	OG (13.5)
Acetone	S	S	OG (20)
THF	S	S	S
DMF	S	S	S
DMSO	S	S	S
n-hexane	Ins	Ins	Ins
Cyclohexane	Ins	Ins	Ins
Chloroform	S	S	S
Dichloromethane	S	S	S
Methanol	S	S	S
Ethanol	S	S	S
n-octyl alcohol	S	S	S

[a]Transparent gel (marked as TG), opacity gel (marked as OG), partial gelation (marked as PG) and clear solutions (marked as S). MGC values are with the unit of mg/mL.

To confirm benzyl group on the terminal truly provided π-π stacking interaction, pyrene is chosen as fluorescence probe to study the relationship between fluorescence emission spectra and the concentration of gelators, which are shown in Figure S2 in the supporting information. As we all know, pyrene tended to get into hydrophobic regions (low polar region) in macromolecular aggregation systems like micelle etc.[21] When being excited by 335 nm light, the fluorescence emission spectra of pyrene is quenched, in which the ratio (I_1 / I_3) of the intensity of first peek (λ_{max} = 374 nm) and third peek (λ_{max} = 394 nm) in Figure S2 is quite sensitive to the microenvironment around pyrene molecules, that is to say, the value of I_1 / I_3 decreased with the decrease of polarity in the microenvironment around pyrene molecules, as shown in Figure 8. From Figure 8 we could find that, when the concentration of **Bzl-Gly-Lys(G3)** increased from 0 to 10 mg/mL, the value of I_1 / I_3 decreased quickly, while the concentration increased from 10 mg/mL to 15 mg/mL, the value of I_1 / I_3 fell slowly. That indicated pyrene entered into a hydrophobic region, and the polarity of this region decreased quickly at first and then slowly with the increasing of gelators' concentration. Considering the data in Table 1, **Bzl-Gly-Lys(G3)** could gelate in dichloromethane with a MGC of 13 mg/mL. When the concentration of **Bzl-Gly-Lys(G3)** is lower than that, gelator formed pre-self-assemblies by hydrophilic hydrogen bond and hydrophobic π-π stacking interaction.

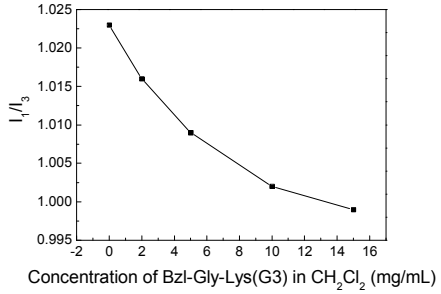


Figure 8 The relationship of the ratio of I_1 / I_3 with the concentration of **Bzl-Gly-Lys(G3)** in Fluorescence probe of pyrene. The solvent is CH_2Cl_2 with pyrene's concentration of × 10^{-6} mol L^{-1}.

In the mean time, the entrance process of pyrene into this pre-self-assemblies will cause a quickly decrease of polarity in the micro-environment. Then with the increasing of the concentration of **Bzl-Gly-Lys(G3)**, only the number and scale of the pre-self-assembly increased while the polar of the microenvironment has no clearly decreases, that is the reason why the value of I_1 / I_3 decreased slowly, which is similar in the report of Suzuki[22]. Fluorescence probe method proves that benzyl group provides π-π stacking interaction during the self-assembling process.

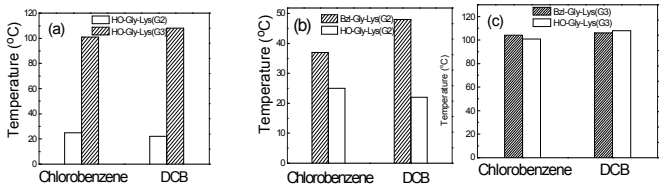


Figure 9 Comparation of the thermal stability of the gels obtained from (a) **HO-Gly-Lys(G2)** and **HO-Gly-Lys(G3)**; (b) **HO-Gly-Lys(G2)** and **Bzl-Gly-Lys(G2)**; and (c) **HO-Gly-Lys(G3)** and **Bzl-Gly-Lys(G3)** in chlorobenzene and DCB (20mg/mL)

The thermal stability of the gels obtained from de-protected gelators still has strong generation dependence. From comparing the thermal stability of the gels obtained from **HO-Gly-Lys(G2)** and **HO-Gly-Lys(G3)** shown in Figure 9a, we can find out the T_{gel} of **HO-Gly-Lys(G3)** gels is 80□ higher than **HO-Gly-Lys(G2)**, indicating that hydrogen bond plays a critical role in the thermal stability of gels. Figure 9b and Figure 9c show the influence of terminal group on the thermal stability of gels from L-Lysine based **Bzl-Gly-Lys(G2)** and **Bzl-Gly-Lys(G3)**, separately. After being de-protected with benzyl group, T_{gel} of **Bzl-Gly-Lys(G2)** gel decreases significantly while T_{gel} of **Bzl-Gly-Lys(G3)** does not. So we could indicate that hydrogen bond is the primary driving force for gelation and π-π stacking

interaction is the auxiliary driving force. For the second generation gelator with low density of hydrogen bond, the missing of auxiliary driving force has a significant influence, but for the third generation with enough hydrogen bond, it has little effect. SEM of **HO-Gly-Lys(G3)** xerogel in Figure S3 in supporting information shows the networks from self-assemble of **HO-Gly-Lys(G3)** also has "fish scale" morphology, with a scale of 2 μm, which indicates that the change of terminal groups does not change the way gelator assembled. That is also confirmed by XRD, as shown in Figure S4 in supporting information.

4. Conclusions

In conclusion, the key effect on the self-assembly mechanism of dendritic gelators is the factor which can influence the driving force of the self-assembling process. In this paper, the result of the investigation of gelation behavior in various organic solvents, Kamlet-Taft model, tube inversion method, ^{1}H NMR, DSC, ATR-FTIR, and rheological measurement certify that the reported dendritic gelators self-assembly with the main driving force of hydrogen bond and the second driving force of π–π stacking. So L-lysine based dendritic gelators tend to gelate solvents with low α and β parameter values which have less influence on the formation of hydrogen bond between gelators, and the lower of the α and β parameter value, the lower MGC of the gelator is, and the higher of the thermal stability of the obtained gels are. Also, the higher generation provides a much denser hydrogen bond density in the gelators, which makes them have higher gelator ability. When the terminal group changes from benzyl to carboxyl which can form hydrogen bonds with solvent molecules, the second driving force of π–π stacking is lacked, and the resultant gelators **HO-Gly-Lys(G1,G2,G3)** have a much weaker gelation ability.

Acknowledgements

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Notes and references

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