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PAPER

Cystine-derived Bis-naphthalimides as Stimuli-Responsive Fluorescent Gelators

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Two cystine-derived bis-napthalimide gelators (**L1**, **L2**) were synthesised and characterised. Both **L1** and **L2** exhibited similar absorptions and emission spectra in solvents such as acetonitrile and DMF. The fluorescence spectra of both compounds featured distinct monomer and long-wavelength excimer emissions in aforementioned solvents. It was found that the excimer emissions for the two compounds could be preferentially quenched by triethylamine, and subsequently restored with hydrofluoric acid. The stimuli-responsive nature of the excimer emissions was demonstrated using anion stimuli in solution and in the gel phase. Thus, the excimer emission for **L1** (or **L2**) could be switched 'off' using fluoride anions, and subsequently re-activated using tetrafluoroborate anions as the chemical stimulus.

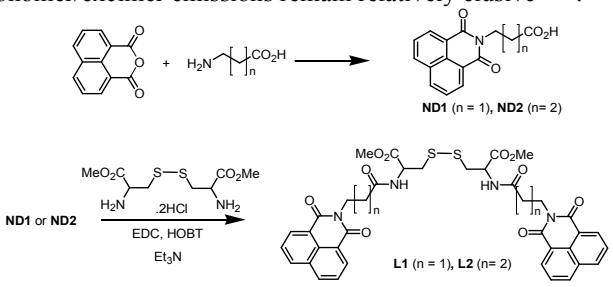
1. Introduction

The versatile luminescent characteristics of naphthalimide derivatives have evoked immense interest, evidenced by the frequent use of this fluorophore in optoelectronic materials[1-4], as ionophoric sensors/probes[5-9] and in stimuli-responsive systems[10,11]. Typically, a stimuli-responsive system should be able to recognize an external stimulus (e.g. physical or chemical input), evaluate the inputs, and then respond through changes in the physical and/or chemical characteristics[2,10,11].

Among the various stimuli-responsive systems identified so far, the importance of low molecular-weight gelators have grown significantly, owing to their potential applications as functional materials[12,13]. Besides being thermo-sensitive, these materials exhibit dynamic self-assembling characteristics that could be triggered by solvent[14], light[15], sound[16], pH[17] and ionic species[18]. An important challenge in this regard has been the development of stimuli-responsive gelators capable of interacting with cations and anions reversibly, with concomitant switching of fluorescence[13,19].

The presence of two naphthalimide motifs in close proximity (*cf.* bis-naphthalimides) can generate monomer and excimer emissions, depending on the solvent, molecular environment and distance separating the fluorophores[20,21]. Apart from these factors, the monomer/excimer emissions of bis-naphthalimide derivatives can also be modulated by coordination of metal ions and self-aggregation[11,19]. For instance, bis-naphthalimide ligands that exhibit unusual enhancement of intramolecular excimer fluorescence upon metal ion coordination[10,12], could be developed as potential sensors for Cu^{2+}, Hg^{2+} and Zn^{2+}.

Because naphthalimide emissions are also environment-sensitive, this fluorophore has been utilised as luminescent turn-on probes for studying ligand-cation interactions[22,23] and in bio-sensing[24-26]. However, compared to metal ions, the interactions of bis-naphthalimides with halide anions, particularly fluoride, and the effect of such interactions on the monomer/excimer emissions remain relatively elusive[27-29].



Scheme 1. Synthesis of bis-naphthalimides **L1** and **L2**.

An important question in this regard was to examine how bis-naphthalimide motif would respond to anionic stimuli (e.g. fluoride anions), in solution and in the gel phase, and whether the interactions could result in perceptible changes in the fluorescent profiles. For this purpose, we synthesized and characterised two L-cystine-based bis-naphthalimides, **L1** and

L2 (Scheme 1) and hence evaluated their fluorescent responses with regard to acid/base and anion stimuli.

2. Experimental

2.1 Materials and methods

All chemicals were commercially available from Sigma-Aldrich or Spectrochem (India) and used as received. Solvents for spectroscopic experiments were distilled under nitrogen atmosphere before use. All ^{1}H and ^{13}C NMR were measured on a 300 MHz Bruker spectrometer, and reported in δ/ppm. The electronic absorption spectra were recorded on a Shimadzu UV-VIS spectrophotometer (Model UV-1800), and Fluorescence spectra were recorded using Hitachi F2500 fluorimeter.

2.2 Synthetic procedures

Synthesis of ND1 and bis-naphthalimide L1:

ND1: Naphthalene-1,8-dicarboanhydride (2.011g, 10mmol) was mixed with β-alanine (1.063g, 10mmol) in a round bottom flask equipped with a magnetic needle. To this mixture, DMF (10mL) was added and allowed to stir at 80°C for about 12 h. The colour of the mixture initially was brown, and after 12 h, a homogeneous red solution was obtained. Subsequently the reaction mixture was concentrated and cooled to 0°C, which produced **ND1** as pale yellow crystals (Yield 69%). ^{1}H NMR (300 MHz, DMSO-d_6/$CDCl_3$) δ_H 8.48 (d, 2H, *J=6.9Hz*), 8.16 (d, 2H, *J=6.9Hz*), 7.67 (t, 2H, *J=7.5Hz*), 4.36 (t, 2H, *J=7.2Hz*), 2.6 (t, 2H); ^{13}C NMR (75 MHz, DMSO-d_6/$CDCl_3$) δ 173.20, 163.81, 133.89, 131.42, 131.07, 127.98, 126.75, 122.35, 35.98, 32.32.

Bis-naphthalimide, **L1**: To a solution of **ND1** (0.540g, 2.0 mmol) in dichloromethane (10mL), N-(3-dimethylamino-propyl)-ethylcarbodiimide hydrochloride (EDC.HCl) (0.400g, 2.1mmol) and 1-hydroxybenzotriazole (HOBT) (0.27g, 2mmol) were added and allowed to stir at 0°C for 30 min. To this mixture, L-cystine methyl ester dihydrochloride (0.341g, 1.0 mmol) and triethylamine (0.7 mL, 5.0 mmol) were added and allowed to stir for 12h. After the reaction was complete, the mixture was concentrated under vacuum, and a viscous material was obtained. Addition of water afforded a pale yellow solid which filtered off, and rinsed with distilled water. The solid product was recrystallised from acetone, and dried in air. Yield 84 %, ^{1}H NMR (300MHz, DMSO-d_6) δ 8.59 (2d, amide NH), 8.39 (4H, m), 7.82 (1H, t, *J=7.2Hz*), 4.55 (1H, bm), 4.22 (2H, s), 3.61(3H, s), 3.336(H2O), 3.050 (3H, s), 2.960(3H, s), 2.933(2H, m), 2.489(2H, s). ^{13}C NMR (75 MHz, DMSO-d_6): 171.79, 171.06, 164.17, 135.12, 132.12, 131.52, 128.22, 128.03, 122.96, 53.07, 52.14, 37.21, 34.14; FT-IR (cm^{-1}): 3448 (amide NH), 3304, 1743 (ester C=O), 1701, 1649 (amide C=O), 1587; ES-MS: m/z 793.81, calc. for ($M+Na^+$)

Synthesis of ND2 and bis-naphthalimide L2:

ND2: Naphthalene-1,8-dicarboanhydride (2.981g, 15 mmol) was mixed with 4-aminobutyric acid (1.556g, 15mmol) in a round bottom flask equipped with a magnetic needle. To this mixture, DMF (30 mL) was added and allowed to stir at 80°C for about 12 hours. The colour of the mixture at the time of mixing was brown. After about 12 hours, a homogeneous yellow-brown solution was obtained. The desired product, **ND2** crystallised from the solution on standing in ice bath. The solid compound was filtered, and washed with EtOH-water to afford a yellow solid. Yield 74%; ^{1}H NMR (300MHz, DMSO-d_6/$CDCl_3$) δ 8.3 (d, 2H), 8.0(d, 2H), 7.5-7.4 (t, 2H), 4.0-3.9(t, 2H);^{13}C NMR (75MHz, DMSO-d_6/$CDCl_3$) 174.53, 163.74, 133.75, 131.20, 130.80, 127.69, 126.62, 122.12, 40.51, 40.23, 39.95, 39.67, 39.39, 39.22, 39.11, 38.83, 31.44, 23.15.

Bis-naphthalimide, **L2**: As described for **L1**. The recrystallised product was obtained as a pale yellow solid. Yield 75%.^{1}H NMR (300MHz, $CDCl_3$) δ_H 8.54 (4H, d, *J = 7.2 Hz*), 8.15 (4H, d, *J = 7.5 Hz*), 7.71 (4H, t, *J = 7.5 Hz*), 7.06 (2H, amide NH), 4.90 (2H, m, *J = 4.2 Hz*), 4.25 (2H, m, *J = 4.5 Hz*), 3.75 (3H, s), 3.24 (4H, d, *J = 5.1 Hz*), 2.39 (4H, t, *J = 4.8 Hz*), 2.14 (4H, m), 1.65 (residual H2O). ^{13}C NMR (75 MHz, $CDCl_3$): 172.33, 171.0, 164.31, 133.97, 131.43, 131.31, 128.0, 126.89, 122.36, 77.41, 52.69, 51.72, 40.57, 39.50, 33.66, 24.14. FT-IR (cm^{-1}): 3310 (amide NH), 1740 (ester C=O), 1693 (amide C=O), 1657, 1587; ES-MS: m/z 821.85, calc. for ($M+Na^+$)

Gel formation with L1 and L2

In a typical gelation experiment, a known amount of the *bis-naphthalimide* gelator (**L1** or **L2**) and solvent (1.00 mL) were mixed in a screw-capped glass vial and kept at 80°C for 2h during which a solution was produced. Upon cooling the solution room temperature, the gel was formed over a period of time. Moreover, gelation of **L2** in chloroform, acetonitrile, DMF and DMSO could be triggered by ultra-sonic irradiation for 2-3 minutes. The stability of the organogel was tested using "inversion" method.

3. Results and Discussion

3.1 Synthesis and characterisations of L1 and L2

In a typical experiment, **ND1,** was synthesised by condensing naphthalene-1,8-dicarboanhydride (1,8-NDA) and 3-amino-propanoic acid, and then coupled to L-cystine methyl ester using EDC-HOBT coupling strategies (Scheme 1); the desired bis-naphthalimide **L1** (or **L2**) was obtained as a solid, and characterised using $^{1}H/^{13}C$ NMR and mass spectroscopy.

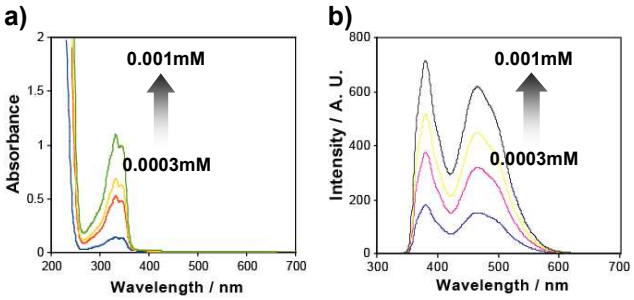


Figure 1. Concentration-dependent (a) UV-visible and (b) Fluorescence spectra of **L1** in MeCN; (c) Possible formation of intramolecular dimers of the bis-naphthalimide motifs[16] (**L1**) depicting the influence of intramolecular N–H···O interactions, and cystine S-S bridges.

The UV-visible absorption spectra of **L1** (Figure 1a) and **L2** were markedly similar, both of which exhibited absorptions at 334nm with shoulder at 346nm. Besides, the fluorescence spectra of the two compounds also displayed similar features.

For instance, when irradiated at 340nm in acetonitrile, bis-naphthalimide **L1** produced two emissions at 381nm and 465nm (Figure 1b) respectively; of these, the emission at 381nm was characteristic of the naphthalimide monomer, while the broad emission at 465nm was attributed to intramolecular dimerisation of naphthalimide motifs[20,30,31].The formation of intramolecular naphthalimide dimers (*i.e.* excimers) could be recognised from the relative intensities of monomer-dimer emissions at 381nm and 465nm respectively, the ratio of which was almost constant ($I_{381/465}$=1.16±0.15) for concentrations up to 0.015mM[30,31]. Similarly, irradiation of **L2** at 340nm in acetonitrile produced two emissions at 382nm and 467nm, corresponding to the naphthalimide monomer and excimer emissions. Notably, the observation of intramolecular excimers for **L1** and **L2** were in accordance with the previous reports of bis-(1,8-naphthalimide) with flexible oligomethylene spacer groups[20,32,33]. The formation of intramolecular naphthalimide dimers (*cf.* **L1** and **L2**) in the ground state was in agreement with the fact that the excitation spectra obtained in both cases were similar[30].

With this perspective, we inferred that excimer emissions for **L1** and **L2** originate from intramolecular dimerisation of the naphthalimide motifs in the ground state. As will be discussed later, the formation of such excimers was possibly favoured by intramolecular hydrogen bonds invoking the amide NH groups, and the hydrophobic interactions between the naphthalimide groups, given the conformational flexibility of the cystine disulfide group. Moreover, it can be pointed out that formation of intramolecular excimers between the two naphthalimide motifs for **L1** and **L2** (> 12 C-C bonds) was comparable to the previous reports for bis-naphthalimides linked by oligoethylene spacers[21,27].

The effects of spacer groups on excimer fluorescence have been illustrated earlier by the development of bis-naphthalimide ligands for cation binding. In a related example, intramolecular excimer emissions (at 470nm) were reported for complexes of $Zn(OTf)_2$ with naphthalimide-imine ligands, wherein excimer switching could be observed depending on the metal/ligand stoichiometry[34]. Again, intramolecular excimer formation was observed following the dimerisation N-benzocrown derived naphthalimides, apparently induced by the coordination of Ba^{2+} cations[11]. Given these spectral features, we were curious to examine the prospect of anion-induced switching of excimer emissions in relation to the monomer emissions of the bis-naphthalimides.

3.2 Effects of acid-base stimuli on L1 and L2

In a related study, we noted that the addition of 3°-amine (i.e. triethylamine) to bis-naphthalimides **L1** (or **L2**) triggered reduction in the emission profiles, particularly the long-wavelength excimer emission. As shown in Figure 2, the addition of triethylamine to **L1** led to substantial quenching of the 465nm emission, compared to the monomer emission at 381nm. This result was understandable since the amino-groups have been known to induce quenching of the long-wavelength emissions via photo-induced electron transfer (PET), as reported earlier for naphthalimide(-spermine) derivatives[30,35].

Following this, we examined the influence of acid on the **L1**/triethylamine mixture, anticipating that protonation of the 3°-amine would block the incipient PET process and hence restore the excimer fluorescence at 465nm. Accordingly, the **L1**/triethylamine solution was titrated using hydrofluoric acid (aq HF, 3.0mM); the emission spectra obtained during the acid titration clearly revealed that the acid stimulus could switch 'on' the excimer emissions at 465nm (Figure 2b). Moreover, using the same amine/acid combination as stimuli, we could induce multiple cycles of reversible quenching and restoration of the 467nm emissions of **L2** in acetonitrile.

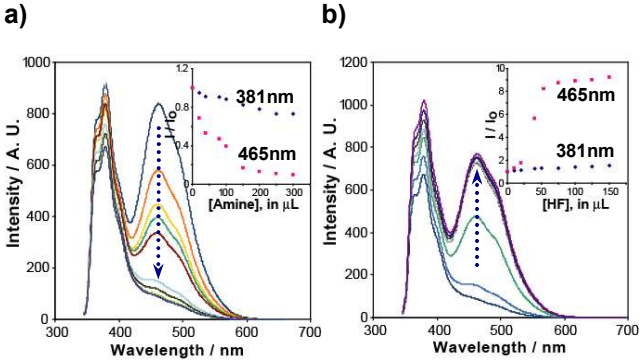


Figure 2. (a) Effect of triethylamine (1.5mM) on the fluorescence emission of **L1** (0.001mM, MeCN), followed by (b) hydrofluoric acid (aq, 3.0mM) to **L1**/triethylamine mixture; (Inset: Plots of I/I_0 vs [triethylamine] and [HF], for the emissions occurring at 381nm and 465nm respectively).

The amine-induced quenching of excimer emissions of **L1** and **L2** could also be observed in solvents such as DMF and DMF-water. This result was in accordance with the suggestion that the fluorescence behaviour of substituted naphthalimides can be influenced by protons, and/or by changes in pH[10,31]. These features were complementary to two-step fluorogenic switches, demonstrated for 2°-amine derived, intramolecularly quenched bis-naphthalimide systems, which could be activated by using protons as inputs[36,37].

3.3 Effects of anions on the fluorescence responses on L1 and L2

Notwithstanding the acid/base or proton-dependent switching of naphthalimide fluorescence in **L1** and **L2**[38,39], we were curious to examine the effects of fluoride (i.e. TBAF) as anion stimuli on the monomer/excimer fluorescence of the bis-naphthalimide derivatives, and hence compare the influence of halide anions including $BF4^-$ anions.

Accordingly, we performed fluorescence titrations of bis-naphthalimide **L1** with fluoride anions (i.e. TBAF) in acetonitrile. As shown in Figure 3a, incremental addition of fluoride (upto 20 equiv) to **L1** caused the emission intensity at 465nm to gradually diminish, whereas the monomer emission at 381nm increased 2-fold[40]. Notably, the changes in

fluorescence at 381nm and 465nm for **L1** with increasing fluoride concentration were such that $I_{381/465}$ increased to 18.3. Although the effects of other halide anions on the excimer fluorescence were minor, we noted distinct fluorescence enhancements for BF_4^- anions. Surprisingly, the addition of BF_4^- anion (~50 equiv) to **L1**/TBAF produced enhancement of both monomer and excimer emissions (as in Figure 3b). This enhancement of excimer fluorescence was unusual because it appeared to override the quenching effects of fluoride anions, due to which the 465nm emission was 'switched-off'. Furthermore, the changes in fluorescence output of **L1** brought about by the addition of fluoride anions, and subsequent addition of BF_4^- anion could be monitored visually under 365nm illumination (Figure 3c).

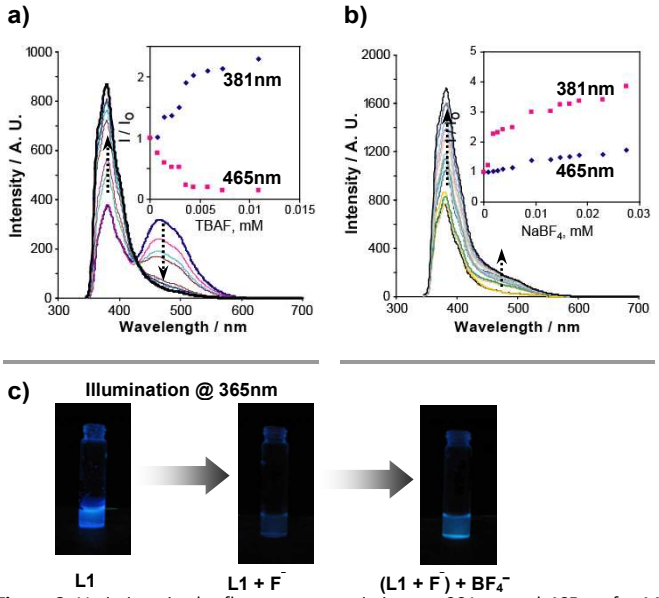


Figure 3. Variations in the fluorescence emissions at 381nm and 465nm for **L1** (0.0005mM; acetonitrile) (a) upon addition of TBAF (Inset shows rel. changes in emissions, I/I_0 vs [TBAF], at 381nm and 465nm); (b) following the addition of BF_4^- anions to **L1**/TBAF mixture (Inset shows the rel. changes in fluorescence, I/I_0 vs [NaBF4], at 381nm and 465nm); (c) Changes in the emissions of **L1** upon successive addition of TBAF, and $NaBF_4$, as viewed under UV-illumination (365nm).

Similarly, we monitored the fluorescence responses of **L2**, in acetonitrile, consequent to the addition of fluoride anions. As shown in Figure 4, the incremental addition of fluoride anion to **L2** was accompanied by gradual disappearance of excimer emission (467nm) while the monomer emission at 382nm increased 1.5 times, with saturation at 25 equiv of the anion. Furthermore, the addition of BF_4^- anions (~55 equiv) to the solution of **L2**/TBAF caused the excimer emission at 467nm to be restored, analogous to **L1**.

The abovementioned results, viz., quenching of excimer emissions of **L1** and **L2** in the presence of fluoride anions, could be analysed as follows: Firstly, interaction of flouride anions with the amide NH groups (of **L1** and **L2**) could disrupt the formation of intramolecular excimers between the naphthalimide motifs[40]. Indeed, quenching of excimer fluorescence in naphthalimides through fluoride-induced disruption of intramolecular hydrogen bonds have been reported earlier[41]. Alternatively, anion-π interactions of the proximal fluoride with the naphthalimide motif could facilitate partial PET process, thereby leading to quenching of excimer fluorescence[30,36].

Secondly, the quenching effects of fluoride anions were rather supressed in polar solvents such as aqueous DMF and in the presence of MeOH. This meant that in protic solvents, such as MeOH or aqueous DMF, the electronegative fluoride anions would preferably be hydrated, than hydrogen bond to the amide NH group of the bis-naphthalimide. In this context, the effects of chloride, bromide and acetate anions on the bis-naphthalimide fluorescence were relatively minor, although acetate anions did produce minor quenching of excimer emissions (Figures S14, S15; ESI) under identical conditions[42].

Also notable was the enhancement of monomer emissions in both cases, **L1** and **L2**, following the addition of fluoride and BF_4^- anions. Again, compared to the highly electronegative fluoride anion, the effects of BF_4^- anions were expected to be

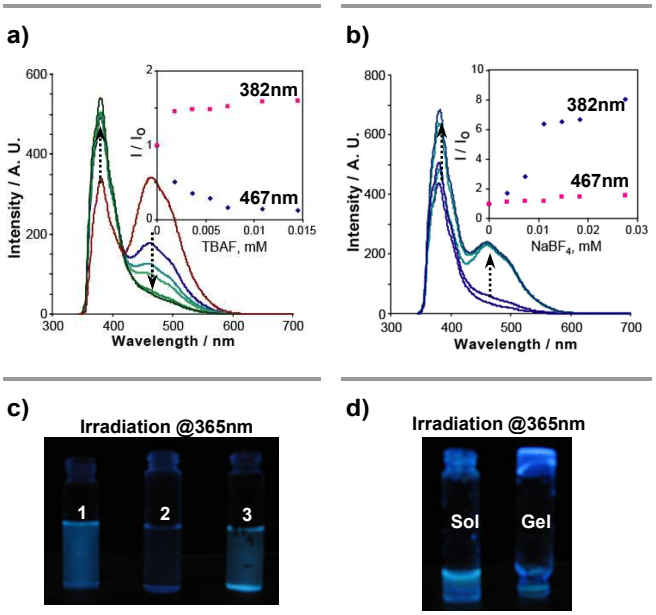


Figure 4. (a) Gradual disappearance of the excimer emission of **L2** (0.0004mM; acetonitrile) at 467nm upon addition of TBAF; (b) Excimer emission at 467nm 'restored' following the addition of BF_4^- anions to the **L2**/TBAF solution; (Inset: rel. changes in emissions, I/I_0 vs [TBAF], and then [$NaBF_4$] monitored at 382nm and 467nm respectively); (c) Fluorescence profiles of **L2** ('**1**') following successive addition of TBAF ('**2**') and $NaBF_4$ ('**3**') in acetonitrile, as observed under UV-illumination (365nm). (d) Fluorescence emission of **L2** in acetonitrile solution and in the gel-state (5mg/mL, acetonitrile), when illuminated with 365nm light.

relatively soft and unlikely to form strong hydrogen bonds. Although the precise nature of interactions of BF_4^- with the bis-naphthalimide was not clear, we inferred that the BF_4^- anion could assist dimerisation of naphthalimide motifs[43] and impede the fluoride-induced PET process. This proposition seemed plausible given the results obtained from FT-IR and ^{1}H NMR investigations of the **L2**/$NaBF_4$ system. The effect of fluoride anion on emissions of **L1** (or **L2**) was also illustrated using NaF; despite low solubility, addition of NaF to the bis-

naphthalimide induced quenching of the excimer emission, albeit minor compared to TBAF. This quenching of the excimer vis-à-vis monomer emissions by NaF could subsequently be reversed upon addition of BF_4^- anions[44].

3.4 Stimuli-responsive fluorescent gels from L1 and L2

Interestingly, both bis-naphthalimides **L1** and **L2** produced fluorescent gel phases in DMSO and DMF[45]; in case of DMSO, the critical gelation concentrations (CGC) were found to be 3mg/mL for **L1** and 5mg/mL for **L2**. Figures 5a and 5b show the scanning electron microscopic (SEM) images of the gels obtained from **L1** and **L2** in DMSO, which indicated formation of fibrous networks involving the gelator molecules. Similar self-assembled entangled networks could be visualised in case of **L2**/DMF gel (Figure 5c,d), and **L2**/acetonitrile gel, which, on close inspection, revealed fibres with dimensions > 2um. The critical gelation concentrations for **L1** and **L2** in DMF were found to be 3g/mL and 6mg/mL respectively. Moreover, **L2** produced thermo-reversible gels in chloroform and acetonitrile that could also be triggered by ultra-sonic treatment[45].

Preliminary insights into the nature of the intermolecular interactions in gel phase vis-a-vis solution could be obtained from fluorescence experiments. For instance, the **L2**/DMF organogel was characterised by emissions at 399nm and 468nm respectively, whereas, the corresponding emissions for **L2** (0.004mM) in dilute DMF solution occurred at 382nm and 460nm (Figure S11, ESI). Such red-shifting of the fluorescence emissions were evident for both **L1** and **L2** in the gel phases, as compared to solution. In particular, the red-shifts observed in the emission spectra for **L2** in the gel state were consistent with weak aromatic-π interactions of the naphthalimide motifs[13,42]. Given that **L1** and **L2** exhibit red-shifted excimer emissions, particularly in the gel state[46], also provided support to the possible intramolecular dimerisation of the pendent naphthalimide groups[47,48].

We proposed that the gelation process involving bis-naphthalimide **L2** (or **L1**) could be driven by multiple supramolecular interactions, viz., intermolecular hydrogen bonding involving the amide and naphthalimide groups and π-π interactions between naphthalimide motifs. While the red-shifting of fluorescence emissions in the gel state did suggest aromatic-π stacking between the naphthalimide motifs, we reasoned that FT-IR and ^{1}H NMR studies could provide valuable insights into the driving forces for gel formation.

In order to examine the effect of hydrogen bonding interactions on the gelation process, we performed FT-IR analysis of **L2** in chloroform/acetonitrile. In dilute solution, the FT-IR spectra of **L2** (0.1mg/mL) indicated a distinct amide NH absorption at 3303cm^{-1}; the absorption at 3303cm^{-1} remained relatively unaffected within the gelator [**L2**]= 1.0mg/mL, and emanated from intramolecular hydrogen bonds involving the amide NH groups. However, at [**L2**]= 2.0mg/mL, a broad absorption appeared at 3470cm^{-1} in chloroform/acetonitrile, that

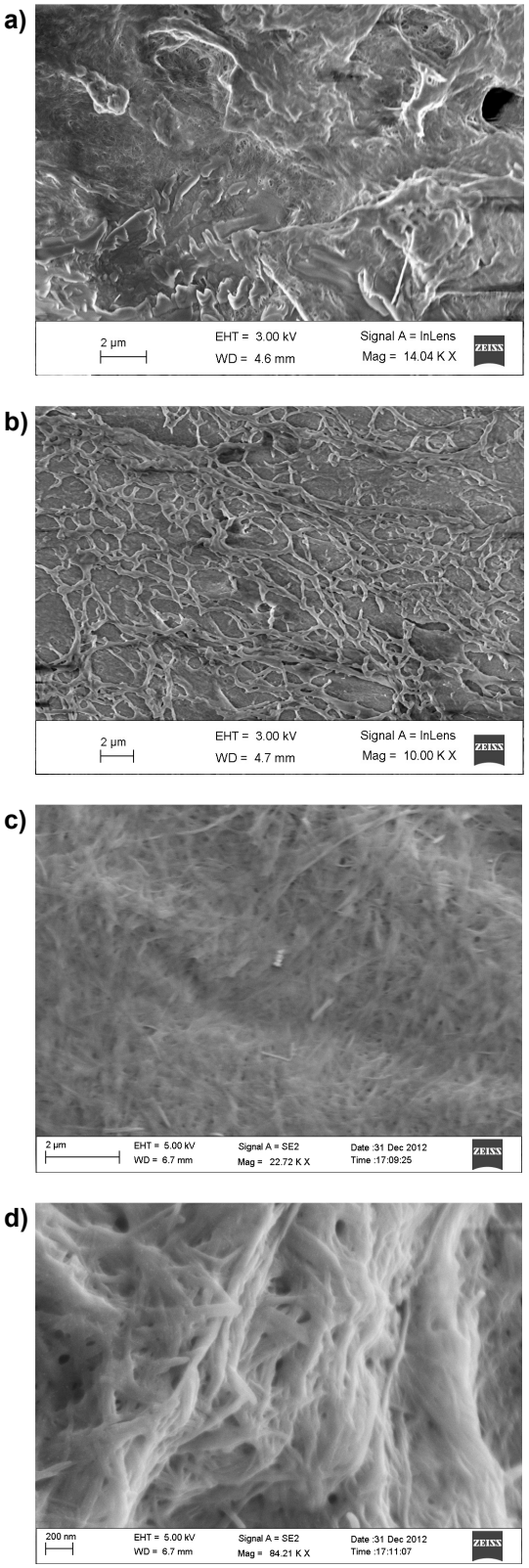


Figure 5. SEM images of the dried organogel obtained from: (a) **L1** in DMSO; (b) **L2** in DMSO; (c), (d) **L2**/DMF gel under different magnifications.

shifted further to 3440cm^{-1} with substantially broadening upon gel formation (Figure S16, ESI), indicating the formation of extensive hydrogen bonded networks.

The crucial role of hydrogen bonding during the gelation process was also investigated using ^{1}H NMR in chloroform-d and acetonitrile-d^3. In this regard, the interactions of fluoride with bis-naphthalimide as described in previous sections could also be substantiated, particularly for **L2** in chloroform-d and acetonitrile-d^3.

As indicated by ^{1}H NMR, increasing the concentrations of **L2** from 0.3mg/mL to 2mg/mL in chloroform-d did not affect either the naphthalimide CH or amide NH resonances significantly (Figure S19, ESI). Given that the hydrogen bonding tendency of chloroform under these conditions was limited, we anticipated intra-molecular hydrogen bonds between the amide NH groups to persist. These features were consistent with the observations made in the FT-IR spectra for **L2** in chloroform. At higher concentration of **L2** (CGC = 5mg/mL, with ultra-sonic irradiation) gel formation was observed, and the naphthalimide CH resonances at 7.72, 8.17, and 8.57ppm shifted slightly upfield (Δδ~0.01ppm), reminescent of weak intra-molecular interactions between the napthalimide motifs. Though the amide NH appeared invariant upto 1.0mg/mL, gelation caused these resonances to shift slightly downfield from 7.07ppm to 7.09ppm, possible indication of extended hydrogen bonding situation. So, a clear correlation could be seen in the behaviour of the amide NH groups, with regard to intra-molecular hydrogen bonding, both from FT-IR and ^{1}H NMR studies. Therefore, we inferred that

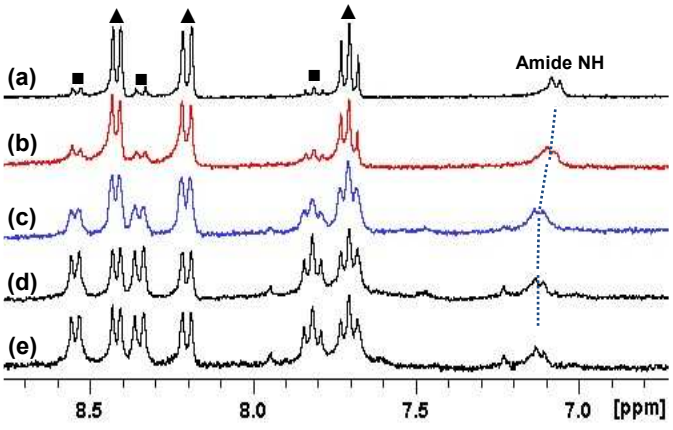


Figure 6. Partial ^{1}H NMR spectra of **L2** (5mg/mL) showing the temperature-dependent variations of the naphthalimide CH and amide NH resonances in acetonitrile-d$_3$: (a) 50°C; (b) 45°C; (c) 35°C; (d) 25°C; (e) 25°C after 12h; (The two sets of naphthalimide CH resonances could be attributed to the inequivalence of the naphthalimide motifs in the solution/sol state, designated as '▲, vis-à-vis the gel phase, indicated as '■'. The increase in temperature could lead to disruption of hydrogen bonds involving the amide NH groups, which accounted for the gradual upfield shifting resonances.

formation of **L2**/chloroform gel was driven be aromatic π-stacking interactions, assisted by hydrogen bonding interactions between the amide NH groups. Further support to the hydrogen bonding situation of amide NH groups could be obtained by gradual addition of TBAF (upto 3 equiv.) to the **L2**/chloroform gel, which caused downfield shift of the amide NH resonance from 7.09 to 7.23 ppm (Figures S20) with partial dissolution of the gel.

Following this, we sought to examine the effect of gelation on the naphthalimide CH and amide NH groups for the **L2**/acetonitrile gel using ^{1}H NMR spectroscopy. Since **L2** caused rapid gelation of acetonitrile, it seemed pertinent to carry out temperature-dependent ^{1}H NMR analysis of the **L2**/acetonitrile-d^3 system.

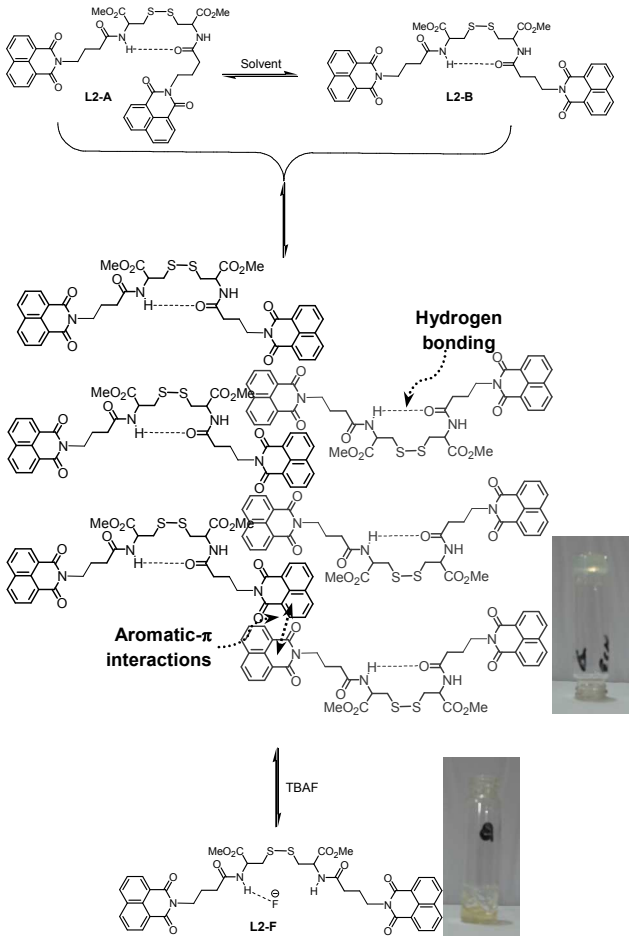
As shown in Figure 6, the solution of **L2** in acetonitrile-d^3 at 50°C produced a distinct set of resonances for the naphthalimide CH protons at 7.70, 8.20 and 8.42ppm along with a minor set of resonances at 7.82, 8.34 and 8.54ppm respectively; the integrated ratios for the major and minor signals were found to be ~9:1. At 50°C, the minor resonances were attributed to **L2** molecules in the incipient gel[47], while the major resonances at 7.70, 8.20 and 8.42ppm, emanated from the solvated **L2** molecules. In other words, the two sets of resonances produced by the naphthalimide CH groups in acetonitrile (*cf.* in chloroform the signals were minor), were reminiscent of the inequivalence of the naphthalimide motifs in the solution/sol state vis-à-vis the gel phase[47].

With lowering of temperature, the set of naphthalimide CH resonances at 7.82, 8.34 and 8.54ppm gradually gained prominence with lowering of temperature. Thus, the intensities of the two sets resonances became almost comparable at 25°C, and concomitantly gelation was initiated. The gradual changes observed in the naphthalimide CH resonances as function of temperature (Figure 6), reflects the importance of aromatic-π interactions during the gelation process. It was noted that gel formation was accompanied by appearance of an additional signal due to the aliphatic CH groups connected to the naphthalimide motif (Figure S21, ESI). However, the effect of gelation on the amide NH resonances of **L2** was minor, with a gradual from 7.07ppm in solution (50°C) to 7.12ppm in the gel phase. With increase in temperature, the amide NH resonance (of **L2**) was shifted upfield; such changes could be explained by the breaking of intermolecular hydrogen bonds associated with the amide NH group, viz. with the solvent and neighbouring gelator molecules.

As illustrated in Scheme 2, the emergence of downfield shifted resonances for naphthalimide CH protons at 7.82, 8.34 and 8.54ppm following gel formation was illuminating because it corroborated the presence of **L2** both as solvated species and in the gel phase. Also noteworthy was the splitting/broadening of the resonance due to the Cys-methyl ester group which could be correlated to the proximal interactions of this residue with the naphthalimide motifs groups during the formation of **L2**/acetonitrile organogel (Figure S21). The temperature-dependent self-assembling process of **L2** in acetonitrile clearly reflected the importance of aromatic-π stacking interactions in the gelation behaviour, which was supplemented by hydrogen bonds between the gelator molecules. Based on the results of the ^{1}H NMR experiments, and given the red-shifted emissions observed for **L2** in the gel phase, it seemed reasonable that the

naphthalimide motifs interacted in head-to-tail manner in the gel phase[13,46].

Moreover, as monitored by ^{1}H NMR, the onset of gelation for **L2**/acetonitrile-d_3 (or chloroform-d) was marked by lower intensity signals, compared to those in solution. This was understandable since formation of the **L2**/acetonitrile gel restricted larger proportion of **L2** gelator molecules to enter the gel structure, thereby reducing the thermal motions of gelator molecules[48].



Scheme 2. (a) Formation of intramolecular hydrogen bonds for **L2** in solvents such as acetonitrile, showing the plausible interaction of the F^- anions (as TBAF) with the bis-naphthalimide; (b) Graphical illustration of the aromatic-π and the plausible hydrogen bonding interactions between the gelator molecules during gel formation, and the fluoride-induced gel-to-sol transformation. (Inset: Photographic images of the **L2**/acetonitrile gel and solution [**L2**] = 5mg/mL).

On the basis of these observations, it was inferred that the self-assembly of gelator molecules of **L2**, in acetonitrile or chloroform was driven aromatic-π stacking between naphthalimide motifs and supplemented by hydrogen bonds involving the amide NH groups (Scheme 2). As mentioned earlier, the FT-IR analysis indicated presence of intramolecular hydrogen bonds in **L2**, which in turn could explain the observations of excimer emission in the fluorescence spectra. This intramolecular nature of the incipient hydrogen bonds was also reflected in the ^{1}H NMR spectra, with the amide NH resonances showing only minor downfield shifts. Considering these aspects, we inferred that hydrogen bonding between the amide NH groups were favored when the gelator molecules adopted bent conformations. Previous studies have shown the importance of intramolecular hydrogen bonding interactions during the formation of self-assembled gels, and how such interactions were favored when the gelator molecules adopted bent conformations[47]. Again, these polar interactions facilitated hydrophobic packing of the naphthalimide groups (Scheme 2), so that the gelator molecules slowly self-assemble into entangled fibrous networks[47]. Infact, the influence of hydrophobic vis-a-vis aromatic-π interactions between the naphthalimide groups and segregation of hydrophilic interactions during the gel formation process was reported recently[46,48].

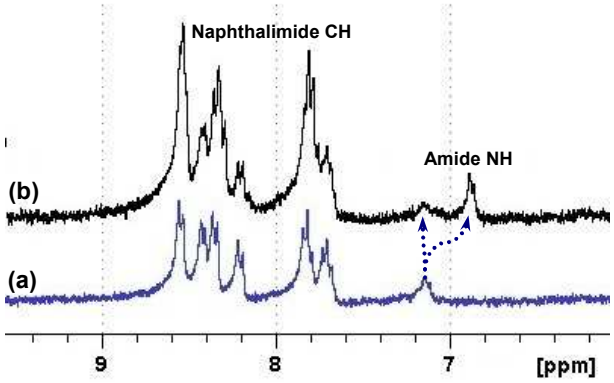


Figure 7. (a) Partial 1H NMR of L2/acetonitrile-d3 gel at room temperature; and (b) disruption of hydrogen bonds involving the amide NH groups, induced by the addition of 1.0 equiv of fluoride anions.

Similar gel-to-sol transformations were noted for the **L2**/acetonitrile gels, upon addition of TBAF, which was also accompanied by quenching of excimer fluorescence. We reasoned that the gel-to-sol transformations emanated from the disruption of the hydrogen bonded network involving the gelator molecules, apparently initiated by the coordination of the fluoride anion to the amide NH groups (Figure 7).

Further support for the effects of TBAF on the gel-to-sol transformation (Scheme 2), and the stimuli-responsive nature of the bis-naphthalimides **L1** and **L2** could be obtained from ^{1}H NMR studies. As evident from the ^{1}H NMR spectra, the addition of TBAF (1.0 equiv.) to **L2**/acetonitrile gel caused shifting of the amide NH resonance from 7.15 to 6.87ppm, along with splitting (Figure 7). Addition of 10 equiv of TBAF was accompanied by gradual dissolution and collapse of the organogel network. This effect of TBAF on the hydrogen bonding network of **L2**/chloroform system could be identified with the disappearance of the absorption at 3304cm^{-1} in the FTIR spectra. Also, the FT-IR spectra of **L2** exhibited distinct features due to intra- and intermolecular hydrogen bonding interactions involving the amide NH in solution and in the gel

phase absorption. The absorption featured at 3303 cm^{-1} in the FT-IR spectra was consistent with intra-molecular hydrogen bonds, and was slightly affected in the gel phase. Accordingly, the ^{1}H NMR spectra of the **L2**/TBAF system in chloroform revealed distinct downfield shifts for the amide NH resonances, which were in accordance with the formation of hydrogen bonded **L2**-anion complex (Figure S20). Subsequent ^{1}H NMR studies of the interactions of $NaBF_4$ with **L2** in acetonitrile-d^3 and in dimethyl sulfoxide-d^6 revealed minor upfield shifts to the naphthalimide CH resonances at 7.77 and 8.32ppm. Such features have often been attributed to anion-π interactions between the BF_4^- anions and the naphthalimide motifs[43].

4. Conclusions

In conclusion, we have synthesised and characterised two cystine-based bis-naphthalimides which form fluorescent gels in acetonitrile, DMF and DMSO. Remarkably, both bis-naphthalimides exhibit fluoride-induced quenching and BF_4^- induced restoration of the excimer emissions, which could be visualized under 365nm UV-illumination. Such 'off/on' switching of excimer emission for the bis-naphthalimides could also be achieved by successive addition of 3°-amine and hydrofluoric acid. ^{1}H NMR studies indicated that the incipient gelation process was driven by hydrophobic and aromatic-π interactions between the naphthalimide motifs, supplemented by hydrogen bonding between the amide NH groups. Addition of fluoride caused disruption of the hydrogen bonds involving the amide NH groups, which led to switching of monomer-excimer fluorescence, and concomitant gel-to-sol transition. Thus, we have illustrated a simple strategy for the design of stimuli-responsive functional materials, wherein the switching of monomer-excimer fluorescence emissions of bis-naphthalimides could be triggered by the introduction anions as chemical stimuli.

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Notes and references

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Electronic Supplementary Information (ESI) available: [Supplementary materials include details of synthesis, characterisation; SEM images for **L1**; ^{1}H NMR studies of **L1** with $NaBF_4$; fluorescence titration plots of **L1** and chloride, bromide and acetate]. See DOI: 10.1039/b000000x/

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