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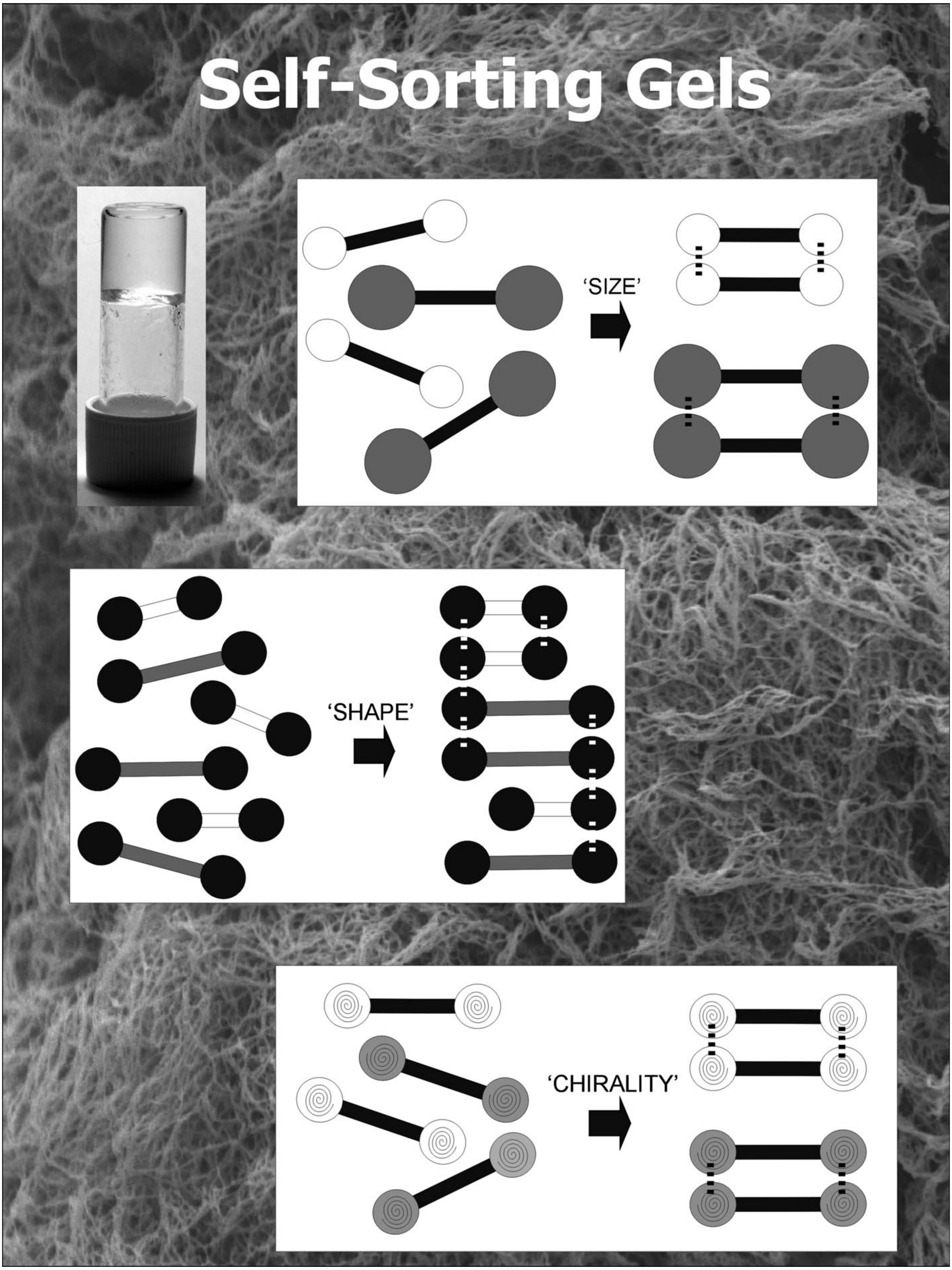

Self-Organisation in the Assembly of Gels from Mixtures of Different Dendritic Peptide Building Blocks

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Abstract: This paper investigates dendritic peptides capable of assembling into nanostructured gels, and explores the effect on self-assembly of mixing different molecular building blocks. Thermal measurements, small angle X-ray scattering (SAXS) and circular dichroism (CD) spectroscopy are used to probe these materials on macroscopic, nanoscopic and molecular length scales. The results from these investigations demonstrate that in this case, systems with different "size" and "chirality" factors can self-organise, whilst systems with different "shape" factors cannot. The "size" and "chirality" factors are directly connected with the molecular information programmed into the dendritic peptides, whilst the shape factor depends on the group linking these peptides together—this is consistent with molecular recognition hydrogen bond pathways between the peptidic building blocks controlling the ability of these systems to self-recognise. These results demonstrate that mixtures of relatively complex peptides, with only subtle differences on the molecular scale, can self-organise into nanoscale structures, an important step in the spontaneous assembly of ordered systems from complex mixtures.

Keywords: chirality · dendrimers · gels · nanotechnology · supramolecular chemistry

Introduction

Perhaps one of the most intriguing phenomena currently being investigated by chemists is the ability of chemical systems to spontaneously generate order from complex mixtures.[1] One mechanism by which systems can self-organise is mediated through non-covalent intermolecular interactions—in particular, well-designed molecules are able to undergo self-sorting.[2] By only forming interactions with specific targets, some molecules are able to recognise the difference between "self" and "non-self" and hence self-assemble in a controlled manner. In particular, the ability of stereochemical information pre-programmed into chiral molecules to drive self-sorting processes has been of intense interest.[3] Self-assembly processes are of crucial importance in the "bottom-up" formation of nanostructured materials,[4] and harnessing self-recognition processes in such materials is a significant challenge.

Supramolecular gels[5] constitute one class of nanostructured self-assembled systems. These soft materials constitute a fascinating arena for the exploration of molecular modifications on "bottom-up" assembly. Perhaps surprisingly, investigations of the self-assembly of nanoscale gel-phase materials from complex mixtures of building blocks has seen relatively little investigation. Chirality effects on self-assembly have been studied;[6] in the vast majority of reported cases, individual enantiomers have a greater propensity to form gels than their corresponding racemate. Indeed, addition of the opposite enantiomer can normally be considered to have a disruptive effect on the global mode of packing.[7] As an example of this, we recently reported a gelation process in which molecular recognition and nanoscale self-assembly based on enantiomeric mixtures were significantly disrupted relative to either of the single enantiomers.[8] In just a handful of rare cases, it has been reported that mixing enantiomers does not lead to a disruptive effect on gelation.[4a–c,9,10] Occasionally, a racemic self-assembled state appears to promote macroscopic gelation when compared with the individual enantiomers which comprise it.[9] There are also a few examples in which racemic mixtures form assem-

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blies with soft materials properties which appear to be identical to those generated from the individual enantiomers.[4a–c,10] This can occur as a consequence of the individual enantiomers self-sorting to yield homochiral aggregates.

We therefore became interested in investigating self-sorting processes in gels in a more general manner. Here, we report the elucidation of the different geometric and structural requirements that are important in the self-organisation of mixtures of our peptidic gelators in organic solution. Using three simple experimental techniques, which reflect nanoscale and macroscopic properties of the gels, we are able to determine which factors control the self-organisation of this system. These techniques were selected because they directly investigate the solvated gel-phase itself, rather than dried samples, which may have modified nanostructures.

The gelators investigated in this paper are illustrated in Figure 1. We previously published a full investigation of their ability to self-assemble.[11] Using NMR methods, we unambiguously demonstrated that this class of gelator self-assembles into gels as a consequence of intermolecular hydrogen bond interactions between the CONH groups in the peptidic head groups. Furthermore, small angle X-ray scattering indicated that for **G2-C12** the diameters of the assembled fibrils corresponded directly with the dimensions of the molecular scale building blocks, indicating the molecules stack in a unidirectional manner. This gave us a basic understanding of the packing of the molecular building blocks. This family of gelators is ideal for probing the behaviour of mixtures, because they have a range of different variable structural features:

a) Molecular "size": gelators **G1** and **G3** have dendritic[12] head groups with different sizes;
b) Molecular "shape": gelators **G2-C6** and **G2-C12** have spacer chains of different lengths connecting the peptidic head groups;

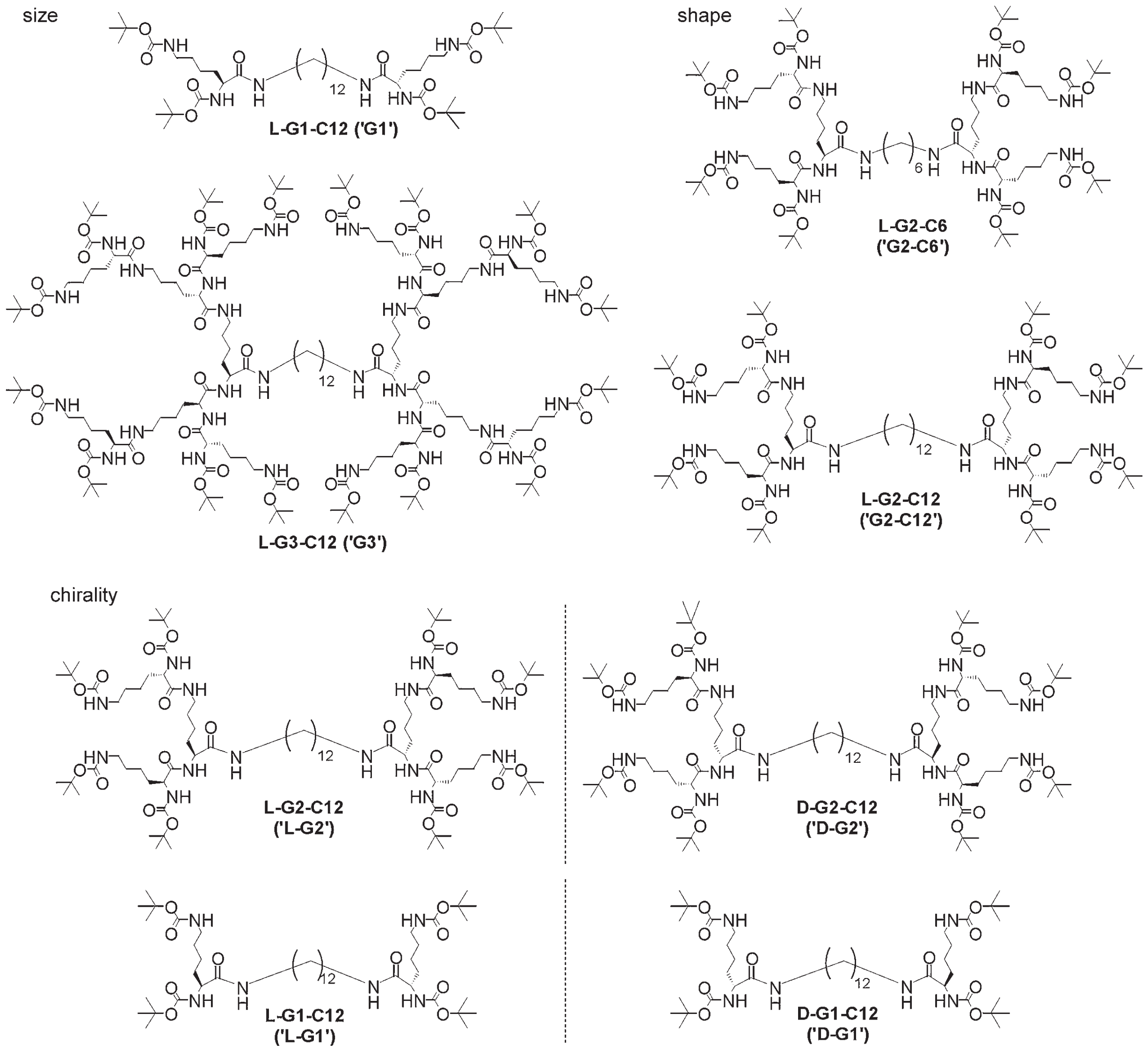


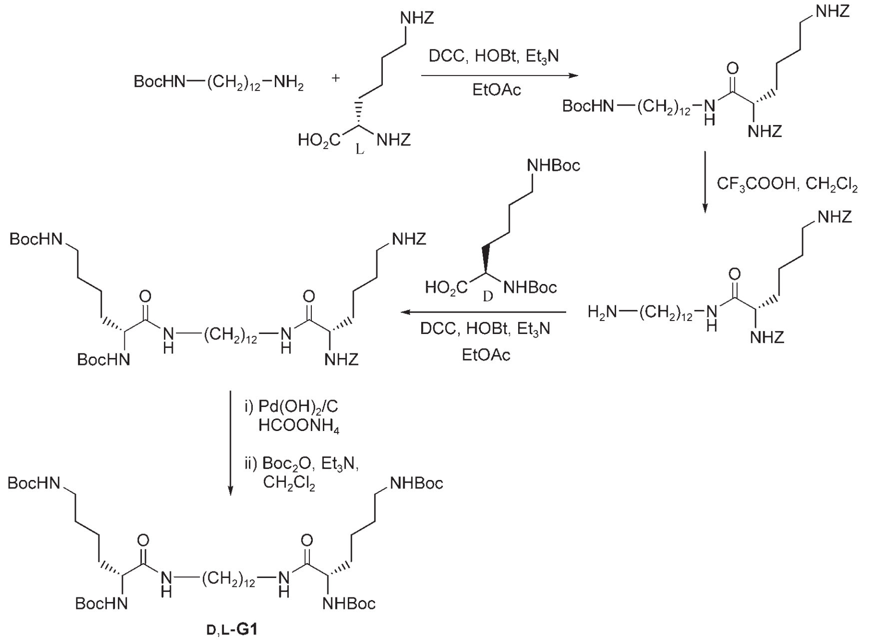
Figure 1. Comparisons between the self-assembling gelators investigated in this paper.

c) Molecular “chirality”: gelators can be constructed using D-lysine, rather than L-lysine (e.g. **D-G2** and **L-G2**).

The nomenclature used in this paper reflects these three key structural features. The full label for each gelator can be described as: chirality(L,D)–size(G1,G2,G3)–shape(C6,C12). We apply a nomenclature priority rule to enhance readability: the peptide size is always stated (**G1**, **G2** or **G3**), however the shape is assumed to be **C12** (unless otherwise stated) and the chirality is assumed to be L (unless otherwise stated).

Results and Discussion

Synthesis of gelators: The gelators investigated in this paper have Boc-protected L-lysine (or D-lysine) head groups covalently connected to each end of diaminoalkanes (Figure 1). The synthesis of these gelators (with L stereochemistry) was previously reported.[11] For this new paper, we synthesised some analogues with the alternative (D) stereochemistry (**D-G1** and **D-G2**). These syntheses were achieved by using a directly analogous strategy to that previously reported (data in the Supporting Information). In addition, diastereomeric *meso*-compound **D,L-G1** was synthesised using an orthogonal protecting group strategy (Scheme 1). In this approach, mono-Boc protection of diaminododecane enabled Z-protected lysine with L stereochemistry to be attached to one end. Subsequently, Boc deprotection followed by coupling with Boc-protected D-lysine and then a swap of protecting groups from Z to Boc allowed the synthesis of the target compound. Experimental data for compound **D,L-G1** were consistent with the proposed structure and are given in the Supporting Information.



Scheme 1. Synthesis of **D,L-G1** using an orthogonal protecting group strategy.

Self-assembly of mixtures—molecular “size”: The thermal properties of **G3** in toluene were investigated as a function of concentration (Figure 2a). The T_{gel} values of all gels were determined using a reproducible tube inversion methodology described in detail in the Supporting Information. The T_{gel} value increased with concentration until reaching a “plateau” value of 97 °C. In the presence of an equimolar concentration of **G1**, the dependence of T_{gel} on [**G3**] was completely unchanged. Mixing **G1** into **G3** therefore has no effect on the macroscopic gelation of **G3**. The gel formed by **G1** alone only has a T_{gel} plateau value of 33 °C. Therefore the mixture behaves like **G3**, the more effective gelator and indicates that compound **G3** is able to self-organise in the presence of **G1**.

Small angle X-ray scattering (SAXS) experiments[13] on **G3** in toluene (20 mM) gave data which could be fitted to an unusual model of ribbon-like assemblies with a persistence length of 15 Å, a width of 93 Å and a thickness of 43 Å (Table 1, and Supporting Information).[14] When the experiment was repeated on a mixture of **G3** (10 mM) and **G1** (10 mM), the data could be fitted to the same model, giving similar dimensions. This indicates that the presence of **G1** does not significantly disrupt the mode of nanoscale self-organisation of **G3**.

Circular dichroism (CD) spectroscopy probes the nanoscale organisation of chiral systems.[15] We studied **D-G1** and **L-G3** in cyclohexane, an optically transparent solvent which supports gelation. Both systems exhibited CD bands at about 220 nm which correspond to the spatial organisation of the CONH groups within homochiral assemblies (**D-G1**: +130 mdeg, **L-G1**: −110 mdeg). These CD bands are temperature dependent, proving they are consequence of the assembly of chiral nanoscale objects, rather than just being due to the inherent chirality of the individual molecules. Measuring CD spectra of the mixtures indicated that the addition of **L-G3** to **D-G1** led to a linear change in the ellipticity (Figure 3a). This linear change is consistent with a proportional mixture of **D-G1** and **L-G3** assemblies being present at each point in the experiment. We therefore propose that **D-G1** and **L-G3** self-sort into their own assemblies based on the difference in molecular “size”.

Molecular “shape”: Thermal experiments (Figure 2b) indicated that the presence of **G2-C6** depressed the T_{gel} plateau value of **G2-C12** from 93 to 83 °C. However, a mixture of **G2-C12** (9 mM) and **G2-C6** (21 mM) had a high T_{gel} value of 80 °C—whereas at these concentra-

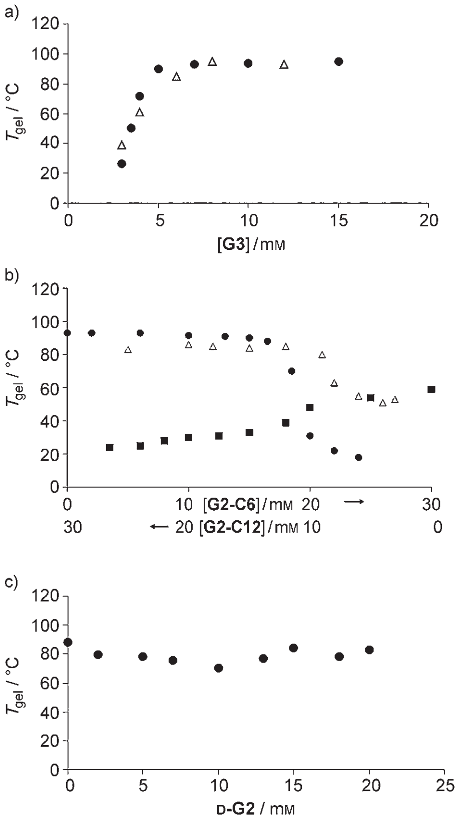


Figure 2. Thermal studies: a) Size: T_{gel} values for **G3** (●) and an equimolar mixture of **G3** and **G1** (△). b) Shape: T_{gel} values for **G2-C6** (■), **G2-C12** (●) and mixtures of **G2-C6** and **G2-C12** in which $[\text{gelator}]_{total}$ = 30 mM (△). c) Chirality: T_{gel} values for mixtures of D-**G2** and L-**G2**, $[\text{gelator}]_{total}$ = 20 mM. Solvent: toluene.

tions, the individual gelators only have T_{gel} values of 28 °C and 50 °C respectively. This indicates that these gelators modify one another's self-assembly, diminishing or enhancing thermal stability, depending on the precise conditions. This is different to what happened on mixing molecular sizes (i.e., **G1** and **G3**).

The SAXS profiles for **G2-C6** and **G2-C12** could be fitted to a model of homogeneous infinite solid cylinders (Table 1). The greater spacer chain length of **G2-C12** gives cylinders with a larger radius (R_c = 17.5 Å) than **G2-C6** (R_c = 12.5 Å). These dimensions approximately correspond with the size of a molecular building block, consistent with the assembly of a molecular-scale fibril.[16] Mixtures of **G2-C12** and **G2-C6** had intermediate radii, and this may indicate that a mixed gelation system with intermediate dimensions is being formed. The SAXS data for the mixture of **G2-C12** (6 mM) and **G2-C6** (14 mM) also had a feature corresponding to dimensions of 66 Å which could not be fitted to the model (Supporting Information). This may be related to the enhanced T_{gel} value observed for this type of mixture. SAXS therefore indicates the ability of these gelators to modify one another's nanoscale self-assembly. This is unlike **G1** and **G3**, where **G1** had little effect on the assembly of **G3**.

Table 1. SAXS data for gels in toluene fitted to models based on ribbon-like or cylindrical assemblies. In each case $[\text{Gelator}]_{total}$ = 20 mM.

		Ribbon-like assemblies			Cylindrical assemblies
	Sample	Length a	Width b	Thickness c	Radius R_c
size	**G3** (20 mM)	15	93	43	–
	G3 (10 mM) + **G1** (10 mM)	15	80	43	–
shape	**G2-C6** (20 mM)	–	–	–	12.5
	G2-C6 (14 mM) + **G2-C12** (6 mM)	–	–	–	14.0
	G2-C6 (10 mM) + **G2-C12** (10 mM)	–	–	–	16.5
	G2-C6 (5 mM) + **G2-C12** (15 mM)	–	–	–	17.5
	G2-C12 (20 mM)	–	–	–	17.0
chirality	L-**G2** (20 mM)	–	–	–	17.5
	L-**G2** (10 mM) + D-**G2** (10 mM)	–	–	–	17.0

The CD spectrum of **G2-C12** has an ellipticity of −120 mdeg, whilst that of **G2-C6** is effectively zero. The presence of just 20 % of **G2-C6** was sufficient to completely inhibit the chiral self-assembly of **G2-C12** (Figure 3b). The loss of CD signal is not proportional, which indicates that **G2-C6** has a disruptive effect on the nanoscale chiral organisation of **G2-C12**.

In combination, these results indicate that differences in the molecular "shape" parameter are therefore insufficient to enable self-organisation. Instead, mixtures of these gelators form mixed nanoscale assemblies with one building block disrupting the other and in which chiral information is lost.

Molecular "chirality": Thermal studies indicated that mixing D-**G2** and L-**G2** had minimal effect on the T_{gel} value, which remained approximately constant at around 80 °C (see Figure 2c). This is an unusual result compared with most chiral gelators as a mixture of enantiomers suppresses gelation.[7,8]

SAXS data for the enantiomeric mixture of L-**G2** (10 mM) and D-**G2** (10 mM) could be fitted to the same model of infinite solid cylinders as L-**G2** (Table 1). Gratifyingly, the data indicated an almost identical radius for the cylinders (R_c = 17.0 Å), demonstrating that mixing the two enantiomers has no impact on the nanoscale organisation of the molecular building blocks.

The two enantiomers had equal and opposite CD bands (L-**G2**: −120 mdeg, D-**G2**: +120 mdeg). Mixing the two enantiomers led to a linear response of the CD signal (Figure 3c). Spector and co-workers have previously proposed that this proportionate response is consistent with resolution (i.e., self-sorting) of enantiomers into mirror image assemblies, with the CD signal at each point being due to a pro-

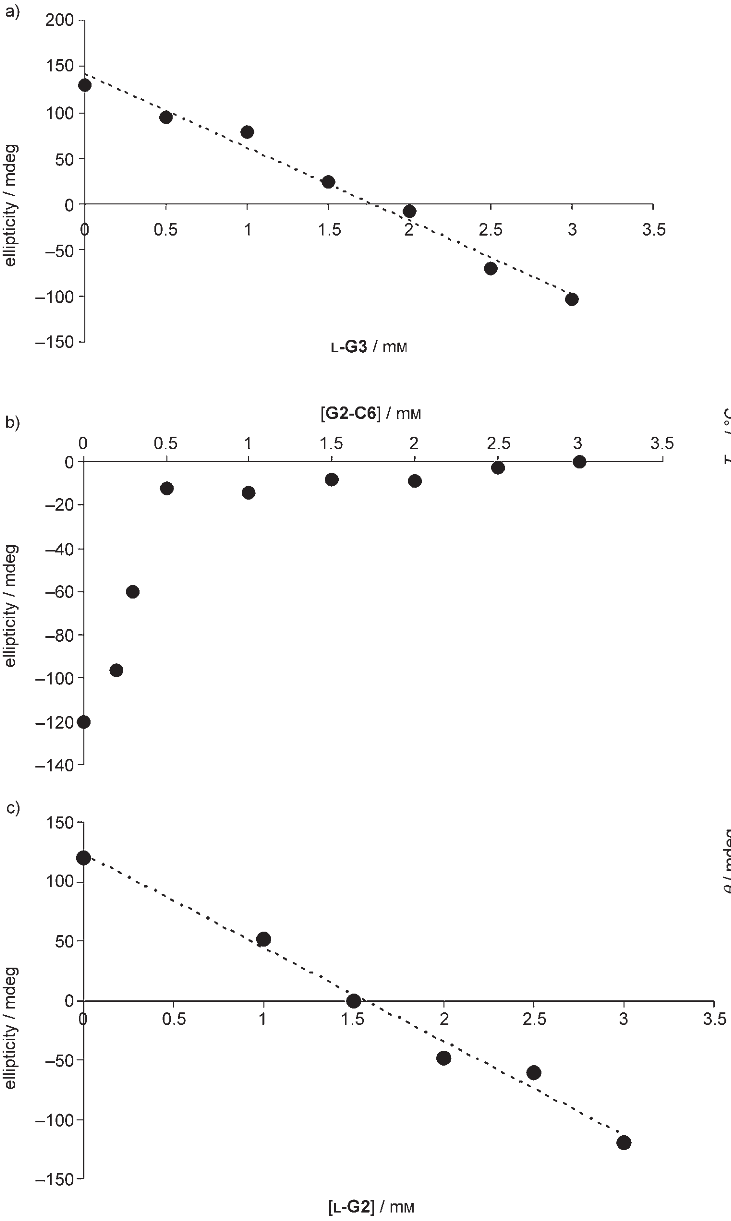


Figure 3. CD studies: a) Size: addition of **L-G3** to **D-G1**. b) Shape: Addition of **G2-C6** to **G2-C12**. c) Chirality: addition of **L-G2** to **D-G2**. Solvent: cyclohexane, [gelator]$_{\text{total}}$ = 3 mM.

portional mixture of left and right handed assemblies.[10c] We therefore propose that self-sorting of enantiomeric mixtures is possible in this case. In previous cases, where enantiomeric building blocks have disrupted each other's self-assembly, we have observed non-linear effects on mixing enantiomers.[8]

To confirm the generality of this observation, we then investigated the self-assembly of mixtures of **L-G1** and **D-G1**. As reported previously,[11] compound **L-G1** forms an optically transparent gel in toluene, with a T_{gel} value of 34 °C at concentrations above about 40 mM. As expected, enantiomer **D-G1** formed gels with effectively identical thermal properties ($T_{\text{gel}} = 33\,°\text{C}$, 60 mM). Mixing one enantiomer (**D-G1**) into the other (**L-G1**) had minimal impact on the macroscopic thermal behaviour of the materials (50:50 mixture, $T_{\text{gel}} = 31\,°\text{C}$, 60 mM, Figure 4a). Once again, this indicates that changing the chirality of the dendritic peptide does not cause disruption of the self-assembly process on the macroscopic level.

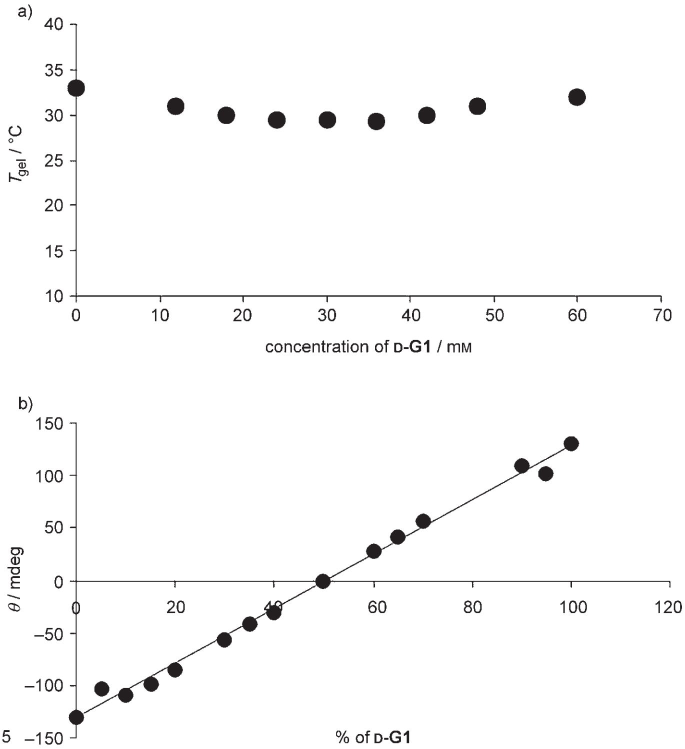


Figure 4. a) Effect of enantiomeric mixing on T_{gel}. Solvent: toluene. For each point, [Gelator]$_{\text{total}}$ = 60 mM; b) Addition of **D-G1** to **L-G1** illustrating a non-disruptive (linear) effect of enantio-mixing. Solvent: cyclohexane, [Gelator]$_{\text{total}}$ = 3 mM.

Gelator **L-G1** exhibited nanoscale chiral organisation, with a negative CD band at about 220 nm. Variable temperature CD spectroscopy performed on **L-G1** demonstrated that increasing the temperature decreased the intensity of the CD band, as the aggregates of **L-G1** disassembled (Figure 5), proving that this CD band is associated with the self-assembly of the gelator molecules and is not an inherent property of isolated **L-G1** molecules. As expected, the CD spectrum of **D-G1** yielded a positive peak at about 220 nm—the mirror image of the spectrum recorded for **L-G1**.

Incremental addition of **D-G1** to the self-assembly composed of **L-G1** led to a proportionate (i.e., linear) decrease in the extent of nanoscale chiral organisation (Figure 4b). Once again, this linear response of CD signal is consistent with resolution (i.e., self-sorting) of two-different enantiomers into mirror-image assemblies (self-sorting), with the assembly at each point being comprised of a mixture of left and right handed forms in the relevant proportion.[10c]

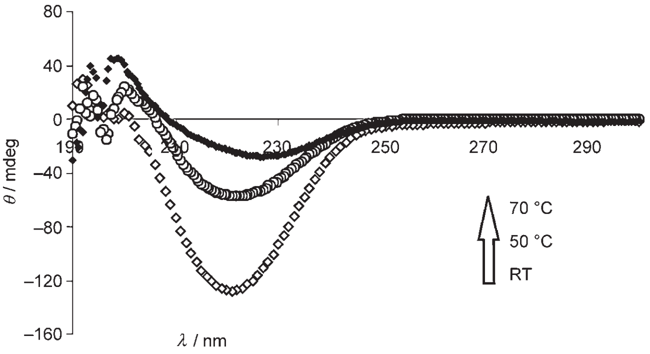


Figure 5. Temperature dependence of the CD spectrum of **L-G1** measured in cyclohexane, $[\text{gelator}]_{\text{total}} = 3$ mM.

Therefore, like the **D-G2** and **L-G2**, gelators **D-G1** and **L-G1** appear to be able to self-organise when assembling from an enantiomeric mixture.

Other researchers have previously used electron microscopy methods to visualise chiral self-sorting processes in helical fibrillar assemblies.[10a] However, in this case, the fibrillar assemblies did not have an obvious helical twist, and therefore the nanoscale chirality could not be visualised by electron microscopy methods (data not shown).

Further investigations of chirality effects (D,L-G1): Finally, we decided to further investigate chirality effects using diastereomer **D,L-G1** in which the two head groups have opposite chiralities, in order to compare behaviour with **D-G1** and **L-G1**, and then determine whether mixtures of diastereomers would be able to self-organise in the same way that mixtures of enantiomers can.

Once again **D,L-G1** was capable of forming a self-supporting gel in toluene ($T_{\text{gel}} = 33$ °C, 60 mM). Measuring T_{gel} as a function of concentration revealed that **D,L-G1** (see Supporting Information) behaved in an analogous manner to **L-G1** with both materials having similar thermal stabilities. Furthermore, in each case, the network building was essentially complete at a concentration of about 40 mM. However, mixing **D-G1** into a sample of **D,L-G1** only gave rise to a partial gel. This is significantly different to what was observed on mixing enantiomeric **D-G1** and **L-G1** when there was minimal effect on macroscopic gelation (Figure 2c). These results indicate that the presence of diastereomeric **D,L-G1** has a significant disruptive effect on the gelation of **D-G1** (and vice versa).

Furthermore, mixing **D,L-G1** into **D-G1** was monitored using CD spectroscopy (Figure 6). This clearly indicated that the presence of **D,L-G1** significantly disrupted the nanoscale chiral organisation of **D-G1**. Even the presence of about 20% of the diastereomer was sufficient to completely inhibit chiral organisation. Once again, this is in stark contrast with the mixture of enantiomers, where a linear response of CD ellipticity was observed and indicates that unlike enantiomers, the diastereomers disrupt one another's assembly.

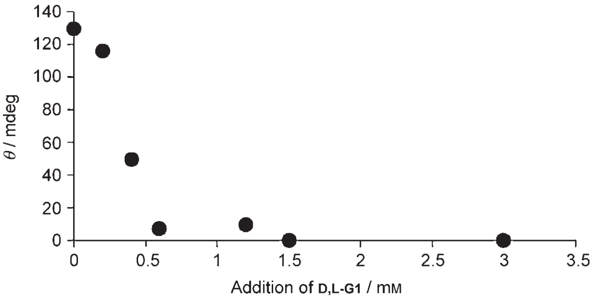


Figure 6. Incremental addition of **D,L-G1** to **D-G1** monitored using CD spectroscopy. Solvent: cyclohexane. $[\text{gelator}]_{\text{total}} = 3$ mM.

Interpretation of the results: In summary, the results demonstrate that of the three parameters investigated, mixtures with different "size" and "chirality" can self-organise their molecular building blocks, while mixtures with different "shape" disrupt one another's self-assembly (Figure 7). Interestingly, the "size" and "chirality" parameters correspond to the molecular information programmed into the peptidic head group and it is the hydrogen-bond interactions between these head groups which enable the self-assembly.[11] We therefore propose that if a mixture has building blocks with different head groups, the molecular recognition pathway is able to discriminate between "self" and "non-self". On the other hand, the molecular "shape" parameter modifies the spacer chain, not the peptide, and we propose that

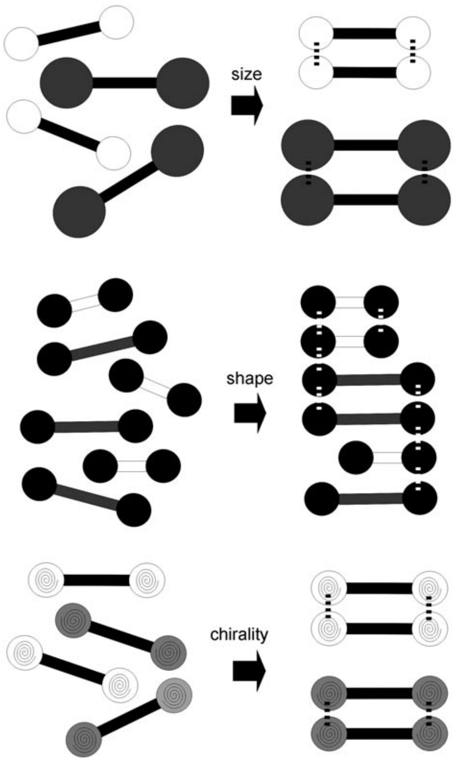


Figure 7. Summary of molecular recognition processes within the mixtures, controlled by interactions between peptidic head groups.

mixtures of these molecules are unable to discriminate "self" and "non-self", having a disruptive effect on one another's self assembly by forming mixed assemblies. It is worth noting that the "shape" parameter is somewhat dependent on the conformation of the flexible aliphatic chain. The X-ray scattering results, however, would indicate that this chain is reasonably extended. Studies using more rigid linking groups are currently in progress in order to fix this parameter more carefully. Nonetheless, we argue that because the head groups drive the assembly process, their identical nature in **G2-C6** and **G2-C12** prevents these molecules being able to effectively differentiate themselves.

These results are supported by the study with compound **D,L-G1**. An enantiomeric mixture of **L-G1** and **D-G1** is capable of chiral self-organisation, but a diastereomeric mixture of **D,L-G1** and **D-G1** is not. This is consistent with our previous model of fibre formation in which the molecular recognition pathway is based on intermolecular hydrogen bonding patterns between peptides.[11] Gelators **L-G1** and **D-G1** have peptide "head groups" with fully opposite chiralities and can hence "ignore" one another during self-assembly. In this case, the enantiomer can only recognise "self". For diastereomeric mixtures of **D,L-G1** and **D-G1**, however, the chirality of one of the head groups is the same in both molecules, and consequently we propose that "partial" molecular recognition process can occur between the different building blocks (i.e.; the head groups with "D" chirality are able to interact). Importantly, the "wrong" chiral head group (L) would then be inserted in the self-assembled stack, resulting in a mismatch of hydrogen-bonding patterns and disruption of the self-assembly process and gelation. Hence, the presence of **D,L-G1** disrupts the gelation of **D-G1** and self-organisation does not take place.

Interestingly, in our previously reported two-component gelation system (Figure 8),[8] we found a disruptive effect on self assembly when using an enantiomeric mixture of dendritic peptides. In this system, the peptides are not permanently bound to the spacer chain, and therefore it is possible to generate complexes with all D stereochemistry, complexes with all L stereochemistry, and complexes with mixed D and L stereochemistry. In analogy with the results in this new paper, it would be expected that the presence of this latter mixed two-component complex would give rise to the disruption of the self-assembly process.

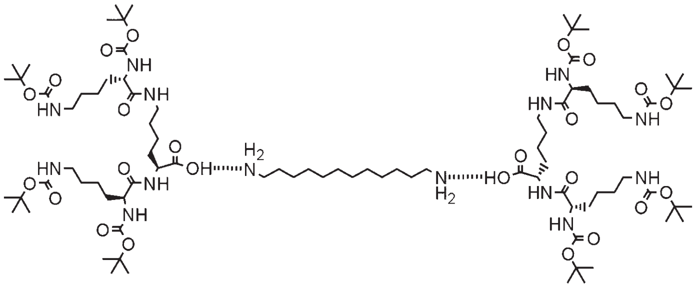


Figure 8. Two-component system in which dendritic head groups can exchange, hence giving rise to a disruptive chirality effect when a mixture of head groups based on L- and D-lysine is employed.[8]

Conclusion

In summary, this paper demonstrates that subtle molecular recognition pathways can be differentiated within mixtures leading to self-organisation. In particular, we have demonstrated that the molecular-scale information programmed into the dendritic peptide groups, in this case, controls the self-organisation of the building blocks within the self-assembly. The organised assemblies which emerge from mixed gelator systems have potential to be harnessed as multifunctional nanomaterials, and work in this direction is currently in progress.

Acknowledgement

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[1] For reviews see: a) J.-M. Lehn, *Chem. Eur. J.* **2000**, *6*, 2097–2102; b) J.-M. Lehn, *Science* **2002**, *295*, 2400–2403.

[2] a) R. Krämer; J.-M. Lehn, A. Marquis-Rigault, *Proc. Natl. Acad. Sci. USA* **1993**, *90*, 5394–5398; b) S. J. Rowan, D. G. Hamilton, P. A. Brady, J. K. M. Sanders, *J. Am. Chem. Soc.* **1997**, *119*, 2578–2579; c) P. N. Taylor, H. L. Anderson, *J. Am. Chem. Soc.* **1999**, *121*, 11538–11545; d) B. Bilgicer, X. Xing, K. Kumar, *J. Am. Chem. Soc.* **2001**, *123*, 11815–11816; e) I. W. Hwang, T. Kamada, T. K. Ahn, D. M. Ko, T. Nakamura, A. Tsuda, A. Osuka, D. Kim, *J. Am. Chem. Soc.* **2004**, *126*, 16187–16198; f) S. G. Telfer, T. Sato, R. Kuroda, J. LeFebvre, D. B. Leznoff, *Inorg. Chem.* **2004**, *43*, 421–429; g) A. X. Wu, L. Isaacs, *J. Am. Chem. Soc.* **2003**, *125*, 4831–4835; h) P. Mukhopadhyay, A. Wu, L. Isaacs, *J. Org. Chem.* **2004**, *69*, 6157–6164; i) N. A. Schnarr, A. J. Kennan, *J. Am. Chem. Soc.* **2003**, *125*, 667–671; j) N. Sreenivasachary, J.-M. Lehn, *Proc. Natl. Acad. Sci. USA* **2005**, *102*, 5938–5943; k) S. M. Liu, C. Ruspic, P. Mukhopadhyay, S. Chakrabarti, P. Y. Zavalij, L. Isaacs, *J. Am. Chem. Soc.* **2005**, *127*, 15959–15967; l) I. Saur, R. Scopelliti, K. Severin, *Chem. Eur. J.* **2006**, *12*, 1058–1066; m) C. Burd, M. Weck, *Macromolecules* **2005**, *38*, 7225–7230.

[3] a) A. Singh, T. G. Burke, J. M. Calvert, J. H. Georger, B. Herendeen, R. R. Price, P. E. Schoen, P. Yager, *Chem. Phys. Lipids* **1988**, *47*, 135–148; b) N. Yamada, T. Sasaki, H. Murata, T. Kunitake, *Chem. Lett.* **1989**, 205–208; c) T. Gulik-Krzywicki, C. Fouquey, J.-M. Lehn, *Proc. Natl. Acad. Sci. USA* **1993**, *90*, 163–167; d) F. J. Winkler, R. Medina, J. Winkler, H. J. Krause, *J. Mass Spectrom.* **1997**, *32*, 1072–1079; e) K. C. Russell, J.-M. Lehn, N. Kyritsakas, A. DeCian, J. Fischer, *New J. Chem.* **1998**, *22*, 123–128; f) L. J. Prins, J. Huskens, F. de Jong, P. Timmerman, D. N. Reinhoudt, *Nature* **1999**, *398*, 498–502; g) J.-M. Vincent, C. Philouze, I. Pianet, J.-B. Verlhac, *Chem. Eur. J.* **2000**, *6*, 3595–3599; h) X. Shi, J. C. Fettinger, M. Cai, J. T. Davis, *Angew. Chem.* **2000**, *112*, 3254–3257; *Angew. Chem. Int. Ed.* **2000**, *39*, 3124–3127; i) E. Murguly, R. McDonald, N. R. Branda, *Org. Lett.* **2000**, *2*, 3169–3172; j) X. D. Shi, J. C. Fettinger, J. T. Davis, *J. Am. Chem. Soc.* **2001**, *123*, 6738–6739; k) S. De Feyter, A. Gesquière, K. Wurst, D. B. Amabilino, J. Veciana, F. C. De Schryver, *Angew. Chem.* **2001**, *113*, 3317–3320; *Angew. Chem. Int. Ed.* **2001**, *40*, 3217–3220; l) Y. Ishida, T. Aida, *J. Am. Chem. Soc.* **2002**, *124*, 14017–14019; m) L. Isaacs, D. Witt, *Angew. Chem.* **2002**, *114*, 1985–1987; *Angew. Chem. Int. Ed.* **2002**, *41*, 1905–1907; n) A. Wu, A. Chakraborty, J. C. Fettinger, R. A. Flowers II, L. Isaacs, *Angew.*

Chem. **2002**, *114*, 4200–4203; *Angew. Chem. Int. Ed.* **2002**, *41*, 4028–4031; o) A. Tessa ten Cate, P. Y. W. Dankers, H. Kooijman, A. L. Spek, R. P. Sijbesma, E. W. Meijer, *J. Am. Chem. Soc.* **2003**, *125*, 6860–6861; p) D. M. Chung, J. S. Nowick, *J. Am. Chem. Soc.* **2004**, *126*, 3062–3063; q) I. W. Hwang, T. Kamada, T. K. Ahn, D. M. Ko, T. Nakamura, A. Tsuda, A. Osuka, D. Kim, *J. Am. Chem. Soc.* **2004**, *126*, 16187–16198; r) B. W. Messmore, P. A. Sukerkar, S. I. Stupp, *J. Am. Chem. Soc.* **2005**, *127*, 7992–7993.

[4] a) A. E. Rowan, R. J. M. Nolte, *Angew. Chem.* **1998**, *110*, 65–71; *Angew. Chem. Int. Ed.* **1998**, *37*, 63–68; b) D. J. Hill, M. J. Mio, R. J. Prince, T. S. Hughes, J. S. Moore, *Chem. Rev.* **2001**, *101*, 3893–4011; c) M. A. Mateos-Timoneda, M. Crego-Calama, D. N. Reinhoudt, *Chem. Soc. Rev.* **2004**, *33*, 363–372; d) G. R. Whitesides, *Small* **2005**, *1*, 172–179; e) D. K. Smith, A. R. Hirst, C. S. Love, J. G. Hardy, S. V. Brignell, B. Huang, *Prog. Polym. Sci.* **2005**, *30*, 220–293; f) P. Jonkheijm, P. van der Schoot, A. P. H. J. Schenning, E. W. Meijer, *Science* **2006**, *313*, 80–83.

[5] For review articles see: a) P. Terech, R. G. Weiss, *Chem. Rev.* **1997**, *97*, 3133–3159; b) O. Gronwald, E. Snip, S. Shinkai, *Curr. Opin. Colloid Interface Sci.* **2002**, *7*, 148–156; c) T. Shimizu, *Polym. J.* **2003**, *35*, 1–22; d) A. R. Hirst, D. K. Smith, *Chem. Eur. J.* **2005**, *11*, 5496–5508.

[6] For an interesting recent review of chirality effects in gels see: A. Brizard, R. Oda, I. Huc, *Top. Curr. Chem.* **2005**, *256*, 167–218.

[7] For selected examples see: a) J.-H. Fuhrhop, P. Schnieder, J. Rosenberg, E. Boekema, *J. Am. Chem. Soc.* **1987**, *109*, 3387–3390; b) J.-H. Fuhrhop, T. Bedurke, A. Hahn, S. Grund, J. Gatzmann, M. Riederer, *Angew. Chem.* **1994**, *106*, 351–352; *Angew. Chem. Int. Ed. Engl.* **1994**, *33*, 350–351; c) M. Jokić, J. Makarević, M. Žinić, *J. Chem. Soc. Chem. Commun.* **1995**, 1723–1724; d) K. Hanabusa, M. Yamada, M. Kimura, H. Shirai, *Angew. Chem.* **1996**, *108*, 2086–2088; *Angew. Chem. Int. Ed. Engl.* **1996**, *35*, 1949–1951; e) S. Bhattacharya, S. N. G. Acharya, A. R. Raju, *Chem. Commun.* **1996**, 2101–2102; f) J. I. Mamiya, K. Kanie, T. Hiyama, T. Ikeda, T. Kato, *Chem. Commun.* **2002**, 1870–1871; g) C. Boettcher, B. Schade, J.-H. Fuhrhop, *Langmuir* **2001**, *17*, 873–877; h) J. Becerril, B. Escuder, J. F. Miravet, R. Gavara, S. V. Luis, *Eur. J. Org. Chem.* **2005**, 481–485; i) T. Koga, M. Matsuoka, N. Higashi, *J. Am. Chem. Soc.* **2005**, *127*, 17596–17597.

[8] A. R. Hirst, D. K. Smith, M. C. Feiters, H. P. M. Geurts, *Chem. Eur. J.* **2004**, *10*, 5901–5910.

[9] a) R. Oda, I. Huc, S. Candau, *Angew. Chem.* **1998**, *110*, 2835–2838; *Angew. Chem. Int. Ed.* **1998**, *37*, 2689–2691; b) J. Makarević, M. Jokić, Z. Raza, Z. Štefanić, B. Kojić-Prodić, M. Žinić, *Chem. Eur. J.* **2003**, *9*, 5567–5580; c) Y. Watanabe, T. Miyasou, M. Hayashi, *Org. Lett.* **2004**, *6*, 1547–1550; d) V. Èaplar, M. Žinić, J.-L. Pozzo, F. Fages, G. Mieden-Gundert, F. Vögtle, *Eur. J. Org. Chem.* **2004**, 4048–4059.

[10] a) B. W. Messmore, P. A. Sukerkar, S. I. Stupp, *J. Am. Chem. Soc.* **2005**, *127*, 7992–7993; b) P. Terech, V. Rodriguez, J. D. Barnes, G. B. McKenna, *Langmuir* **1994**, *10*, 3406–3418; c) M. S. Spector, J. V. Selkinger, A. Singh, J. M. Rodriguez, R. R. Price, J. M. Schnur, *Langmuir* **1998**, *14*, 3493–3500.

[11] B. Huang, A. R. Hirst, D. K. Smith, V. Castelletto, I. W. Hamley, *J. Am. Chem. Soc.* **2005**, *127*, 7130–7139.

[12] For a review of dendritic gels see: a) A. R. Hirst, D. K. Smith, *Top. Curr. Chem.* **2005**, *256*, 237–273; for examples see: b) G. R. Newkome, G. R. Baker, M. J. Saunders, P. S. Russo, V. K. Gupta, Z. Q. Yao, J. E. Miller, K. Bouillion, *J. Chem. Soc. Chem. Commun.* **1986**, 752–753; c) G. R. Newkome, G. R. Baker, S. Arai, M. J. Saunders, P. S. Russo, K. J. Theriot, C. N. Moorefield, L. E. Rogers, J. E. Miller, T. R. Lieux, M. E. Murray, B. Phillips, L. Pascal, *J. Am. Chem. Soc.* **1990**, *112*, 8458–8465; d) G. R. Newkome, C. N. Moorefield, G. R. Baker, R. K. Behera, G. H. Escamilla, M. J. Saunders, *Angew. Chem.* **1992**, *104*, 901–903; *Angew. Chem. Int. Ed. Engl.* **1992**, *31*, 917–919; e) G. R. Newkome, X. Lin, Y. Chen, G. H. Escamilla, *J. Org. Chem.* **1993**, *58*, 3123–3129; f) W.-D. Jang, D.-L. Jiang, T. Aida, *J. Am. Chem. Soc.* **2000**, *122*, 3232–3233; g) W.-D. Jang, T. Aida, *Macromolecules* **2003**, *36*, 8461–8469; h) C. Kim, K. T. Kim, Y. Chang, H. H. Song, T.-Y. Cho, H.-J. Jeon, *J. Am. Chem. Soc.* **2001**, *123*, 5586–5587; i) C. Kim, S. J. Lee, I. H. Lee, K. T. Kim, H. H. Song, H.-J. Jeon, *Chem. Mater.* **2003**, *15*, 3638–3642; j) C. Marmillon, F. Gauffre, T. Gulik-Krzywicki, C. Loup, A.-M. Caminade, J.-P. Majoral, J.-P. Vors, R. Rump, *Angew. Chem.* **2001**, *113*, 2696–2699; *Angew. Chem. Int. Ed.* **2001**, *40*, 2626–2629; k) W. Zhang, S. O. Gonzalez, E. E. Simanek, *Macromolecules* **2002**, *35*, 9015–9021; l) E. R. Zubarev, M. U. Pralle, E. D. Sone, S. I. Stupp, *J. Am. Chem. Soc.* **2001**, *123*, 4105–4106.

[13] *Small Angle X-ray Scattering*(Eds.: O. Glatter, O. Kratky), Academic Press, London, **1982**.

[14] O. Pelletier, C. Bourgaux, A. Diat, P. Davidson, J. Livage, *Eur. Phys. J. E* **2000**, *1*, 2 191–198.

[15] For an overview of CD spectroscopy see: N. Berova, K. Nakanishi, R. W. Woody, *Circular Dichroism: Principles and Applications*, 2nd ed., Wiley-VCH, Weinheim, **1994**.

[16] Other researchers have used SAXS to probe the fundamental nanoscale building blocks of gels: A. Aggeli, I. A. Nyrkova, M. Bell, R. Harding, L. Carrick, T. C. B. McLeish, A. N. Semenov, N. Boden, *Proc. Natl. Acad. Sci. USA* **2001**, *98*, 11857–11862.

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