JACS
JOURNAL OF THE AMERICAN CHEMICAL SOCIETY

Perspective

pubs.acs.org/JACS

The Past, Present, and Future of Molecular Gels. What Is the Status of the Field, and Where Is It Going?

Richard G. Weiss

Department of Chemistry and Institute for Soft Matter Synthesis and Metrology, Georgetown University, Washington, D.C. 20057-1227, United States

Supporting Information

ABSTRACT: A Perspective is presented on the history and current understanding of molecular gels and the factors that must be considered to characterize them. The abilities of the most important structural, dynamic, and rheological tools available currently to provide the information necessary to follow the formation of a molecular gel from its initial sol phase and then to define it at different distance and time scales are discussed. Approaches to determining *a priori* when a molecule will gelate a selected liquid, as well as possible methodologies for overcoming current limitations in understanding molecular gels, are presented. Finally, some of the many potential and realized applications for these materials are enumerated.

This Perspective presents a personalized assessment of the state-of-the-art of molecular gels—a burgeoning field of soft matter science. It will identify current problems and speculate on future developments within the field. At the outset, the author declares that there is no paradigm for discerning when a selected liquid will be gelated by a particular molecule (i.e., a gelator) or even the properties of a molecular gel after it is formed. The prospects for creating such a paradigm in the foreseeable future are slim, despite the enormous efforts that have been made in the past several decades to understand the basic principles governing this type of self-assembly.[1] Although the first molecular gel of which the author is aware, lithium urate in water,[2] was reported in 1841, little progress was made to understand such materials until fairly recently. Figure 1, a plot of the number of annual citations to "molecular gels" in the Web of Science database between 1970 and 2013, attests to both the significant efforts to exploit and understand molecular gels and the growing interest in this field; note the explosive increase in citations starting in 1991. The range of structures known to act as molecular gelators is very broad, spanning very simple molecules (such as long *n*-alkanes[3]) and very small molecules (such as *N*,*N*′-dimethylurea[4] and D-sorbitol[5]) to complex, elegantly designed ones (such as complex peptide amphiphiles, represented by 16(VGA)*n*, with n = 2, 4, or 6,[6] Figure 2). Some of the identified impediments to progress in the field may be overcome by instrumental advances that will allow temporal and spatial aspects of molecular gels to be interrogated without significantly disturbing their native states; examples of some of the popular techniques that can lead to large changes to gel structures during analyses are discussed herein.

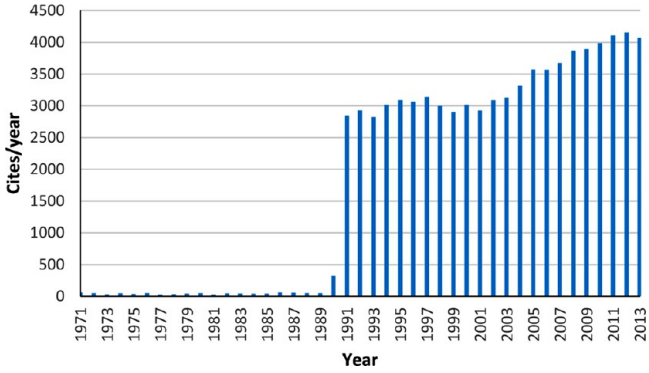


Figure 1. Histogram of citations by year to "molecular gels" in the Web of Science.

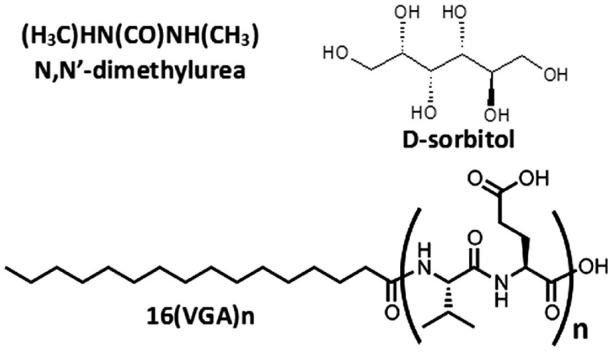


Figure 2. Structures of two structurally simple and one more-complex self-assembling molecules.

First, molecular gels will be defined.[7] Even if not universally accepted, the definition given will be used for the purposes of this Perspective. In the remaining sections, the state of the art and future challenges will be discussed critically from the viewpoint of what we know and what we need to learn in order to advance the field:

1. What is a molecular gel?
2. Classification of molecular gel properties and problems associated with controlling them

Received: April 3, 2014
Published: May 16, 2014

   dx.doi.org/10.1021/ja503363v | *J. Am. Chem. Soc.* 2014, 136, 7519−7530

3. Gel structures at different distance scales: sample structural interrogation using different instrumental approaches
4. Perspectives for *a priori* design of molecular gelators
5. Perspectives for following the early stages of self-assembly of molecular gelators into 3D networks
6. Potential and realized applications of molecular gels
7. Conclusions and challenges

As mentioned above, many challenges stand between our knowledge today and our ability to create reliable *a priori* methodologies to make molecular gels, the goal addressed in section 4 and the "holy grail" of this field of science. Being able to predict definitively that a selected liquid will be gelated by a particular molecule remains out of our current grasp. Gelation of this type is, for now, an empirical science, and the vast majority of new structural types are discovered serendipitously.[8] The reasons are related to factors mentioned in sections 1 and 2. Although seemingly trivial, documentation of the steps leading to gel formation and storage is frequently inadequate, leading to ambiguities and inabilities to relate directly data from different laboratories.

1. WHAT IS A MOLECULAR GEL?

A relatively large number of reviews,[9−26] as well as some books and book chapters,[27−30] have been devoted to aspects of molecular gels. The interested reader is directed to them for in-depth studies and summaries of various aspects of gel properties. This is not a review, and there will be no comprehensive citation of even the seminal articles relating to the different aspects discussed. However, molecular gels rely on many of the same principles of self-assembly that have been investigated elegantly in crystalline materials.[31,32]

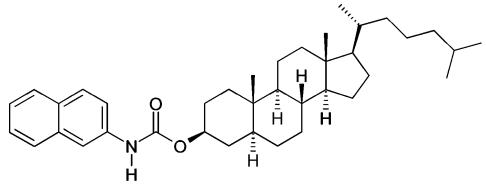
More than 80 years ago, Dorothy Jordon Lloyd stated for all gel types that "...the colloid condition, the gel, is easier to recognize than to define."[33] Although Loyd's pragmatic dictum may seem enigmatic, it is true even today because the composition and structure of the matrix of a viscoelastic material, as well as its rheological properties, must be considered when defining properly a gel (whether it be molecular or any other type). Regardless, all gels (including polymeric gels[34]), except inorganic sol−gels,[35] which are not within the class of materials discussed here, have a liquid component and a microphase-separated component, a gelator. Although microgels do have at least two components, they lack a continuous network,[36,37] and they will not be discussed here for that reason. Most of the molecular gel systems undergo microphase separation by nucleation phenomena rather than by spinodal decomposition mechanisms.[38] At least a part of the gelator molecules are in the form of a continuous structure—a three-dimensional (3D) network, commonly referred to as a self-assembled fibrillar network (SAFiN), although the elements of the SAFiN are not fibrillar in some molecular gels. Regardless, the network must permeate the liquid and, although dynamic, be permanent on the time scale of an analytical experiment. As a result, the material is "solid-like" in its rheological behavior:[39] the storage modulus (G') must remain larger than the loss modulus (G'') over a large frequency range (including low frequencies) within the linear viscoelastic region; the mechanical strength of a gel is related to the absolute magnitudes of the moduli and their ratio, G'/G''.[40] It must be emphasized that some systems meet all or nearly all of the structural criteria for being gels but fail the rheological requirements. For example, many dispersions of partially hydrolyzed poly(vinyl acetate)s with borate cross-linkers do not flow perceptibly over periods of minutes and have 3D microstructures (i.e., they meet the structural criteria for being called "gels"), but they do not meet the rheological criterion that their G' remain larger than their G'' over a large frequency range (including low frequencies) within their linear viscoelastic regions.[41] Although frequently ignored, such systems involving molecular gelators should be considered in studies directed to gaining a basic understanding of molecular gels, because they too can provide important insights into the mechanisms of 0D→1D self-assembly (i.e., single molecules aggregating into objects with very large aspect ratios).

Unlike polymer gels, in which the basic elements of a 3D network are one-dimensional (1D) objects,[42] molecular gels are composed of zero-dimensional (0D) objects on the micrometer scale that self-assemble through non-covalent interactions into 1D objects; rarer are molecular gels in which the self-assembly is 0D→2D (i.e., platelets)→3D objects.[3] As a result of the nature of the intermolecular interactions among the gelator molecules as well as among the gelator molecules and the liquid component, these gels are almost always thermally reversible with their sol phases. The sols consist of individual gelator molecules or their aggregates without a continuous network. An important exception to the reversibility is when heating or otherwise perturbing the sol phase results in chemical changes to at least one of the gel components.

2. CLASSIFICATION OF MOLECULAR GEL PROPERTIES AND PROBLEMS ASSOCIATED WITH CONTROLLING THEM

Gel stability can be defined in several ways: the melting temperature of a gel (T_{gs}) in the "plateau" concentration regime (i.e., where the gel-to-sol and sol-to-gel transition temperatures, T_{gs} and T_{sg}, respectively, are nearly independent of gelator concentration, usually ≥2 wt %), the lowest gelator concentration at which gels form at room temperature (critical gelator concentration, cgc), the gel lifetime at room temperature, the heat of gel melting or formation from differential scanning calorimetry (DSC), and the moduli from rheological measurements. *Gelator efficiency* depends on some of the same criteria (i.e., cgc values and lifetimes of gels at room temperature) as well as the range of liquids gelated.[43]

As alluded to above, molecular gels are typically prepared by heating a (solid) gelator and a liquid component until an apparent solution/sol obtains, and then cooling it to below T_{sg}. The degree to which the gelator molecules remain aggregated in the sol phase and the rate at which the cooling occurs can influence the nature of the gel that is formed. A drastic example of how the difference between T_{sg} and the temperature at which a sol (composed of 1 wt % 5α-cholestanyl-3β-yl *N*-(2-naphthyl) carbamate (CNC) in octane is incubated can influence the



CNC

structure of a SAFiN is shown in Figure 3. Also, the sol-to-gel transitions are susceptible to hysteresis effects, and even the gel-

dx.doi.org/10.1021/ja503363v | J. Am. Chem. Soc. 2014, 136, 7519−7530

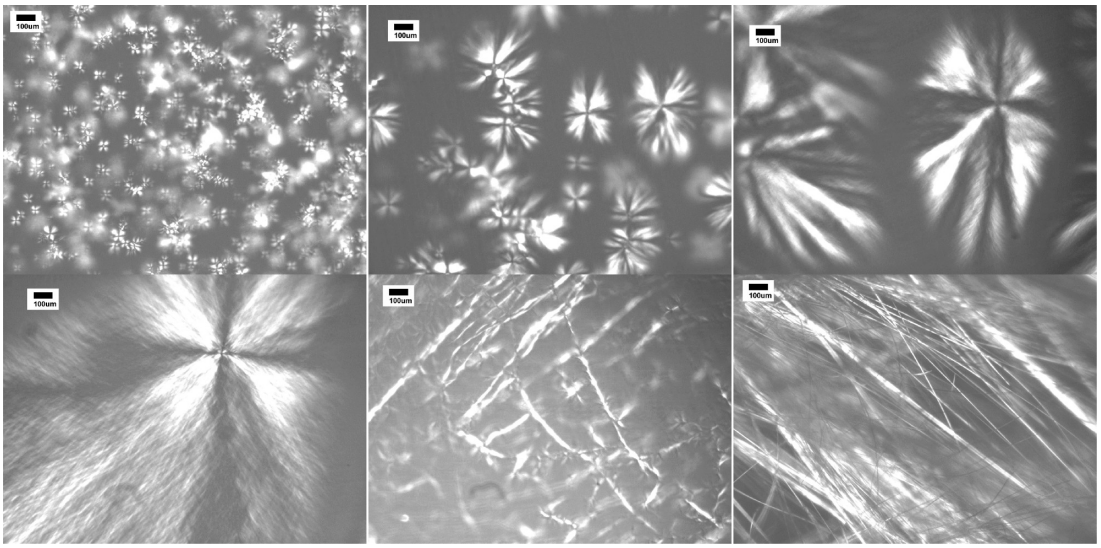


Figure 3. Optical micrographs of 1.0 wt % CNC/*n*-octane gels formed upon thermostatting sols at different temperatures (top left to right and bottom left to right): 0.0, 15.6, 25.1, 31.6, 37.4, and 42.3 °C. The sample at 42.3 °C is not a gel; T_{sg} is ca. 40 °C. Reprinted with permission from ref 44. Copyright 2005 American Chemical Society.

to-sol transitions can be sensitive to the rate of heating and the history of the gel.[44] Thus, molecular gels can undergo Ostwald ripening[45] or even a complete phase change over time because the gel state is inherently less stable than its macro phase-separated state.

An additional characteristic of molecular gels, their thixotropy, is not well understood either. Although several reasonable hypotheses have been advanced to explain the structural requirements for a molecular gelator to lead to gels with a high degree of thixotropy and the time for such gels to re-form after suffering destructive shear,[46] they remain without a general explanation. Both of these thixotropic properties are important to application of gels for many purposes and to understand (this author believes) the nature of chain entanglements and junction zones, some of which are "permanent" (in that they are retained in the SAFiNs for periods of several minutes) and others of which are "transient". Currently, it is possible to synthesize molecules that are derived from known thixotropic molecular gelators, but the degree of thixotropy of their gels (including the classes of liquids they will gelate) and the kinetics of recovery of their viscoelasticity cannot be predicted. Molecular gels showing almost complete recovery of their viscoelastic properties[47,48] or almost instantaneous recovery after application of destructive shear[49,50] have been reported. A challenge for future investigations will be to learn the details of how and why some SAFiNs are capable of such behaviors while others are not.

These and other variables, which will be discussed below, are symptomatic of the complexity of molecular gel systems—*caveat emptor* when attempting to reproduce a molecular gel using a recipe from the literature! To correlate data collected in different laboratories (or even by different researchers in one laboratory!), *very detailed descriptions of the steps taken to prepare and store molecular gels should be included in the experimental sections of articles.* The current lack of standardized protocols is a serious impediment to exploiting the large number of compendia on gel compositions that could be used to advance the field.

3. GEL STRUCTURES AT DIFFERENT DISTANCE SCALES: SAMPLE STRUCTURAL INTERROGATION USING DIFFERENT INSTRUMENTAL APPROACHES

Bulk samples can be viewed with the naked eye to determine crudely whether a gel has been formed. On the several micrometer distance scale, optical and other microscopes can provide useful information about the supramolecular arrangement of the SAFiN, such as the approximate sizes and shapes of the fibers or whether they are in the aggregated form of spherulites, rods, etc. These observations can be made easily on unadulterated gel samples. For more detailed spatial information, techniques with higher magnifying power are needed. Although indirect methods such as small-angle neutron scattering and small-angle X-ray scattering (SAXS; especially with synchrotron radiation) can yield very useful information about SAFiNs in pristine gels, they rely on data analyses with models that may be difficult to apply, and the availability of appropriate solvents can be a problem in some cases.

Even with those difficulties, these scattering techniques have yielded very valuable and detailed information about molecular gel structures.[51,52] A recent example follows the kinetics of formation of SAFiN elements and their sizes and fractal dimensions upon pulsed synchrotron SAXS interrogation of sols of 7−10 wt % (*R*)-12-hydroxystearic acid in aromatic and saturated hydrocarbon solvents, immediately after quenching them to below their gelation temperatures.[53] It was found that the cross-sectional dimensions of the fibers remained constant after nucleation at ∼82 and ∼100 Å and the fractal dimensions (using Dickinson's approach[54]) were 2.0−2.3 and 1.4−1.6 in toluene and dodecane, respectively. Perhaps more importantly, some of the events preceding nucleation could be followed.

A common practice within the gel community, when preparing samples for X-ray diffraction (XRD), atomic force microscopy (AFM), scanning electron microscopy (SEM), and transmission electron microscopy (TEM) measurements, is to place a dab of the gel into a tube or onto a substrate or grid and remove the liquid at room temperature. Then, the dried xerogel or semidried residue is examined. Although born of necessity in many cases, this manner of sample preparation is fraught with

dx.doi.org/10.1021/ja503363v | J. Am. Chem. Soc. 2014, 136, 7519−7530

danger if the intent is to associate network structures of molecular gels and their xerogels. Unfortunately, fiber bundling and morphology changes can accompany the removal of the liquid component because the gelator molecules and their fibers are given ample time to diffuse and rearrange; many gelators are polymorphous, and the crystalline packing arrangement within the gel fibers is not necessarily the thermodynamically most stable one! Also, some molecular gel networks are not crystalline, but removal of the liquid leads to crystallization.

A method for obtaining information about molecular packing in fibers of some gels that does not require sample cooling or liquid removal is available.[55] A crude subtraction of the amorphous XRD background from the liquid component of a gel can be made using the neat liquid. Provided the remaining signals from the gel diffraction pattern are detectable, they can be analyzed as the fiber packing arrangement. Indexing of this pattern produces the unit cell parameters. Additional information—the molecular packing of gelator molecules at the atomic resolution level—can then be obtained if the theoretical powder diffraction pattern of a single crystal of the gelator matches the diffraction pattern of the gel. Unfortunately, suitable crystals for structural analyses of gelators are not common, and even when solved, they may be of a different morph than the one within the gel!

If extremely benign methods to remove the liquid component of a molecular gel can be employed, the pristine SAFiN structure in the form of an aerogel (or even a xerogel) can be retained with relatively good confidence. Extraction of the liquid with supercritical carbon dioxide is one method to do so. It has been applied in a limited number of cases[56] because the actual conditions of temperature and pressure release must be controlled very carefully and the range of liquids that can be removed in this way is limited. Regardless, supercritical extraction is a promising procedure to isolate fibers of molecular gels without initiating morphological changes. It has been used with dichroic infrared and fluorescence spectral data, in conjunction with *ab initio* calculations, to determine the packing arrangements of 2,3-dialkyloxyanthracene molecules in aerogel and xerogel fibers.[57]

Methods that freeze the samples exceedingly rapidly, at rates of ca. 100 000 °C/s (i.e., cooling to cryogenic temperatures, below −170 °C in milliseconds), minimize the possibility of morphological changes at the intermolecular and interfibrillar distance scales. Subsequent partial or complete removal of the liquid component at low temperatures does not alter the sample morphology because the kT available to the gelator molecules is very small. However, such methods have not been fully developed for flash-freezing gels with organic liquids; most cryo-studies have been conducted on aqueous gels because the common coolants (e.g., liquid ethane) can dissolve organogels while cooling them.[58,59] However, liquid nitrogen slushes and other cooling techniques are available for preparing molecular organogel samples for SEM and TEM analyses, and they will undoubtedly become more prevalent in the future.

A variety of additional techniques can be used to freeze-fracture and etch the sample surfaces and then to sputter on a layer of a heavy metal if SEM contrast is problematic. TEM measurements on cryo-prepared gel samples are very difficult because the samples are usually too thick to ensure that single fibers along one plane orthogonal to the electron beam are being imaged. To avoid this complication, cryo-tomography methods are being developed, and depth resolution less than 10 nm is now possible.[60] Although it has been exploited predominantly by biologists to investigate the structures of cells, proteins, etc., cryo-tomography is certainly possible for molecular gel samples. A very nice example for a (polymeric) pectin gel made by Andrew Leis can be seen at http://csironewsblog.com/2013/10/14/. Development of future instrumental and sample preparation techniques[61−63] should make imaging of gel networks in cryo-gels more routine. The information accessible from such studies will enhance enormously our understanding of the actual gel networks.

Although it is unlikely that cryo-SEM or cryo-TEM measurements will attain sufficient resolution in the near future needed to obtain the molecular packing arrangements within the fibers of a gel, sub-nanometer resolution is possible from analyses of single-wavelength and synchrotron XRD studies. Recent demonstration of "single-crystal" (i.e., atomic resolution) structural information from synchrotron-derived diffraction data on multiple, unoriented, sub-micrometer-sized crystals suggests that detailed structural packing within fibers may become possible in the near future. Also, cryo-crystallization techniques that allow aggregates of sub-micrometer-sized crystals to be analyzed by single-crystal techniques may also permit atomic-level resolution of gelator structures in SAFiNs to be determined more easily.[64] Although this technique has not been used to date to investigate gel structures, it should be possible to do so if appropriate precautions in data interpretation are exercised.

Radiation from pulsed synchrotrons offers a very powerful tool to interrogate the organization of molecular gelators in their fiber networks at or near atomic resolution. This capability with micrometer-sized crystals of biological interest has been demonstrated,[65−67] and report of an example with molecular gels should be just a matter of time—and instrument availability! Also, related techniques may make it possible to view fiber growth. Pulsed excitation to excited states of molecules, coupled with pulsed synchrotron probing of structural changes, has been achieved.[68,69]

Pulsed X-ray free electron lasers[70−72] are now being used to attain near atomic resolution of structures in micrometer-sized crystals. For the time being, the studies have focused on molecules of biological interest. However, the same techniques, with minor modifications, should be applicable to fibers of molecular gel networks, if not the intact networks. At this time, the financial and human resources necessary to perform these studies are enormous. Thus, access to the instrumentation for solving the crystalline structures of gel fibers will be possible only when technological advances reduce the costs. Also, because the primary cross-sectional dimensions of many molecular gel fibers are in the sub-micrometer and few nanometer range, only bundles of such units would be amenable to the current technologies. Because the high energy of the X-rays used for these purposes normally damages the materials being interrogated, the microcrystals are flowed across the electron beams, and their femtosecond-pulsed duration is sufficiently short to avoid most radiation damage. This arrangement may create additional difficulties in interpretation of SAFiN structures because they will not be intact. A diagram of the experimental arrangement for structure analysis using a free electron laser is shown in Figure 4.

Even with atomic-resolution fiber-packing information, two key pieces of structural information are missing, and better or more easily applied techniques to determine them would be very welcome. The first piece is the orientation of the molecules with respect to the axes of the fibers. Only in a

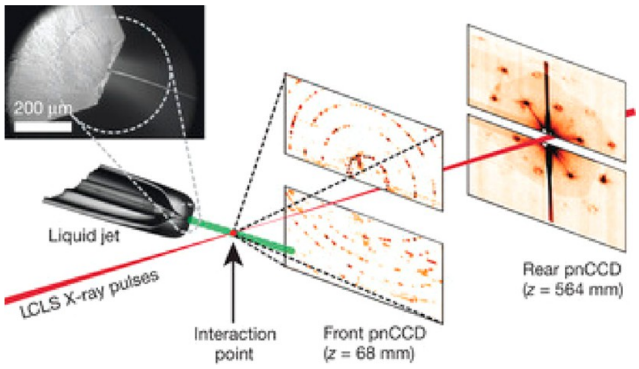


Figure 4. Crystallite materials are flowed in a jet perpendicular to the pulsed X-ray beam. The inset shows an environmental scanning micrograph image of the nozzle with a focusing gas and the crystallites in a liquid. Low- and high-angle diffractions from single pulses are recorded by the pairs of CCD cameras at right that are synched to the laser rep rate. Reprinted with permission from ref 71. Copyright 2011 Macmillan Publishers Ltd.

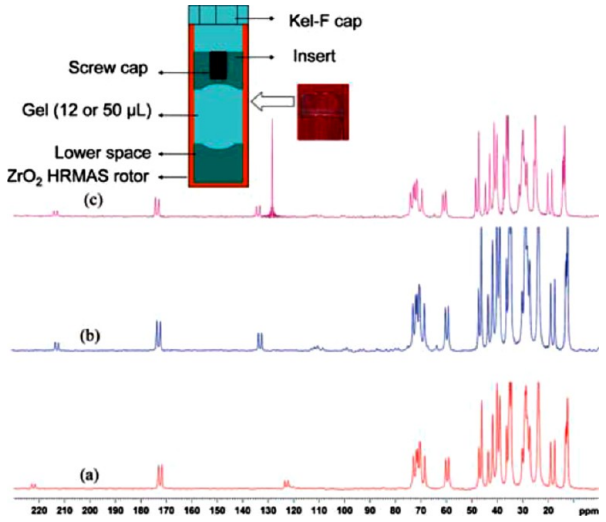


Figure 5. Schematic of the rotor and gel sample used to record the $^{13}C\{^1H\}$ CP-MAS NMR spectra of ethyl cholate gels in benzene-d_6 at (a) 5 and (b) 4 kHz spinning rates and (c) in benzene at 4 kHz. Reprinted with permission from ref 75. Copyright 2010 Royal Society of Chemistry.

few cases has this information been retrieved. One approach, that is not applicable generally, has been to examine the optical birefringence of the network objects and assign packing orientations on that basis. Perhaps the most elegant approach, and a prototype for future investigations, is the use of polarized radiation to interrogate the directions of the transition dipoles for absorption and emission in a gelator with UV−vis active chromophore.[73] In principle, it should be possible to employ polarized IR absorption and Raman as well, although the author is unaware of any such examples.

The second piece of "missing" information is the modes of packing at junction zones (i.e., at the intersection points between fibers). There does not appear to be a useful means to examine these junction zones at this time. Although they represent a small mass/volume fraction of the overall network, they probably play an important role in determining the macroscopic elastic properties of a molecular gel because they are considered to be more disordered and weaker than than the fibers themselves. Despite these complications, some interesting approaches to the structures of other materials may lead eventually to methods for analyzing the structures of junction zones.[74] In that regard, one report of high-resolution CP-MAS spectra of a gel has appeared.[75] It was achieved using a microbore rotor with a screw cap to keep the liquid component from being ejected (Figure 5). Even at 5 kHz spinning speeds, the gel phase was able to withstand the centripetal force exerted on it. The potential power of this technique was demonstrated by the fact that, consistent with X-ray data, two distinct sets of ethyl cholate signals could be discerned. Although weak gels may not be able to survive under these conditions, many others should be able to. With appropriate pulse-sequencing and spinning rates, it may be possible to extract the spectral component at junction zones when the SAFiNs are highly branched, even though the spectra will be dominated by the more crystalline and better ordered molecules within the fibers! Even if that information cannot be obtained, the CP-MAS spectral data, combined with information from other techniques, should enable researchers to unravel some of the mysteries about molecular packing within SAFiNs.

Learning how the gelator molecules are arranged at junction zones is extremely important if one wishes to design gels that melt at high temperatures, are thixotropic, and are rheologically strong: it is reasonable to assume that the junction zones melt before the bulk of the fibers, and that they "break" first and reform first when a gel is subjected to high mechanical strain. Clearly, more attention to the junction zones is needed in order to design gels with specific properties.

New methodologies for these structural measurements that do not require liquid removal and are minimally invasive are beginning to appear. The NMR study mentioned above is an excellent example that should be expanded upon by others. Another is AFM measurements on self-assembled materials that are immersed in a liquid. A pioneering example by Whitten and co-workers followed *in situ* the aggregation of a stilbene-linker steroid gelator in a 1-octanol sol into fibers (Figure 6).[76] More recently, in the amplitude modulation mode, a tip has been shown to be able to distinguish the force exerted by the liquid and by a stearic acid monolayer assembly.[77] In addition, it has been possible to image the network of a molecular gel using a similar approach (Figure 7).[78] As these techniques become more developed and more generally applicable, a wealth of information about pristine gel network structures will become available. Thus, atomic resolution has been achieved by AFM imaging of dry samples.[79,80] Hopefully, future instrumental improvements will allow similar resolution with wet samples! Even with that, there are potential problems with AFM techniques for viewing SAFiNs—the manner in which the substrate (surface) on which a sample is placed and how the fibers of the gel network interact with it have not been explored as they need be; the surface interactions may alter the shapes, distributions, and connectivities of the fibers.

4. PERSPECTIVES FOR *A PRIORI* DESIGN OF MOLECULAR GELATORS

Both stability and efficiency of gels must be correlated with structural information at different distance scales in order to develop *specific* design criteria, with general applicability, for new molecular gelators. Current models for predicting whether a molecule that is not a homologue or isomer of a known molecular gelator will be able to gelate a particular liquid are

dx.doi.org/10.1021/ja503363v | J. Am. Chem. Soc. 2014, 136, 7519−7530

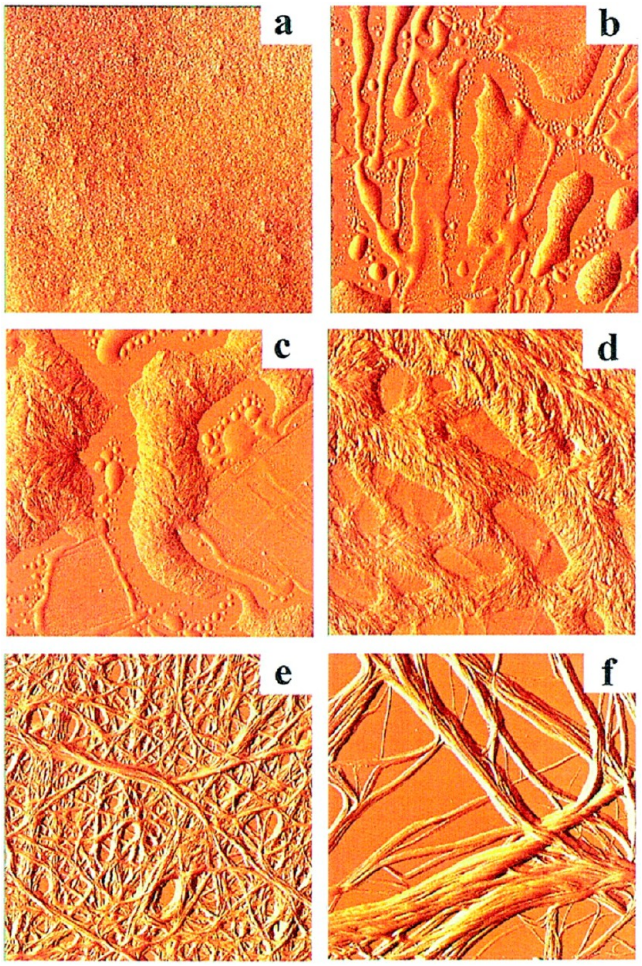


Figure 6. Amplitude-mode AFM images of the sol-to-fibrous network transition of a 1.6 wt % stilbene-linker-steroid gelator in 1-octanol. The images were acquired after the sol phase was cooled to room temperature for (a) 0, (b) 10, (c) 15, (d) 18, (e) 21, and (f) 31 min. The size of each image is 12 μm × 12 μm. Reprinted with permission from ref 76. Copyright 2000 American Chemical Society.

very limited in scope.[81−84] Serendipitous discoveries of new structural classes of molecular gelators still dominate the field!

Some new approaches, especially those applying state-of-the-art computational techniques, may be able to decipher the important aggregation and packing factors that lead to the needed aggregation, nucleation, and 1D growth for SAFiN formation. Any of these computational approaches must yield hypotheses that can be tested by experimentalists. In this regard, both coarse-grained and fine-grained calculations will be useful, as will both quantum mechanical and statistical mechanical treatments.

For example, combining powerful multiprocessor clusters and grid resources with computational and modeling approaches, such the so-called Kitaigorodskii−Aufbau Principle (KAP),[85,86] to study how molecular gelators associate at different stages of their self-assembly, may yield important insights. In that regard, density functional theory (DFT), molecular dynamics, and other types of calculations are being used to discern details of association between molecular gelators at the early stages of their aggregation and to correlate the results of those calculations with experimental observations.[87,88]

Statistical mechanical models that differentiate spherulitic and rod-like growth patterns should be exploited as well. For example, Douglas and co-workers[89−91] have studied self-assembly in model systems that exhibit chain self-assembly by Monte Carlo methods, the formation of thermally reversible gels of flexible chains with associating groups, the dynamics of chain growth by self-assembly following a temperature quench, and phase field modeling of the origin of spherulitic growth forms starting from fiber crystal growth. The latter is very important to understanding the overall nature of the SAFiNs observed after the gels have formed, but it does not address another challenge for future investigations: Why do some molecular gelators and liquids form SAFiN fibers with rectangular cross sections, others are tapes or ribbons, and still others are tubular or other shapes?[92−94] Very few examples have been able to unravel the complexity associated with following the development of such SAFiNs.[95−98]

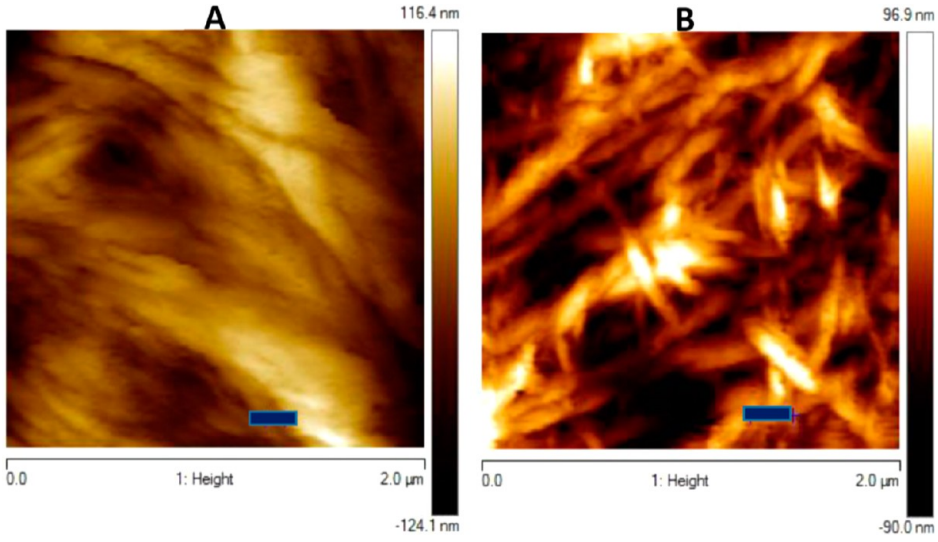


Figure 7. AFM images at 23 °C of hydrogels containing 2 wt % of (A) *N*-propyl-*n*-(*R*)-12-hydroxyoctadecylammonium chloride and (B) *N*-propyl-*n*-(*R*)-12-hydroxyoctadecylammonium bromide. Scale bar is 200 nm. Reprinted with permission from ref 78. Copyright 2013 American Chemical Society.

dx.doi.org/10.1021/ja503363v | *J. Am. Chem. Soc.* 2014, 136, 7519−7530

Empirical approaches are being developed as well. They rely upon detailed comparisons of the thermodynamic properties of a gelator and each of the solvents in which gelation is sought.[99] An example is the Schröder−van Laar equation.[100] However, interpretation of results from it are not always reliable because some users do not correct the gelator concentrations within the SAFiNs for the cgc's (that remain dissolved within the gel phase). More importantly, it assumes that melting of the SAFiNs leads to ideal solutions when, in fact, most melting processes lead to aggregated molecular gelators in the sol phases. Despite this recognized "caveat", the simplicity of the equation has sparked its use in many literature examples (including some from the laboratory of the author). It does have qualitative value in establishing the degree to which the molecular gelators are solvated by the liquid component as the fibrous networks are lost. A better approach may be to correlate gelation (or lack thereof) with the enthalpies and entropies for dissolving molecular gelators in their liquid components.[101]

Among the most promising of these are Hansen solubility parameters,[102−105] which dissect the energetic properties of the molecules involved into dispersive (δ_d), polar (δ_p), and hydrogen-bonding (δ_h) interaction components.[106] Other approaches include the use of Hildebrand and Flory−Huggins interaction parameters,[107−109] which may not treat entropic aspects of gelation correctly; the original equations should be reexamined and modified. Solvatochromic treatments are easier to apply but are much more limited in the information they provide. Regardless, in all of the approaches, there are several possible properties of gels/solutions which can be used. They include the dynamics of gelation[110] and rheology of the gels,[111] gel melting temperatures,[112,113] cgs's,[112] etc. At this point, the one(s) which is (are) most appropriate has not been established. For now, the Hansen parameters for many structurally complicated molecular gelators must be calculated using an additive functional group approach that does always yield reasonable values. In addition, because some of these treatments have been developed for polymer aggregation and crystallization, they may require modifications to be truly applicable to predicting when, if, and why molecular gels will form. Perhaps these treatments will be most informative when they are applied to one molecular gelator and a series of homologous liquids containing the same functional group.

One of those modifications may be difficult to implement in a general way. It may be inappropriate to treat systems with mixtures of miscible liquids as homogeneously distributed solvents if interactions between functional groups on the molecular gelator and one of the liquid components are very strong with respect to the interactions with the other. In those cases, the solvation shell around the gelator molecules, and even around specific parts of them, can be enriched in the more favorably interacting component. As a result, the bulk solvent parameters will not be appropriate measures. In spite of this problem, some examples with mixtures treated as homogeneously distributed solvents have yielded very interesting insights into how gelation occurs. In one case, Hansen solubility spheres (see, for example, Figure 8) were used to understand why glucono-appended 1-pyrenesulfonyl molecules containing α,ω-diaminoalkane spacers (P*n*) can form gels in some water/tetrahydrofuran mixtures even though the P*n* are insoluble in both water and tetrahydrofuran, and the molecular structure of the P*n* should favor selective solvation at its different parts by water or tetrahydrofuran.[112] The number of examples of this sort is currently too small to state the limitations of this form of analysis.

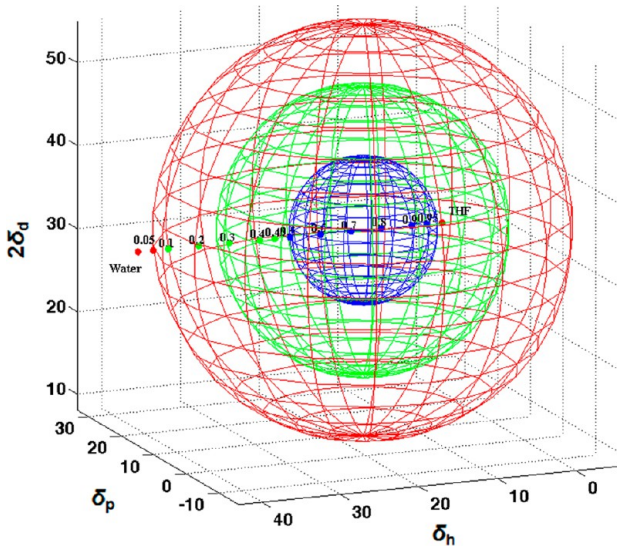
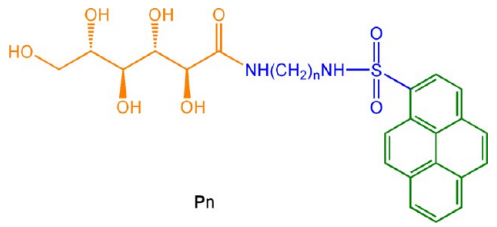
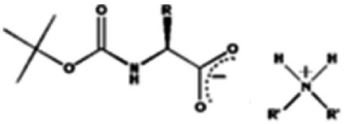


Figure 8. Hansen solubility spheres for 2.0 wt % P7 in mixtures of water and tetrahydrofuran with spheres/shells: blue, soluble; green, gel; and red, insoluble. Reprinted with permission from ref 112. Copyright 2013 American Chemical Society.



The most commonly employed approaches to predict molecular gelation have been summarized recently in a "user-friendly", instructive format[105] that should be a good starting point for further development of such treatments. It demonstrates the need for such developments and the potential wealth of information that they may provide. However, totally unexpected molecular gelator systems that open new perspectives and possibilities are being discovered constantly. For example, it is doubtful that anyone could have predicted that mixing $NiCl_2{\cdot}6H_2O$, a variety of simple amines, and methanol would yield molecular gels[114] or that a simple salt, dicyclohexylammonium *tert*-butyloxyglycinate (GLY-C), in nitrobenzene would be capable of yielding very strong, self-healing, and moldable gels (Figure 9)![115]



GLY-C (R=H, R'=cyclohexyl)

Another, much more complex example of the construction of a shape-persistent, elastic gel involves stringing together molecules containing dialkylammonium, benzocrown ether, and 1,2,3-triazole groups. First, intermolecular, reversible complexation of the ammonium and crown groups produces 1D chains. Then, the SAFiN is produced and gelation is accomplished by cross-linking the chains with Pd(II) ions that

dx.doi.org/10.1021/ja503363v | J. Am. Chem. Soc. 2014, 136, 7519−7530

Figure 9. (A) 7.0 wt % GLY-C-in-nitrobenzene gel. (B) Gel from panel A under ca. 117 g of weight. (C) Gel from panel A carved into a sculpture of a mother holding a child. The author saw this sculpture in a hermetically sealed case (to avoid solvent loss) in Kolkata ca. 2 years after it was made; it was still in good condition. Reprinted with permission from ref 115. Copyright 2012 Wiley-VCH Verlag.

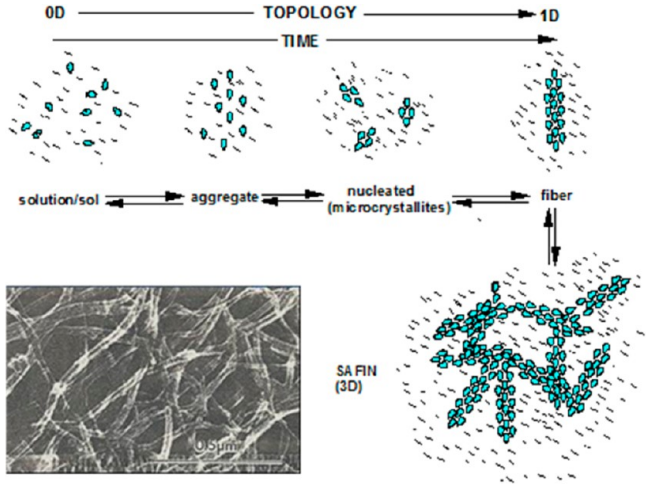
interact with the triazole moieties.[116] Such examples of clever "engineering" to pass from 0D to 3D self-assembled systems are becoming more prevalent in the literature. They may be useful because they can be tailored for specific applications by combining properties of simple molecular gelators, as one would elements in a toolbox.

5. PERSPECTIVES FOR FOLLOWING THE EARLY STAGES OF SELF-ASSEMBLY OF MOLECULAR GELATORS INTO 3D NETWORKS

Although much has been learned during the past decade about the supramolecular assembly of polymeric chains (topologically 1D objects) into a variety of 2D and 3D objects,[9,117−119] much less is known about the *initial* steps that take small molecules (topologically 0D objects at even sub-micrometer length scales) to (topologically) 1D objects. In fact, the manner in which 1D objects, especially those composed of polymeric chains,[120] convert to 2D and 3D objects has received much more attention than the 0D→1D transformations because experimental observations of the events using IR, NMR, ESR, fluorescence, circular dichroism, light scattering, various microscopies, diffraction, and other tools become much easier as the degree of aggregation and, thus, the size of the objects under scrutiny increase. For example, some SAFiNs may form as depicted in Scheme 1,[30] while in others, new growths may develop on the sides of fibers or by tip-splitting (i.e., branching at the ends of growing fibers), giving rise to branched networks or spherulites.[121−125] Surfactant molecules not leading necessarily to crystalline SAFiN structures may follow a yet different pathway.[126] Unraveling the dynamics of these intermediate steps is critical to understanding the final network structures.[127]

Significant advances have been made to interpret these various modes of aggregation from their inception using data sets for any of several parameters that are sensitive to the degree of molecular gelator aggregation. One, alluded to above, is the model devised by Liu and co-workers to account for the presence or absence of fiber branching during SAFiN growth.[121] The Avrami treatment,[128,129] a power-law-dependent equation, has been found to yield useful insights into the modes by which molecular gelators nucleate and grow in a number of liquids.[44,50] Another power-law-dependent approach has been applied to the slow gelation of di-*O*-benzylidene

Scheme 1. Cartoon Representation of the Steps in the Evolution of LMOGs (0D Objects, Teardrops) to Fibers (1D objects) and, in Some Cases, to SAFiNs (3D Objects) in Liquids (Wavy Lines); Shown at the Lower Left Is a Freeze-Fracture Electron Micrograph of a SAFiN[8a]



[a]Reprinted with permission from ref 30. Copyright 2013 Wiley-VCH Verlag GmbH & Co. KGaA.

sorbitol in organic liquids using NMR data.[130] The recent isodesmic and cooperative classifications for these processes hold even greater promise for revealing how gelator molecules assemble.[131] In isodesmic processes, molecular gelators add to (and are lost from) an aggregated/nucleated assembly with a rate constant that does not change as a function of the progress toward complete SAFiN formation (i.e., the change in free energy for fiber growth is constant); in cooperative processes, the growth of fibers can be separated into steps involving aggregates that are intrinsically less stable than the growing fibers that emanate from them. As a result, initial aggregation is the rate-determining step in SAFiN formation. These two types of growth are analogous to the continuous and spontaneous nucleation designations used by Avrami, but they are capable of yielding more-detailed information than available from the Avrami constants. The three approaches rely on analyses of experimental data and, therefore, require very good and extensive data sets. In a recent example, the latter model has been applied elegantly, in combination with DFT calculations, by George and co-workers to conclude that a coronene bisimide derivative aggregates into 1D fibers via an isodesmic process.[132] With a sufficiently large body of examples, it may be possible to discern fundamental patterns relating molecular structure and aggregation growth characteristics.

Even with the aid of KAP and DFT types of calculations, the initial aggregation events remain elusive. Currently, it is possible to observe the rates of aggregation and orientations of only *two* molecular gelator molecules uniquely if the pair possesses a unique physical feature, such as an excimer fluorescence.[44] However, from that point forward, until the aggregate reaches a size amenable to observation by one of the methods mentioned in section 3 (i.e., many thousands of molecules), there is a blind spot in our knowledge. Even then, the aggregates are not monodisperse—there is a distribution of aggregate sizes along the temporal path to SAFiN growth.

Mass spectrometry may offer the means to view experimentally the rates at which two molecular gelator

molecules "aggregate" and then follow their growth and distribution as a function of time into larger aggregates, consisting of as many as hundreds of molecules. The basic ideas and equipment for this approach have been laid out by Cooks and co-workers.[133] If a stream of microdroplets consisting of a dilute solution of a molecular gelator and a gelatable liquid is directed toward the inlet of an orbitrap time-of-flight (or functionally similar) mass spectrometer, the degree to which the gelator molecules have aggregated can be determined. The selection of the liquid and the droplet temperature can be varied to probe different degrees of aggregation using m/z ratios of the isotopic peaks. It may also be possible to follow the kinetics of gelator aggregation from the initial stages,[134] although some instrumental advances may be needed to do so.

6. POTENTIAL AND REALIZED APPLICATIONS OF MOLECULAR GELS

The introduction sections to most articles on molecular gels cite many *potential* applications for them. However, few have been realized as of yet due to a number of factors. One of these is that many molecular gels have limited lifetimes at ambient temperatures and must be kept in sealed containers to avoid evaporation or changes in the composition of their liquid components. In some cases, this problem can be overcome by using very high-boiling and moisture-insensitive liquids. Other problems are more difficult and expensive to overcome; for example, if molecular gels are to be used for medical purposes (e.g., as drug delivery agents), all of their components must be approved by an authorized health agency, such as the Food and Drug Agency in the United States.

Despite these hurdles, several interesting uses of molecular gels have been realized. For example, dibenylidene sorbitol has been used to strengthen polymeric materials; it retains its fibrous networks even when cooled from polymer melts.[135] Several ingenious uses of enzymes to make or destroy gels in cells have been developed.[136,137] They may lead to new and very specific therapies involving spatially specific drug release. Many other exciting new applications can be envisioned,[25] and there is every reason to believe that many of them may find their way into our daily lives eventually. Some are mentioned here. The list is not inclusive; let the reader's mind wander into new ones!

Can the use of sonication and microwave irradiation be expanded to make gels *in situ* in molecular gelator/liquid sols that are not gels when cooled?[138−140] Can UV−vis radiation be used more broadly to construct or destroy molecular gels either reversibly[141,142] or irreversibly[143] for specific purposes? Can magnetic[144] and electric[145] fields be used more generally to align fibrillar networks? Can molecular gels with magnetic nanoparticles,[146] catalytic sites,[147] or liquids consisting of liquid crystals[148] be adapted for industrial uses? Can molecular gels become a viable means to clean oil and chemical spills?[149−151] Can molecular gels be used to reveal details about more complex systems related to blood clotting, the onset of Alzheimer's disease,[152] and silk fiber extrusion?[153−155] Can molecular gels be used as templates to fabricate more robust materials on a commercial scale?[156,157] Can the use of molecular gels in the food industry be expanded?[158−161] Can luminescent gels be employed in real-world analytical applications as sensors and light guides?[144,162−165] Can molecular gels supplant polymeric ones for some cleaning/restoration projects in conservation science with works of cultural heritage?[166−168] Can "recipes" be found for synthesizing very strong or weak molecular gels, and ones with reversible adhesion or fast thixotropic recovery? Currently, such materials are discovered by chance, although they may be useful as dental adhesives.[169]

7. CONCLUSIONS AND CHALLENGES

With so many questions awaiting answers, the prospects should be bright for imaginative scientists to make important inroads to understanding the basic properties of molecular gels and devising methods to enhance their applications. However, the solutions will require inputs from scientists with a wide range of interests—soft matter, self-assembly, thermodynamics, rheology, structural techniques, theory, etc.—working together, because molecular gels is a field of study that epitomizes interdisciplinarity. The author hopes that this Perspective will stimulate others to join the hunt for answers and to formulate additional questions.

■ ASSOCIATED CONTENT

Supporting Information

Complete refs 65, 70, and 71. This material is available free of charge via the Internet at http://pubs.acs.org.

■ AUTHOR INFORMATION

Corresponding Author

weissr@georgetown.edu

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

This article is dedicated to Prof. Henri Bouas-Laurent on the occasion of his 80th birthday. The author thanks the U.S. National Science Foundation (Grant CHE-1147353) and The Gulf of Mexico Research Initiative for financial support and The Indian Institute of Science, where most of this manuscript was written, for a Pfizer Visiting Professorship. He is extremely grateful to his colleagues and collaborators, especially Pierre Terech, without whose help and guidance over the years this article would not have been possible.

■ REFERENCES

(1) van Esch, J. H. *Langmuir* **2009**, *25*, 8392−8394.
(2) Von Lipowitz, A. *Liebigs Ann. Chem. Pharm.* **1841**, *38*, 348−355.
(3) Abdallah, D. J.; Sirchio, S. A.; Weiss, R. G. *Langmuir* **2000**, *16*, 7558−7561.
(4) George, M.; Tan, G.; John, V. T.; Weiss, R. G. *Chem.—Eur. J.* **2005**, *11*, 3243−3254.
(5) Grassi, S.; Carretti, E.; Dei, L.; Branham, C. W.; Kahr, B.; Weiss, R. G. *New J. Chem.* **2011**, *35*, 445−452.
(6) Stupp, S. I.; Zha, R. H.; Palmer, L. C.; Cui, H.-G.; Bitton, R. *Faraday Discuss.* **2013**, *166*, 9−30.
(7) Although molecular gels are commonly separated into hydrogel and organogel subcategories, they will not be here because the author considers water to be just another liquid (albeit a complex one!).
(8) Lin, Y.-c.; Kachar, B.; Weiss, R. G. *J. Am. Chem. Soc.* **1989**, *111*, 5542−5551.
(9) Dastidar, P. *Chem. Soc. Rev.* **2008**, *37*, 2699−2715.
(10) Estroff, L. A.; Hamilton, A. D. *Chem. Rev.* **2004**, *104*, 1201−1217.
(11) Terech, P.; Weiss, R. G. *Chem. Rev.* **1997**, *97*, 3133−3159.
(12) Sangeetha, N. M.; Maitra, U. *Chem. Soc. Rev.* **2005**, *34*, 821−836.
(13) Buerkle, L. E.; Rowan, S. J. *Chem. Soc. Rev.* **2012**, *41*, 6089−6102.

(14) Das, D.; Kar, T.; Das, K. *Soft Matter* **2012**, *8*, 2348−2365.
(15) Suzuki, M.; Hanabusa, K. *Chem. Soc. Rev.* **2009**, *38*, 967−975.
(16) Steed, J. W. *Chem. Soc. Rev.* **2010**, *39*, 3686−3699.
(17) Smith, D. K. *Chem. Soc. Rev.* **2009**, *38*, 684−694.
(18) Dawn, A.; Shiraki, T.; Haraguchi, S.; Tamaru, S.; Shinkai, S. *Chem.—Asian J.* **2011**, *6*, 266−282.
(19) Kartha, K. K.; Mukhopadhyay, R. D.; Ajayaghosh, A. *Chimia* **2013**, *67*, 51−63.
(20) Babu, S. S.; Praveen, V. K.; Ajayaghosh, A. *Chem. Rev.* **2014**, *114*, 1973−2129.
(21) George, M.; Weiss, R. G. *Acc. Chem. Res.* **2006**, *39*, 489−497.
(22) Abdallah, D. J.; Weiss, R. G. *Adv. Mater.* **2000**, *12*, 1237−1247.
(23) Yu, G.; Yan, X.; Han, C.; Huang, F. *Chem. Soc. Rev.* **2013**, *42*, 6697−6722.
(24) Tam, A. Y.-Y.; Yam, V. W.-W. *Chem. Soc. Rev.* **2013**, *42*, 1540−1567.
(25) Hirst, A. R.; Escuder, B.; Miravet, J. F.; Smith, D. K. *Angew. Chem., Int. Ed.* **2008**, *47*, 8002−8018.
(26) Piepenbrock, M.-O. M.; Lloyd, G. O.; Clarke, N.; Steed, J. W. *Chem. Rev.* **2010**, *110*, 1960−2004.
(27) Terech, P., Weiss, R. G., Eds. *Molecular Gels, Materials with Self-Assembled Fibrillar Networks*; Springer: Dordrecht, 2006.
(28) Fages, F., Ed. *Low Molecular Mass Gelators: Design, Self-Assembly, Function*; Topics in Current Chemistry *256*; Springer-Verlag: Berlin, 2005.
(29) Escuder, B., Ed. *Functional Molecular Gels*; Royal Society of Chemistry: Cambridge, 2014.
(30) Caran, K. L.; Lee, D.-C.; Weiss, R. G. In *Soft Fibrillar Materials: fabrication and applications*; Liu, X.-Y., Li, J.-L., Eds.; Wiley-VCH Verlag: Weinheim, 2013; Chap. 1.
(31) Kuzmenko, I.; Rapaport, H.; Kjaer, K.; Als-Nielsen, J.; Weissbuch, I.; Lahav, M.; Leiserowitz, L. *Chem. Rev.* **2001**, *101*, 1659−1696.
(32) Desiraju, G. R. *Crystal design: structure and function*; Wiley: Hoboken, NJ, 2003.
(33) Jordon Lloyd, D. *Colloid Chemistry*, Vol. *1*; Alexander, J., Ed.; The Chemical Catalog Co.: New York, 1926; p 767.
(34) Rogovina, L. Z.; Vasil'ev, V. G.; Braudo, E. E. *Polym. Sci., Ser. C* **2008**, *50*, 85−92.
(35) Brinker, C. J.; Scherer, G. W. *Sol-Gel Science: The Physics and Chemistry of Sol-Gel Processing*; Academic Press: San Diego, 1989.
(36) Kawaguchi, H. *J. Oleo Sci.* **2013**, *62*, 865−871.
(37) Lyon, L. A.; Fernandez-Nieves, A. In *Annual Reviews in Physical Chemistry*, Vol. *63*; Johnson, M. A., Martinez, T. J., Eds.; Annual Reviews: Palo Alto, CA, 2012; pp 25−43.
(38) Jones, R. A. L. *Soft Condensed Matter*; Oxford University Press: New York, 2002.
(39) Flory, P. J. *Discuss. Faraday Soc.* **1974**, *57*, 7−18.
(40) Raghavan, S. R.; Cipriano, B. H. In *Molecular Gels, Materials with Self-Assembled Fibrillar Networks*; Weiss, R. G., Terech, P., Eds.; Springer: Dordrecht, 2006; pp 233−244.
(41) Angelova, L. V.; Terech, P.; Natali, I.; Dei, L.; Carretti, E.; Weiss, R. G. *Langmuir* **2011**, *27*, 11671−11682.
(42) Burchard, W.; Ross-Murphy, S. B. *Physical Networks, Polymers and Gels*; Elsevier: London, 1990.
(43) Hirst, A. R.; Coates, I. A.; Boucheteau, T. R.; Miravet, J. F.; Escuder, B.; Castelletto, V.; Hamley, I. W.; Smith, D. K. *J. Am. Chem. Soc.* **2008**, *130*, 9113−9121.
(44) Huang, X.; Terech, P.; Raghavan, S. R.; Weiss, R. G. *J. Am. Chem. Soc.* **2005**, *127*, 4336−4344.
(45) Chou, C. M.; Hong, P. D. *Macromolecules* **2004**, *37*, 5596−5606.
(46) Lu, P. J.; Zaccarelli, E.; Ciulla, F.; Schofield, A. B.; Sciortino, F.; Weitz, D. A. *Nature* **2009**, *453*, 499−503.
(47) Nanda, J.; Biswas, A.; Banerjee, A. *Soft Matter* **2013**, *9*, 4198−4202.
(48) Basak, S.; Nanda, J.; Banerjee, A. *Chem. Commun.* **2014**, *20*, 2356−2359.
(49) Lescanne, M.; Grondin, P.; d'Aléo, A.; Fages, F.; Pozzo, J.-L.; Mondain Monval, O.; Reinheimer, P.; Colin, A. *Langmuir* **2004**, *20*, 3032−3041.
(50) Huang, X.; Raghavan, S. R.; Terech, P.; Weiss, R. G. *J. Am. Chem. Soc.* **2006**, *128*, 15341−15352.
(51) Terech, P. In *Molecular Gels, Materials with Self-Assembled Fibrillar Networks*; Weiss, R. G., Terech, P., Eds.; Springer: Dordrecht, 2006; pp 275−324.
(52) Anne, M. In *Molecular Gels, Materials with Self-Assembled Fibrillar Networks*; Weiss, R. G., Terech, P., Eds.; Springer: Dordrecht, 2006; pp 325−361.
(53) Takeno, H.; Mochizuki, T. *Colloid Polym. Sci.* **2013**, *291*, 2783−2789.
(54) Dickinson, E. *J. Chem. Soc., Faraday Trans.* **1997**, *93*, 111−114.
(55) Ostuni, E.; Kamaras, P.; Weiss, R. G. *Angew. Chem., Int. Ed.* **1996**, *35*, 1324−1326.
(56) Terech, P.; Aymonier, C.; Loppinet-Serani, A.; Bhat, S.; Banerjee, S.; Das, R.; Maitra, U.; Del Guerzo, A.; Desvergne, J. P. *J. Phys. Chem. B* **2010**, *114*, 11409−11419.
(57) Placin, F.; Desvergne, J. P.; Belin, C.; Buffeteau, T.; Desbat, B.; Ducasse, L.; Lassègues, J. C. *Langmuir* **2003**, *19*, 4563−4572.
(58) Orlova, E. V.; Saibil, H. R. *Chem. Rev.* **2011**, *111*, 7710−7748.
(59) Danino, D.; Talmon, Y. In *Molecular Gels. Materials with Self-Assembled Fibrillar Networks*; Weiss, R. G., Terech, P., Eds.; Springer: Dordrecht, 2006; pp 253−274.
(60) Schur, F. K. M.; Hagen, W. J. H.; de Marco, A.; Briggs, J. A. G. *J. Struct. Biol.* **2013**, *184*, 394−400.
(61) Milne, J. L. S.; Borgnia, M. J.; Bartesaghi, A.; Tran, E. E. H.; Earl, L. A.; Schauder, D. M.; Lengyel, J.; Pierson, J.; Patwardhan, A.; Subramaniam, S. *FEBS J.* **2013**, *280*, 28−45.
(62) Carlson, D. B.; Gelb, J.; Palshin, V.; Evans, J. E. *Microsc. Microanal.* **2013**, *19*, 22−29.
(63) Cinquin, B. P.; Do, M.; McDermott, G.; Walters, A. D.; Myllys, M.; Smith, E. A.; Cohen-Fix, O.; Le Gros, M. A.; Larabell, C. A. *J. Cell. Biochem.* **2014**, *115*, 209−216.
(64) Choudhury, A. R.; Islam, K.; Kirchner, M. T.; Mehta, G.; Guru. *J. Am. Chem. Soc.* **2004**, *126*, 12274−12275.
(65) Kern, J.; Alonso-Mori, R.; Hellmich, J.; et al. *Proc. Natl. Acad. Sci. U.S.A.* **2012**, *109*, 9721−9726.
(66) Wulff, M.; Schotte, F.; Naylor, G.; Bourgeois, D.; Moffat, K.; Mourou, G. *Nucl. Instrum. Methods Phys. Res. A* **1997**, *398*, 69−84.
(67) Nishiyama, Y.; Sugiyama, J.; Chanzy, H.; Langan, P. *J. Am. Chem. Soc.* **2003**, *125*, 14300−14306.
(68) Collet, E.; Lorenc, M.; Cammarata, M.; Guerin, L.; Servol, M.; Tissot, A.; Boillot, M.-L.; Cailleau, H.; Buron-Le Cointe, M. *Chem.—Eur. J.* **2012**, *18*, 2051−2055.
(69) Benedict, J. B.; Makal, A.; Sokolow, J. D.; Trzop, E.; Scheins, S.; Henning, R.; Graber, T.; Coppens, P. *Chem. Commun.* **2011**, *47*, 1704−1706.
(70) Boutet, S.; Lomb, L.; Williams, G. J.; et al. *Science* **2012**, *337*, 362−364.
(71) Chapman, H. N.; Fromme, P.; Barty, A.; et al. *Nature* **2011**, *470*, 73−77.
(72) Bogan, M. J. *Anal. Chem.* **2013**, *85*, 3464−3471.
(73) Giansante, C.; Raffy, G.; Schafer, C.; Rahma, H.; Kao, M. T.; Olive, A. G. L.; Del Guerzo, A. *J. Am. Chem. Soc.* **2011**, *133*, 316−325.
(74) Toudic, B.; Garcia, P.; Odin, C.; Rabiller, P.; Ecolivet, C.; Collet, E.; Bourges, P.; McIntyre, G. J.; Hollingsworth, M. D.; Breczewsk, T. *Science* **2008**, *319*, 69−71.
(75) Nonappa; Lahtinen, M.; Behera, B.; Kolehmainen, E.; Maitra, U. *Soft Matter* **2010**, *6*, 1748−1757.
(76) Wang, R.; Geiger, C.; Chen, L.; Swanson, B.; Whitten, D. G. *J. Am. Chem. Soc.* **2000**, *122*, 2399−2400.
(77) Amadei, C. A.; Santos, S.; Pehkonen, S. O.; Verdaguer, A.; Chiesa, M. *J. Phys. Chem. C* **2013**, *117*, 20819−20825.
(78) Mallia, V. A.; Seo, H.-I.; Weiss, R. G. *Langmuir* **2013**, *29*, 6476−6484.
(79) Zhang, J.; Chen, P.-C.; Yuan, B.-K.; Ji, W.; Cheng, Z.-H.; Qiu, X.-H. *Science* **2013**, *342*, 611−614.

(80) de Oteyza, D. G.; Gorman, P.; Chen, Y.-C.; Wickenburg, S.; Riss, A.; Mowbray, D. J.; Etkin, G.; Pedramrazi, Z.; Tsai, H.-Z.; Rubio, A.; Crommie, M. F.; Fischer, F. R. *Science* **2013**, *340*, 1434−1437.
(81) Li, J.-L.; Yuan, B.; Liu, X.-Y.; Hu, H.-Y. *Cryst. Growth Des.* **2010**, *10*, 2699−2706.
(82) Schoonbeek, F. S.; van Esch, J. H.; Hulst, R.; Kellogg, R. M.; Feringa, B. L. *Chem.—Eur. J.* **2000**, *6*, 2633−2643.
(83) Gesquiere, A.; Abdel-Mottaleb, M. M. S.; De Feyter, S.; De Schryver, F. C.; Schoonbeek, F.; van Esch, J.; Kellogg, R. M.; Feringa, B. L.; Calderone, A.; Lazzaroni, R.; Bredas, J. L. *Langmuir* **2000**, *16*, 10385−10391.
(84) Zweep, N.; Hopkinson, A.; Meetsma, A.; Browne, W.; Feringa, B. L.; van Esch, J. H. *Langmuir* **2009**, *25*, 8802−8809.
(85) Abdallah, D. J.; Bachman, R. E.; Perlstein, J.; Weiss, R. G. *J. Phys. Chem. B* **1999**, *103*, 9269−9278.
(86) Perlstein, J.; Steppe, K.; Vaday, S.; Ndip, E. M. N. *J. Am. Chem. Soc.* **1996**, *118*, 8433−8443.
(87) Dou, C. D.; Li, D.; Gao, H. Z.; Wang, C. Y.; Zhang, H. Y.; Wang, Y. *Langmuir* **2010**, *26*, 2113−2118.
(88) Vujicic, N. S.; Glasovac, Z.; Zweep, N.; van Esch, J. H.; Vinkovic, M.; Popovic, J.; Zinic, M. *Chem.—Eur. J.* **2013**, *19*, 8558−8572.
(89) Gránásy, L.; Pusztai, T.; Borzsonyi, T.; Warren, J. A.; Douglas, J. F. *Nat. Mater.* **2004**, *3*, 645−650.
(90) Gránásy, L.; Pusztai, T.; Tegze, G.; Warren, J. A.; Douglas, J. F. *Phys. Rev. E* **2005**, *72*, 011605/1−15.
(91) Raghavan, S. R.; Douglas, J. F. *Soft Matter* **2012**, *8*, 8539−8546.
(92) Selinger, J. V.; Spector, M. S.; Schnur, J. M. *J. Phys. Chem. B* **2001**, *105*, 7157−7169.
(93) Corezzi, S.; Fioretto, D.; De Michele, C.; Zaccarelli, E.; Sciortino, F. *J. Phys. Chem. B* **2010**, *114*, 3769−3775.
(94) Tanaka, F. In *Molecular Gels. Materials with Self-Assembled Fibrillar Networks*; Weiss, R. G., Terech, P., Eds.; Springer: Dordrecht, 2006; Chap. 1.
(95) Aggeli, A.; Nyrkova, I. A.; Bell, M.; Harding, R.; Carrick, L.; McLeish, T. C. B.; Semenov, A. N.; Boden, N. *Proc. Natl. Acad. Sci. U.S.A.* **2001**, *98*, 11857−11862.
(96) Shimizu, T.; Masuda, M.; Minamikawa, H. *Chem. Rev.* **2005**, *105*, 1401−1443.
(97) Terech, P.; Jean, B.; Ne, F. *Adv. Mater.* **2006**, *18*, 1571−1574.
(98) Boettcher, C.; Schade, B.; Fuhrhop, J.-H. *Langmuir* **2001**, *17*, 873−877.
(99) Edwards, W.; Lagadec, C. A.; Smith, D. K. *Soft Matter* **2011**, *7*, 110−117.
(100) Atkins, P.; de Paula, J. *Physical Chemistry*, 8th ed.; W. H. Freeman: New York, 2006; pp 189−193.
(101) Muro-Small, M. L.; Chen, J.; McNeil, A. J. *Langmuir* **2011**, *27*, 13248−13253.
(102) Raynal, M.; Bouteiller, L. *Chem. Commun.* **2011**, *47*, 8271−8273.
(103) Hanabusa, K.; Matsumoto, M.; Kimura, M.; Kakehi, A.; Shirai, H. *J. Colloid Interface Sci.* **2000**, *224*, 231−244.
(104) Bonnet, J.; Suissa, G.; Raynal, M.; Bouteiller, L. *Soft Matter* **2014**, *10*, 3154−3160.
(105) Lan, Y.; Corradini, M. G.; Liu, X.; May, T.; Borondics, F.; Weiss, R. G.; Rogers, M. A. *Langmuir* **2014**, submitted.
(106) Hansen, C. M. *Hansen Solubility Parameters: A User's Handbook*, 2nd ed.; CRC Press: Boca Raton, 2007.
(107) Fan, K.; Niu, L.; Li, J.; Feng, R.; Qu, R.; Liu, T.; Song, J. *Soft Matter* **2013**, *9*, 3057−3062.
(108) Feng, L.; Cavicchi, K. A. *Soft Matter* **2012**, *8*, 6483−6492.
(109) Niu, L.; Song, J.; Li, J.; Tao, N.; Lu, M.; Fan, K. *Soft Matter* **2013**, *9*, 7780−7786.
(110) Diehn, K. K.; Oh, H.; Hashemipour, R.; Weiss, R. G.; Raghavan, S. R. *Soft Matter* **2014**, *10*, 2632−2640.
(111) Terech, P.; Pasquier, D.; Bordas, V.; Rossat, C. *Langmuir* **2000**, *16*, 4485−4494.
(112) Yan, N.; Xu, Z.; Diehn, K. K.; Raghavan, S. R.; Fang, Y.; Weiss, R. G. *J. Am. Chem. Soc.* **2013**, *135*, 8989−8999.
(113) Yan, N.; Xu, Z.-Y.; Diehn, K. K.; Raghavan, S. R.; Fang, Y.; Weiss, R. G. *Langmuir* **2013**, *29*, 973−805.
(114) Dey, S.; Datta, D.; Chakraborty, K.; Nandi, S.; Anoop, A.; Pathak, T. *RSC Adv.* **2013**, *3*, 9163−9166.
(115) Sahoo, P.; Sankolli, R.; Lee, H.-Y.; Raghavan, S. R.; Dastidar, P. *Chem.—Eur. J.* **2012**, *18*, 8057−8063.
(116) Yan, X.; Xu, D.; Chi, X.; Chen, J.; Dong, S.; Ding, X.; Yu, Y.; Huang, F. *Adv. Mater.* **2012**, *24*, 362−369.
(117) Whitesides, G. M.; Boncheva, M. *Proc. Natl. Acad. Sci. U.S.A.* **2002**, *99*, 4769−4774.
(118) Jonkheijm, P.; van der Schoot, P.; Schenning, A. P. H. J.; Meijer, E. W. *Science* **2006**, *313*, 80−83.
(119) Smulders, M. M. J.; Schenning, A. P. H. J.; Meijer, E. W. *J. Am. Chem. Soc.* **2008**, *130*, 606−611.
(120) Te Nijenhuis, K. *Thermoreversible Networks*; Advances in Polymer Science *130*; Springer Verlag: Berlin, 1997.
(121) Wang, R. Y.; Liu, X. Y.; Narayanan, J.; Xiong, J. Y.; Li, J. L. *J. Phys. Chem. B* **2006**, *110*, 25797−25802.
(122) Li, J. L.; Liu, X. Y.; Strom, C. S.; Xiong, J. Y. *Adv. Mater.* **2006**, *18*, 2574−2578.
(123) Wang, R. Y.; Liu, X. Y.; Xiong, J. Y.; Li, J. L. *J. Phys. Chem. B* **2006**, *110*, 7275−7280.
(124) Liu, X. Y. *Top. Current Chem.* **2005**, *256*, 1−37.
(125) Li, J. L.; Liu, X. Y.; Wang, R. Y.; Xiong, J. Y. *J. Phys. Chem. B* **2005**, *109*, 24231−24235.
(126) Raghavan, S. R. *Langmuir* **2009**, *25*, 8382−8385.
(127) M. Lescanne, M.; Colin, A.; Mondain-Monval, O.; Fages, F.; Pozzo, J.-L. *Langmuir* **2003**, *19*, 2013−2020.
(128) Avrami, M. *J. Chem. Phys.* **1939**, *7*, 1103−1112.
(129) Avrami, M. *J. Chem. Phys.* **1940**, *8*, 212−224.
(130) VanderHart, D. L.; Douglas, J. F.; Hudson, S. D.; Antonucci, J. M.; Wilder, E. A. *Langmuir* **2011**, *27*, 1745−1757. This article also describes a useful method to estimate the size of crystalline domains in SAFiNs when more than one type of molecular packing in microdomains is present.
(131) de Greef, T. F. A.; Smulders, M. M. J.; Wolffs, M.; Schenning, A. P. H. J.; Sijbesma, R. P.; Meijer, E. W. *Chem. Rev.* **2009**, *109*, 5687−5754.
(132) Kulkarni, C.; Munirathinam, R.; George, S. J. *Chem.—Eur. J.* **2013**, *19*, 11270−11278.
(133) Perry, R. H.; Cooks, R. G.; Noll, R. J. *Mass Spectrom. Rev.* **2008**, *27*, 661−699.
(134) Fabris, D. *Mass Spectrom. Rev.* **2005**, *24*, 30−54.
(135) Wilder, E. A.; Hall, C. K.; Spontak, R. J. *J. Colloid Interface Sci.* **2003**, *267*, 509−518.
(136) Li, J. Y.; Gao, Y.; Kuang, Y.; Shi, J. F.; Du, X. W.; Zhou, J.; Wang, H. M.; Yang, Z. M.; Xu, B. *J. Am. Chem. Soc.* **2013**, *135*, 9907−9914.
(137) Majumder, J.; Deb, J.; Das, M. R.; Jana, S. S.; Dastidar, P. *Chem. Commun.* **2014**, *50*, 1671−1674.
(138) Naota, T.; Koori, H. *J. Am. Chem. Soc.* **2005**, *127*, 9324−9325.
(139) Ke, D.; Zhan, C.; Li, A. D. Q.; Yao, J. *Angew. Chem., Int. Ed.* **2011**, *50*, 3715−3719.
(140) Wang, C.; Zhang, D.; Zhu, D. *J. Am. Chem. Soc.* **2005**, *127*, 16372−16373.
(141) Murata, K.; Aoki, M.; Suzuki, T.; Harada, T.; Kawabata, H.; Komori, T.; Ohseto, F.; Ueda, K.; Shinkai, S. *J. Am. Chem. Soc.* **1994**, *116*, 6664−6676.
(142) Hachisako, H.; Nakayama, H.; Ihara, H. *Chem. Lett.* **1999**, 1165−1166.
(143) Kumar, R.; Raghavan, S. R. *Soft Matter* **2009**, *5*, 797−803.
(144) Shklyarevskiy, I. O.; Jonkheijm, P.; Christianen, P. C. M.; Schenning, A. P. H. J.; Del Guerzo, A.; Desvergne, J.-P.; Meijer, E. W.; J. C. Maan, J. C. *Langmuir* **2005**, *21*, 2108−2112.
(145) Ko, Y. G.; Shin, S. S.; Choi, U. S.; Park, Y. S.; Woo, J. W. *ACS Appl. Mater. Interfaces* **2011**, *3*, 1289−1298.
(146) Bonini, M.; Lenz, S.; Falletta, E.; Ridi, F.; Carretti, E.; Fratini, E.; Wiedenmann, A.; Baglioni, P. *Langmuir* **2008**, *24*, 12644−12650.

(147) Bachl, J.; Hohenleutner, A.; Dhar, B. B.; Cativiela, C.; Maitra, U.; Konig, B.; Diaz, D. D. *J. Mater. Chem. A* **2013**, *1*, 4577−4588.
(148) Hikmet, R. A. M.; Kemperman, H. *Nature* **1998**, *392*, 476−479.
(149) Bhattacharya, S.; Krishnan-Ghosh, Y. *Chem. Commun.* **2001**, 185−186.
(150) Jadhav, S. R.; Vemula, P. K.; Kumar, R.; Raghavan, S. R.; John, G. *Angew. Chem., Int. Ed.* **2010**, *49*, 7695−7698.
(151) Trivedi, D. R.; Dastidar, P. *Chem. Mater.* **2006**, *18*, 1470−1478.
(152) Hamley, I. W. *Chem. Rev.* **2012**, *112*, 5147−5192.
(153) Jin, H. J.; Kaplan, D. L. *Nature* **2003**, *424*, 1057−1061.
(154) Ning Du, N.; Yang, Z.; Liu, X. Y.; Li, Y.; Xu, H. Y. *Adv. Funct. Mater.* **2011**, *21*, 772−778.
(155) Vepari, C.; Kaplan, D. L. *Prog. Polym. Sci.* **2007**, *32*, 991−1007.
(156) Jung, J. H.; Park, M.-S.; Shinkai, S. *Chem. Soc. Rev.* **2010**, *39*, 4286−4302.
(157) Das, U. K.; Banerjee, S.; Dastidar, P. *Chem.—Asian J.* **2013**, *8*, 3022−3031.
(158) Hughes, N. E.; Marangoni, A. G.; Wright, A. J.; Rogers, M. A.; Rush, J. W. E. *Trends Food Sci. Technol.* **2009**, *20*, 470−480.
(159) Toro-Vazquez, J. F.; Morales-Rueda, J.; Torres-Martinez, A.; Charo-Alonso, M. A.; Mallia, V. A.; Weiss, R. G. *Langmuir* **2013**, *29*, 7642−7654.
(160) Schaink, H. M.; van Malssen, K. F.; Morgado-Alves, S.; Kalnin, D.; van der Linden, E. *Food Res. Int.* **2007**, *40*, 1185−1193.
(161) Mezzenga, R.; Schurtenberger, P.; Burbidge, A.; Michel, M. *Nat. Mater.* **2005**, *4*, 729−740.
(162) Sajisha, V. S.; Maitra, U. *Chimia* **2013**, *67*, 44−50.
(163) Dey, N.; Samanta, S. K.; Bhattacharya, S. *ACS Appl. Mater. Interfaces* **2013**, *5*, 8394−8400.
(164) Lee, H.; Jung, S. H.; Han, W. S.; Moon, J. H.; Kang, S.-W.; Lee, J. Y.; Jung, J. H.; Shinkai, S. *Chem.—Eur. J.* **2011**, *17*, 2823−2827.
(165) Ajayaghosh, A.; George, S. J.; Praveen, V. K. *Angew. Chem., Int. Ed.* **2003**, *42*, 332−335.
(166) Carretti, E.; Bonini, M.; Dei, L.; Berrie, B. H.; Angelova, L. V.; Baglioni, P.; Weiss, R. G. *Acc. Chem. Res.* **2010**, *43*, 751−760.
(167) Baglioni, P.; Chelazzi, D.; Giorgi, R.; Poggi, G. *Langmuir* **2013**, *29*, 5110−5122.
(168) Angelova, L. V.; Berrie, B. H.; de Ghetaldi, K.; Kerr, A.; Weiss, R. G. *Stud. Conserv.* **2014**, DOI: 10.1179/2047058413Y.0000000112.
(169) Wilder, E. A.; Wilson, K. S.; Quinn, J. B.; Skrtic, D.; Antonucci, J. M. *Chem. Mater.* **2005**, *17*, 2946−2952.