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Triggering Gel-Sol Transition by Weak Magnetic Field

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ABSTRACT

The self-assembly of small molecules into fiber-like structures is a mysterious process as the physics underlying such self-assembly is not clear. The energy necessary for this process exceeds the one provided by common dispersion interactions and hydrogen bonding. The recent results obtained by the scientific group of Prof. Naaman for the Weizmann Institute of Science fed light on the nature of the forces providing for the self-assembly of chiral molecules and attributed these forces to the spin exchange interactions. Therefore, the self-assembly of chiral molecules should be magneto-sensitive. We found such sensitivity in solutions of trifluoroacetylated α-aminoalcohols, and the process was inhibited by the magnetic field when fibers grew on the surface of the substrate. On the contrary, in the bulk, the self-assembly was enhanced by the magnetic field and led to the formation of the dense gel, while no gelation was observed in the absence of the external magnetic field. The latter observations are the theme of this short report aimed to declare the effect itself but does not pretend to describe it in full.

Introduction

The magnetic field can affect many processes, including biological ones in various aspects, which was summarized in the review by Zadeh-Haghighi and Simon.[1] In particular, the static magnetic field of significant induction (9.4 T) inhibits the DNA synthesis in mice, therefore, suppressing the tumor growth[2]. It was also reported that a magnetic field could inhibit apoptosis and therefore increase the risk of cancer.[3,4] Besides that, extremely low-frequency electromagnetic field can cause DNA fragmentation in human cells.[5] Besides that, the relatively weak static magnetic field of 0.2 T significantly affects the rate of the DNA synthesis rate.[6] The observations described provide for the fundamental importance of the interaction of the magnetic field with soft matter, which requires some simplified models to analyze mechanisms of magnetic field action. Here we consider one of the examples of such models, the gelation of the solution of low molecular weight organic substances.

The driving force for the gelation in solutions of low molecular weight substances can be either polymerization of monomers (so-called chemical gels) or formation of anisometric supramolecular structures (so-called physical gels).[7,8] Making up the physical gels occurs due to the self-ordering of gelator molecules providing for the formation of supramolecular fibers stabilized by non-covalent bonds. In general, the molecules of substances capable of physical gels forming are either elongated or disk-shaped.[7–9] In the first case, the formation of gel lattice elements occurs due to the interaction of the side surfaces of elongated molecules.[9,10] In the second case, the gel lattice elements form due to the self-ordering of the molecules into the quasi-one-dimensional stacks of flat molecules.[11] Occasionally, the lattice of physical gel can be composed of small isometric molecules having no pronounced short or long axes in the shape of their molecules.[12]

There are only a few examples of the small isometric molecules capable of gel-forming. These include several amino acids.[13,14] some carbohydrates,[15]) and chiral trifluoroacetylated alpha-aminoalcohols (TFAAAs).[12] TFAAAs can spontaneously assemble into quasi-one-dimensional supramolecular structures (strings), precipitating from cooling or drying homochiral solutions. The strings have distinct XRay spectra reflecting the long-range order in the TFAAA molecules packing (irrespective to the solvent used) and are helical in their structure that was demonstrated earlier by circular dichroism data.[12] Unfortunately, the direct structural data were otained only for the dried samples, while, in real gels, the concentration of TFAAAs are too small for XRay analysis. The strings comprised gel lattice and were never observed in solutions of achiral TFAAAs.[12,16] The latter indicates the decisive role of chirality in this process. The thickness of TFAAA strings varies from several nanometers (so-called elementary strings) to hundreds of micrometers (so-called thick strings), with the length up to several centimeters. Thick strings are supercoiled fibers twisted of thinner strings, resulting in a complex hierarchical structure with many sequential structural levels of different spatial scales.[12] The twisting direction of thick strings changes with the transition from one structural level to another, similar to biological macromolecules.[17–19]

The formation of strings on a substrate during solutions' drying (so-called xerogels) is sensitive to the properties of the

substrate.[20] The strings did not form on electro-conductive surfaces such as, for example, graphite. The process of xerogels formation is effectively suppressed by the weak (much smaller than kT) magnetic fields.[21] Taking into account the chirality of TFAAA molecules is necessary for strings' forming, the sensitivity of the process of their growth to the magnetic fields points to the significant role of spin polarization and exchange interactions in this process.[21,22]

The phenomenon of spin polarization accompanies ordinary charge polarization in chiral molecules and reduces to the appearance of some excess spin density at the opposite poles of the molecule.[22] Spin orientation at the opposite poles of the molecule depends on the chirality sign, which can serve as a selection factor in the processes of intermolecular binding[23] and adsorption.[24] As the spin polarization produces "partially unpaired" electrons, spin-polarized molecules become sensitive to external magnetic fields, as well as, to the spins of surrounding nuclei. Indeed, the interaction with an external magnetic field removes the symmetry restriction on the singlet-triplet conversion, which can completely neutralize the effects of spin selectivity. The latter was directly shown for TFAAA xerogels, as their formation was suppressed by the external magnetic field.[21]

Considering the role of the substrate in strings' growth,[20] it became unclear which of two components, TFAAA or substrate, are responsive for magneto-sensitivity in experiments with xerogels.[21] To verify if the TFAAA molecules or the substrate provided for the magneto-sensitivity, we have conducted a set of experiments on the magneto-sensitivity of the bulk gels: TFAAA-7 (Fig. 2) in glycerol. Glycerol was chosen due to its high viscosity and low evaporation rate, which significantly facilitated the experiments and did not affect their primary conditions and prerequisites. Indeed, the system was represented by a solution of chiral TFAAA in an achiral solvent, however, due to the peculiarities of glycerol, there were no difficulties with its evaporation and measurement of the viscosity of solutions.

Results

1 Results

1.1 Optical Microscopy

The optical microscopy examination revealed noticeable differences between the samples incubated in a constant magnetic field and those incubated without it. In the samples incubated without a magnetic field, we found relatively short crystallites, having the coefficient of anisometry (i.e. the ratio of the length and diameter) of the order of 5–10 (Fig. 1A), although the strings were observed occasionally. The crystallites' diameter was about 10–15 μm. On the contrary, the samples incubated in a constant magnetic field (0.18 T, 50 hours) contained a lot of intensely branching strings, having significant (more than 100) anisometry coefficients (Fig. 1B). The strings, also having distinct crystal-like structure and long-range order in their structure[12]. were much thinner than the crystallites found in the control samples and had diameters of several microns. In addition to the strings and crystallites, the isometric granules always formed in almost all specimens. The number of such granules varied significantly from sample to sample randomly.

Therefore, a relatively weak external magnetic field drastically changed the morphology of the supramolecular structures formed in the solution of TFAAA-7R in glycerol. In the absence of the field, the specimens contained relatively short and thick, crystal-like structures, while under the magnetic field, they contained much thinner and intensively branching strings.

1.2 Viscosity

After 50 hours of incubation, the TFAAA-7R solution flowed out completely from the samples incubated without an external magnetic field. The re-examination of these samples with the optical microscope after 30 minutes did not reveal either crystallites or glycerol remained in the gap between the glasses. Thus, this solutions were viscous liquids with crystallites suspended in them.

According to the Navier-Stokes equation, the profile of a stationary flow of a viscous fluid between two parallel vertical planes, under the gravity force action, can be written as:

$$V(x) = \frac{\rho g}{2\eta}\left(\frac{L^2}{4} - x^2\right)$$

where ρ is the density of the liquid (glycerol, 1260 kg/m^3), η is its viscosity (1.48 Pa·s), g is the free-fall acceleration (9.8 m/s^2), L is the distance between the planes (0.5 mm), and x is a coordinate perpendicular to the planes, with the origin in the middle between them. Accordingly, the profile-averaged flow rate would be:

$$< V >= \frac{\rho g L^2}{12\eta}$$

In our case, the profile-averaged velocity was ~ 0.17 mm/sec. Thus, considering the size of the coverslips (3 cm), glycerol should leak out from the gap between the slides in about three minutes. This assessment agrees with our observations since, in a half-hour, there was no solution left in the gap between the slides in the case of the specimens incubated without the field.

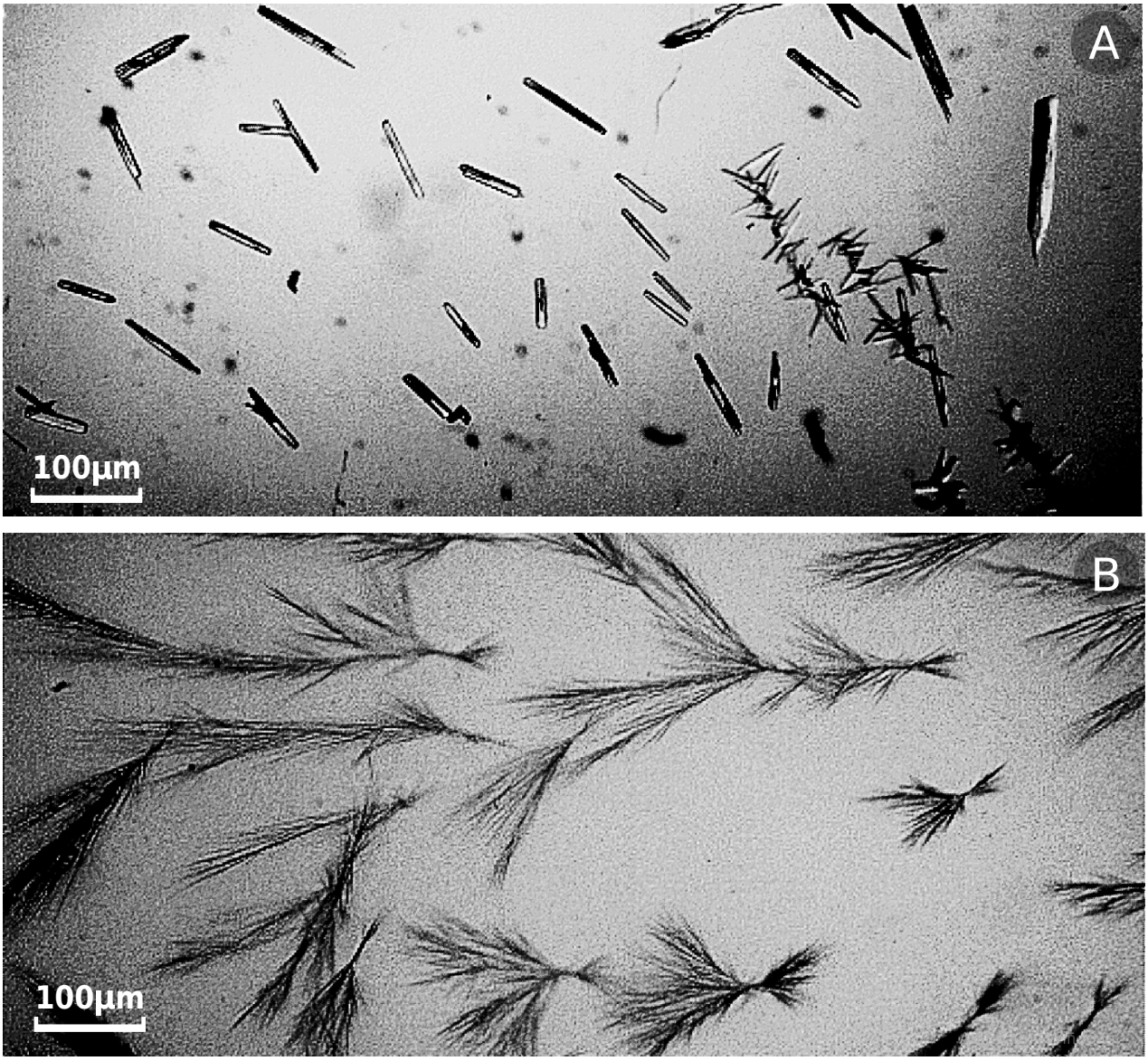

Figure 1. Examples of optical microphotographs of the TFAAA-7R/glycerol solutions (10 mg/ml) after 50 hours incubation at 20 °C either in the normal conditions (A), or in the magnetic field of the induction of 0.18 T (B).

On the contrary, the solution did not leak out from the specimens incubated in a magnetic field with an induction of ~ 0.18 T. This means that we did not observe the leakage of the liquid onto the glass substrate. After a half an hour, the repeated microscopic examination revealed the same strings in the gap between the glasses. Moreover, no leakage of the solutions occurred even after 10 hours of incubation in a vertical position. Thus, the viscosity of TFAAA-7R solutions incubated in a magnetic field increased at least 200 times compared to pure glycerol and amounted to more than 300 Pa·s. Such a large values are not typical even for high-molecular-weight epoxy resins, whose viscosity under normal conditions does not exceed 25 Pa·s.

Discussion

Studying the structure of solutions and precipitates of TFAAA-7R in glycerol revealed strong magnetosensitivity of this system. In these solutions, a relatively weak magnetic field provoked growing highly-elongated supramolecular strings which comprises the gel scaffold. On the other hand, in the absence of the external magnetic field, TFAAA-7R precipitated in the form of rod-shaped crystals (Fig. 1). Besides the qualitatively different morphology of precipitates, the solution possessed qualitatively different rheological properties depending on the magnetic field: the solutions incubated in the field became a gel (due to the strings' forming), and their viscosity increased drastically. Therefore, in the TFAAA-7R/glycerol system, the magnetic field

induced gelation due to the self-ordering of TFAAA molecules and the formation of quasi-one-dimensional supramolecular strings.[12,25]

Since TFAAA-7R and glycerol molecules are non-magnetic, the revealed magnetosensitivity and the chirality of TFAAA-7R (obligate for the strings' growth[12]) indicate a significant role of the exchange interactions[21,22] in the phenomenon under consideration. Since the interaction with an external magnetic field removes the symmetry restriction on the singlet-triplet conversions, the magnetic field would definitely affect the exchange interactions between TFAAA molecules.

Strings' forming is a threshold phenomenon: at the TFAAA concentration below a certain threshold, strings do not grow.[12] The concentration of 10 mg/mL lays below the critical concentration of string formation for the TFAAA-7R/glycerol system, and the solution did not gelate in control experiments. Therefore, the gelation of solution of TFAAA-7R in glycerol under the action of a magnetic field at the same concentration of TFAAA implies a decrease in the critical concentration caused by the magnetic field action. Since the threshold concentration of string formation (C^*) explicitly depends on the energy of TFAAA molecule binding to the face of the growing string (W),[21] the observed effect indicates an increase in this energy under the magnetic field action:

$$C^* \sim e^{-\frac{W}{kT}}$$

In turn, such an increase corresponds to an increase in the contribution of the exchange energy to the total binding energy, since neither van der Waals forces nor hydrogen bonds depend on a magnetic field. Indeed, the existing estimates on the energy of the TFAAA molecule binding to the face of the growing string comprise up to 70 kJ/mole.[26]

The strings' growth intensified in TFAAA-7R in glycerol solutions under the magnetic field action. At the same time, in the heptane solutions of another member of the homologous series of TFAAA (TFAAA-5R), the effect had the opposite sign.[21] In addition to minor differences in the structure of TFAAA molecules, the fundamental difference between the TFAAA-5/heptane and TFAAA-7R/glycerol systems was the formation of strings on the surface in the former, and in the bulk in the latter system. Consequently, the TFAAA-5/heptane system included the third component, the surface of the substrate where the strings grew. The essential role of substrate properties was shown earlier:[20] strings consistently formed on dielectric substrates (mica, glass); somewhat less stably formed on the surfaces of semiconductors (silicon); and did not form on the electroconductive substrates (graphite, metals). Thus, the higher the concentration of free electrons on the substrate surface, the lower the probability of string formation.[20]

Let us assume a competition between two processes: the binding of the TFAAA molecules to other TFAAA molecules and their attachment to the substrate. Then, in the TFAAA-5/heptane/glass system, the effect of an external magnetic field will be determined by the ratio between the magnitudes of the effects that the magnetic field has on the actual growth of strings and on the binding of the molecules to the substrate. If the rate of adsorption on the substrate[24] increases to a greater extent than the rate of strings' growth, the magnetic field would inhibit the strings' growth.

Conclusions

The observed effect of gelation under magnetic field action is a macroscopic one. That is, under the magnetic field, the state of the condensed phase switches between two qualitatively different regimes in a macroscopic amount of matter. The reason for the change in the state of solution, of course, is the formation of strings at the microscopic level, but the growth of strings leads to a change in the macroscopic properties of the whole solution. Theoretically, the opportunity of the viscosity changing using a magnetic field can have some technological applications. Similar effects of increasing the viscosity of a suspension in a magnetic field were described, for example, in suspensions of cellulose nanowhiskers. In these suspensions, the increase in viscosity was associated with the orientation of the fibers in a magnetic field.[27] However, the amplitude of this effect was several orders of magnitude smaller than the described effect of reducing the critical concentration of string formation.

In addition to the practical aspect, the revealed effect of increase in the energy of chiral molecules self-ordering in the anisometric structures under the a magnetic field, can be of fundamental importance for the problem of the chirality of living matter. According to our theory, the ability of some chiral molecules to form supramolecular helices was the "special" property that served as the main selection factor at the early stages of chemical evolution.[14] Our result implies a weak magnetic field can significantly reduce the critical concentrations necessary for the formation of the supercoiled prebiological structures. Therefore, this effect could save a significant amount of evolutionary time accelerating self-ordering essential for complication of structures. Of course, in our experiments, the magnetic field inductance was many orders of magnitude higher than the inductance of the modern geomagnetic field. However, the insignificance of effects in the past seemed to be fully compensated by the huge time that the prebiological evolution stage has taken.

Methods

Pure R-enantiomer of seventh member of the homologous series of trifluoroacetylated α-aminoalcohols (TFAAA-7R, Fig. 2) was synthesized according to the procedure described earlier[28]. Glycerol (Khimmed, Russia) was heated to a temperature

of 60–70 °C and mixed with TFAAA-7R powder under stirring (final concentration 10 mg/ml). Then, 15 μl of the hot solution was dropped onto the surface of the glass slide and covered with a coverslip (the gap was $\sim$ 0.5 mm). Both the slide and coverslip were thermostated at 20 °C before the specimen preparation. The obtained specimens were incubated in a thermostat (20 °C) either between permanent magnets or without magnets for 50 hours. After incubation, the samples were examined under an optical microscope (LOMO-6, LOMO, Russia) and then tested for viscosity.

The concentration of TFAAA-7R was chosen to be below the critical concentration of strings forming[12], which was assessed to be approximately 15–18 mg/ml for glycerol. Therefore, we became able to verify the magnetic field influence only, regardless of all other factors.

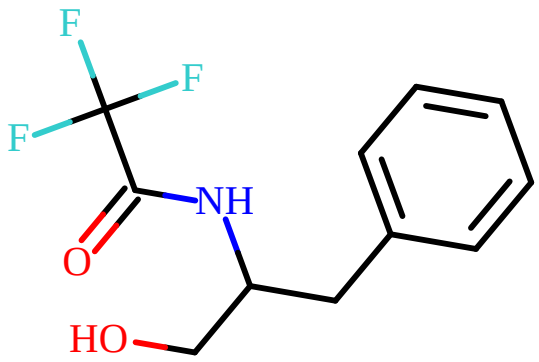

Figure 2. Chemical structure of TFAAA-7R molecule.

The magnetic field was generated by a pair of coaxial cylindrical Nd magnets (N38 alloy), having 55 mm in diameter and 25 mm length. The specimens were placed in the middle of the gap between the magnets on their common axis. The distance between the surfaces of the magnets was 37 mm, which corresponded to a field induction in the sample of about 0.18 T (1800 G). The magnetic field induction was measured using a linear-output Hall sensor AD22151 (Analog Devices, USA) as described earlier[21].

The viscosity of the solution in the samples was measured as follows: the specimens were placed vertically on a glass surface allowing the solution to flow out freely from the gap between the glasses. Specimens were incubated in a vertical position for 30 minutes and then reexamined microscopically.

The experiments were repeated six times. The results were more than prominent, as the difference in the behavior of the samples incubated in the magnetic field and without it was qualitatively different. The gelation was observed in all six samples incubated in the external magnetic field and was not in the samples incubated without it.

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Author contributions statement

S.V. Stovbun – Conceptualization. Writing – review & editing.
A.M. Zanin – Experimental – Conducting experiments.
A.A. Skoblin – Formal Analysis. Writing – initial draft.
M.G. Mikhaleva – Experimental – Specimens analysis.
D.A. Kuznetsov – Conceptualization. Writing – review & editing. D.V. Zlenko – Conceptualization. Visualization. Writing – review & editing.

Data availability statement

The datasets used and/or analyzed during the current study available from the corresponding author on reasonable request.