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Cooperative Two-Component Self-Assembly of Mono- and Ditopic Monomers

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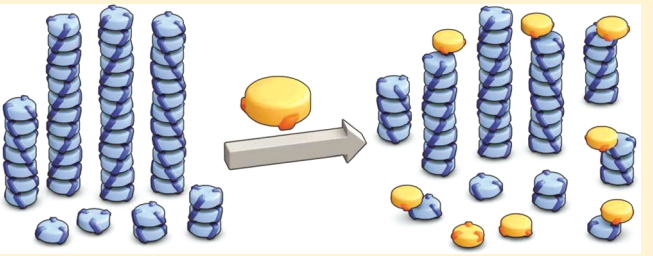
Supporting Information

ABSTRACT: A *N*-methylated benzene-1,3,5-tricarboxamide (BTA) was synthesized, characterized, and introduced as a monotopic BTA monomer capable of interacting with the supramolecular polymer formed via the cooperative self-assembly of the analogous ditopic BTA monomers. Using optical spectroscopy and viscometry, in combination with mathematical modeling and DFT calculations, we were able to understand in detail the consequence of introducing a second monotopic component in the self-assembly of BTA monomers into long supramolecular polymers, taking explicitly the cooperative nature of the self-assembly process into account. To this end, a binary self-assembly model that includes both the monotopic and ditopic BTA monomer and that addresses the presence of both monomers and polymers (characteristic of a cooperative supramolecular polymer) was developed and successfully applied to model the viscometry data. The binary self-assembly model presented herein can be more generally applied to other cooperative supramolecular polymers to which a second component is added that can interact with the monomers and/or polymers and thus can contribute to a better understanding of more complex self-assembling systems.



INTRODUCTION

The concept of self-assembly, whereby relatively small and simple molecular building blocks arrange themselves via noncovalent interactions into larger aggregates, has become an attractive approach for the preparation of functional nanostructures.[1−7] Moreover, the necessity for a comprehensive understanding of the supramolecular polymerization mechanisms in order to allow the rational design of self-assembled functional nanostructures is acknowledged by more and more researchers.[8−12] Nowadays, for single-component self-assembly of monomers into one-dimensional aggregates, the corresponding mathematical models have been fully developed to describe—and predict—the properties of these aggregates.[13]

A next step toward more complex, functional assemblies involves the introduction of a second component, as this opens up the route to new phenomena such as chiral amplification,[14] end-capping,[15,16] energy transfer,[17,18] or the preparation of supramolecular block copolymers.[19] Depending on how the components interact, control over one or more properties of the assemblies becomes possible, e.g., the helicity of the aggregates or the averaged length of the assemblies. However, predicting the behavior of such a binary supramolecular system is not trivial as it can include nonlinear behavior, as for example in the case of chiral amplification. Moreover, in the particular case of a cooperative supramolecular polymerization there is a bimodal distribution of monomeric and polymeric species, and the interaction between the added component and the monomeric or polymeric species is not necessarily equal.[20]

One approach to characterize a supramolecular polymer and to control the degree of polymerization (DP) entails the introduction of a monotopic chain stopper as a second component to a supramolecular polymer.[15,16,21−24] For example, Bouteiller and co-workers have studied the effect of adding a monotopic monomer to their bis-urea supramolecular polymers, which self-assemble via a cooperative mechanism.[15] The authors showed that introduction of a chain stopper eliminated the concentration dependence of the molar mass of the bis-urea supramolecular polymer and allowed them derive the molecular weight and dimensions of the end-capped polymer chains. In a later publication these studies were extended to include rheometry and dynamic light scattering.[25] To describe the cooperative supramolecular polymerization in the presence of a monotopic chain stopper, the authors considered conditions in which the number of monomers is relatively small, which allowed them to only consider the interactions between

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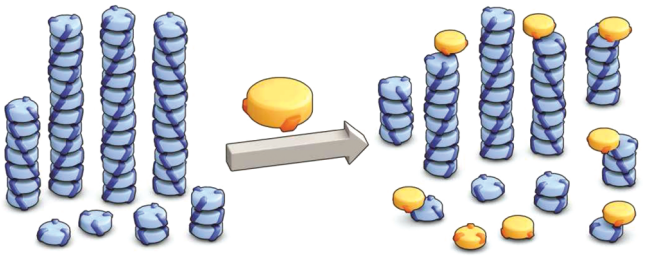
Scheme 1. Schematic Representation of the Introduction of a Monotopic Monomer to a Ditopic Monomer That Self-Assembles into Long 1-D Assemblies via a Cooperative Mechanism[a]



[a] As depicted, the monotopic monomer could interact with the end of the stacks, with monomers, with both, or with neither.

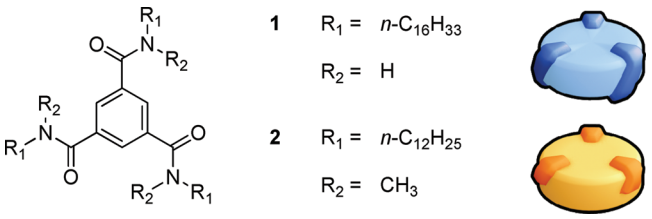
the monotopic derivative and polymer chains (i.e., ignoring the interactions between the monotopic derivative and monomers).[25,26]

A general problem, however, is that in the case of a cooperative supramolecular polymer it is not always known *a priori* whether a second component will interact mostly with the polymers, the monomers, or both. For example, as recently reported by our group, for the cooperative supramolecular polymerization of zinc porphyrins in the presence of the axial ligand pyridine it was found that the axial ligand preferentially binds to the free monomers in solution and not to the end of the assemblies.[27] As a result, rather unexpected self-assembly behavior was observed: upon dilution, the average length of the assemblies was found to increase. Similar behavior can be found in protein systems in which protein unfolding occurs upon the addition of a denaturant, while renaturation takes place upon dilution.[28]

A second consideration that should be addressed when describing a binary system of mono- and ditopic derivatives involves the connectivity of the two binding sites in the ditopic monomer. In most examples reported hitherto, the functional groups of the ditopic monomers are electronically uncoupled. As a result, an isodesmic self-assembly mechanism[13] is observed in such uncoupled systems, since a binding event at one of the two binding sites does not affect the second binding site. In contrast to these systems, for electronically coupled monomers it is not straightforward to prepare a monotopic analogue, since modification of one side of the molecule can affect the binding affinity of the other side of the molecule. As a result, the binding strength of the monotopic monomer might be different as compared to the ditopic monomer.

Herein we report the supramolecular polymerization of a ditopic monomer in the presence of a monotopic derivative (Scheme 1), which we characterized taking the above-outlined considerations explicitly into account: i.e., a possible difference in affinity of the monotopic derivative for the monomers and polymers, and the relative binding strength of the monotopic derivative, compared to the ditopic analogue. To this end we developed a general model to describe this binary system: a monotopic derivative that can interact with ditopic monomers that self-assemble in a cooperative fashion. As a model system to address the effect of adding a monotopic monomer to a supramolecular polymer that self-assembles via a cooperative growth mechanism, we selected the benzene-1,3,5-tricarboxamide (BTA) monomer.[29−32] Previously, on the basis of high-resolution temperature-dependent spectroscopy, we could identify and quantify a

Chart 1. Molecular Structure of Ditopic 1 and Monotopic 2; a Schematic Representation of Each Monomer Is Also Depicted



cooperative self-assembly mechanism for this supramolecular polymer in dilute alkane solution.[33] In addition, by mixing enantiomeric derivatives or by mixing chiral with achiral monomers, we could study two-component systems by means of chiral amplification studies.[34−37] We here show that using optical spectroscopy and viscometry in combination with mathematical modeling and DFT calculations, we are able to understand in detail the consequence of a second monotopic component in the self-assembly of BTA monomers into long supramolecular polymers.

RESULTS AND DISCUSSION

Design of the Monotopic Monomer. The supramolecular polymer reported in this study is based on achiral BTA derivative **1** (Chart 1), having hexadecyl chains to increase the solubility in methylcyclohexane (MCH, *vide infra*). The design of the monotopic monomer is based upon *N*-methylation of the three amide groups present in the C_3-symmetrical BTA molecules. *N*-Alkylation has already been reported to prevent hydrogen-bonding in self-assembled systems.[15,38−41] To this end, BTA monomer **2** (Chart 1) was designed, which lacks the N−H groups. As a result, *N*-methylated BTA **2** cannot act as hydrogen bond donor, and it is therefore merely a hydrogen bond acceptor via the carbonyl groups and hence can be considered the monotopic analogue of **1**. The monotopic derivative **2** was readily synthesized by reaction of *N*-methyldodecylamine with trimesyl chloride.[42]

Probing the Stack Growth of BTA 1 by Optical Spectroscopy and Viscometry. Before studying the supramolecular polymerization of BTA monomer **1** with solution viscometry, UV−vis spectroscopy was employed to study the self-assembly of **1** in MCH (Figure 1A). The temperature-dependent UV−vis absorption of a 1.4×10^{-4} M solution in MCH shows a clear nonsigmoidal transition from the molecular dissolved state to the aggregated state, indicative of a cooperative growth mechanism (Figure 1A).[13] The origin of this cooperativity can be attributed to both a conformational and an electronic effect; the former arises because for polymerization to occur the amide groups in the monomer need to rotate out of the plane in a parallel fashion; the latter effect is related to polarization effects (and to the orientation of the dipoles) which change during aggregation and thereby influence the intermolecular hydrogen bonding strength.[43]

The temperature-dependent UV−vis absorption data of **1** were analyzed using a temperature-dependent nucleation−elongation model[11,44] which yielded an enthalpy release, h_e, of -56 kJ mol^{-1}, a K_a value of 8×10^{-4}, and an elongation temperature of 357 K. As a result, the predicted degree of polymerization for **1** is in the order of 100 monomers at room temperature (at a concentration of 1.4×10^{-4} M in MCH).[42]

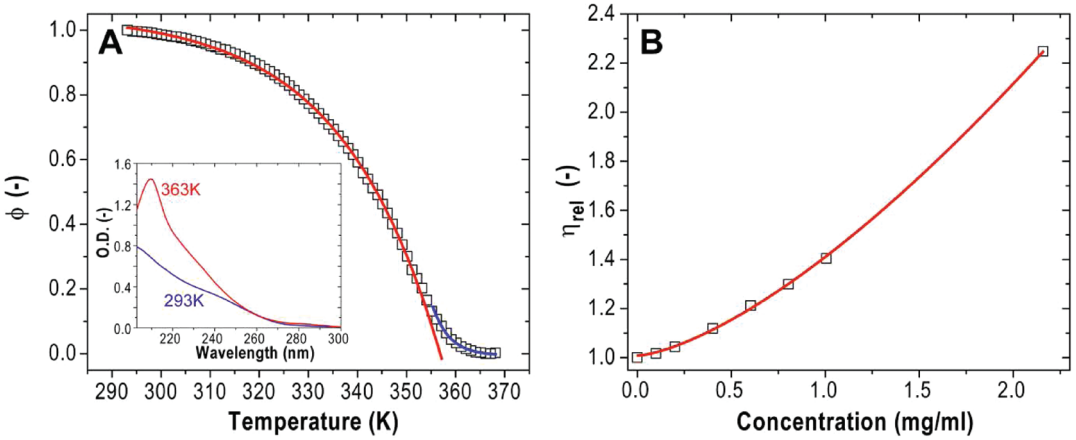


Figure 1. (A) Degree of aggregation, ϕ, for **1** as derived from the temperature-dependent UV−vis data monitored at 223 nm, with fit for the elongation regime (red line) and the nucleation regime (blue line). The inset shows the UV−vis absorption at 363 and 293 K. Concentration: 1.4×10^{-4} M in MCH. (B) Relative viscosity versus concentration of **1** in MCH at 20 °C, fitted with a power law function. The highest concentration (2.2 mg mL^{-1}) corresponds to 2.5×10^{-3} M.

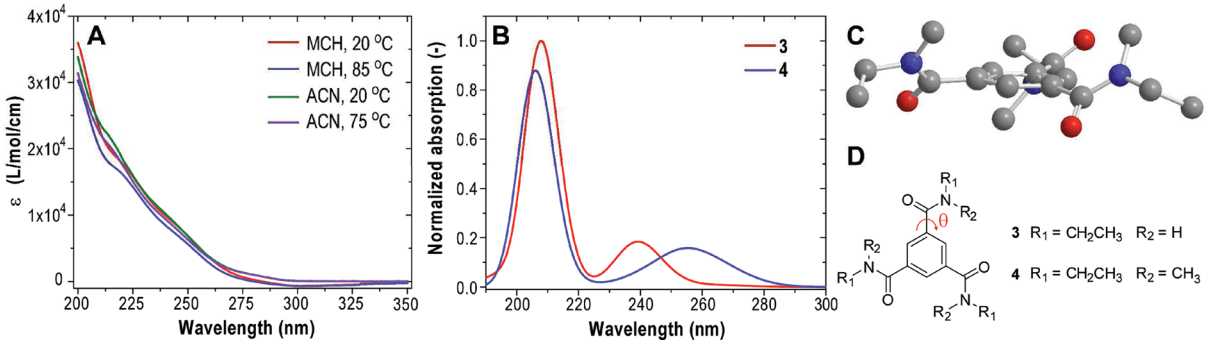


Figure 2. (A) UV−vis absorption for **2** in MCH at 20 and 85 °C and in ACN at 20 and 75 °C. Concentration: 2.0×10^{-4} M for both solvents. (B) Predicted UV−vis spectrum for BTA monomers **3** and for **4** calculated using TD-DFT (time-dependent DFT) calculations. (C) Optimized structure of **4** in the gas phase, determined by DFT calculations at the PBE/6-311G+(d,p) level of theory (hydrogen atoms are omitted for clarity). (D) Structures of BTA monomers used in the DFT calculations. The torsion angle θ is also highlighted.

We applied Ubbelohde viscometry on MCH solutions of BTA **1** to observe the formation of the self-assembled stacks of **1**. Concentration-dependent viscosity measurements could be performed over a wide range of concentrations (Figure 1B). The viscosity data in Figure 1B show an exponential increase in the relative viscosity, η_{rel}, with increasing concentration.[42,45] The data could be fitted with a power-law relation, resulting in an exponent of 1.5. This value is close to the value of 1.7 reported for the concentration dependence of the viscosity of a rodlike, fast-breaking chain.[25,46,47] The rodlike shape is in agreement with the results of SANS experiments,[42] which revealed a broad regime in which the scattering intensity scaled with Q^{-1} (when plotted on a double-logarithmic scale), indicative of cylindrical objects. Fitting the data using a cylindrical form factor yielded a radius of about 12 Å, in agreement with the dimensions of the molecule, as well as with the value of 13 Å reported by Hanabusa.[48] Unfortunately, the length of the stacks could not be determined reliably from the SANS experiments, as no leveling of the scattering intensity at low Q values was observed. Therefore, on the basis of SANS data, it could only be concluded that the stack length exceeds ∼500 Å. The fast-breaking character is in line with the dynamic nature of the supramolecular system, as reported previously.[33] The rapid increase in viscosity of **1** upon raising the concentration confirms the cooperative self-assembly mechanism and indicates that long stacks are present in solution.

Spectroscopic and Computational Characterization of Monotopic BTA Monomer 2. Ubbelohde viscometry on solutions of *N*-methylated BTA **2** in MCH did not reveal an increase in viscosity upon increasing concentration (up to a concentration as high as 1.0 mg mL^{-1}), suggesting that in contrast to BTA monomer **1**, *N*-methylated BTA **2** does not self-assemble into supramolecular polymers of considerable length in solution.[42]

UV−vis spectroscopy was employed to confirm that *N*-methylated BTA **2** is molecularly dissolved in MCH. To this end, solutions of BTA **2** were studied in MCH and in acetonitrile (ACN) at 20 °C and at elevated temperature (85 and 75 °C for MCH and ACN, respectively). The latter solvent was chosen as it is a good solvent for BTAs.[33] For both solvents and both temperatures very similar UV−vis spectra were obtained (Figure 2A). This indicates that in both solvents BTA **2** is not aggregated but molecularly dissolved, irrespective of the temperature. However, in contrast to previously reported BTAs and to the results for **1**, we do not observe an absorption maximum of the monomer of **2** at 208 nm (see for instance the inset in Figure 1A). This could suggest that due to the *N*-methylation the absorption maximum of BTA **2** has shifted to lower wavelengths.

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To rationalize this effect, DFT calculations were performed on BTA **3** and *N*-methylated BTA **4** (Figure 2D), bearing short ethyl side chains to reduce computational costs. The equilibrium geometries of monomeric BTAs **3** and **4** were obtained by full geometry optimization at PBE/6-311G+(d,p) level of theory. Previous calculations on a derivative of monomeric BTA **3** bearing a methyl side chain have shown that the average torsion angle, θ (Figure 2D), in the optimized geometry of the BTA monomer takes a value of ~12° at the same level of theory.[49] In contrast, the average torsion angle, θ, in the optimized geometry of *N*-methylated BTA **4** takes a value of 41° as a result of an increased steric hindrance exerted by the *N*-methyl groups. Surprisingly, the equilibrium geometry of *N*-methylated BTA **4** is characterized by an antiparallel arrangement of the carbonyl groups; i.e., two carbonyl groups are pointing downward while one carbonyl is pointing upward (Figure 2C).[50] This was further confirmed by single point calculations on *N*-methylated BTA **4** in which the torsion angle of one of the carbonyl groups was incremented from −40° (antiparallel arrangement) to +40° (parallel arrangement).[42] In addition, as reported in the literature, X-ray structure analysis on crystals of tris(*N*,*N*-diethyl)trimesamide (in the presence of hydroquinone) also revealed an antiparallel arrangement of the carbonyl groups.[51] The preference for the antiparallel orientation of the amide groups in *N*-methylated BTA **4** finds its origin in the fact that the large torsion angle, θ, of *N*-methylated BTA **4** results in a large and unfavorable dipole moment when all the carbonyl groups are orientated in a parallel arrangement.[42] Next, time-dependent DFT (TD-DFT) calculations on the optimized geometry of BTAs **3** and **4** were performed. The calculated normalized absorption spectra indeed reveal a blue shift of the absorption maximum as a result of *N*-methylation (Figure 2B). This shift can be rationalized by the increased out-of-plane rotation of the amide groups in *N*-methylated **4** which results in a shorter conjugation length and hence a blue-shifted absorption maximum.

Addition of Monotopic *N*-Methylated BTA Monomer to Solutions of 1. Using Ubbelohde solution viscometry, the effect of introducing *N*-methylated BTA monomer **2** to a solution of BTA **1** in MCH was studied. Experiments were performed at two concentrations of **1**, i.e., 0.94 and 1.92 mg mL^{-1}. This concentration was kept constant while the monotopic monomer **2** was added in increasing concentration.

Upon addition of **2** a clear decrease in the relative viscosity could be measured for both concentrations, indicating that the (average) stack length of **1** is reduced by the introduction of **2** (Figure 3). Upon closer inspection of the data, a rather large fraction of **2** needs to be added to observe a decrease in viscosity: more than 20% of the monotopic derivative needs to be added to reduce the viscosity by more than 75%, which is considerably more than the 2% that was observed for the ureidopyrimidinone supramolecular polymer reported previously by our group.[16] This suggests that the affinity of monotopic monomer **2** for the end of the stacks of monomers **1** is only moderate in strength.[52]

Mathematical Modeling. To understand the effect of the monotopic monomer on the BTA supramolecular polymer, we developed a mass-action model which allowed us to determine all the relevant association constants (Scheme 2).

The two-component self-assembly of BTAs **1** and **2** was analyzed using the mass-action model depicted in Scheme 2, which takes into account both the cooperative self-assembly mechanism of **1** and the 1:1 binding of **2** with monomeric and

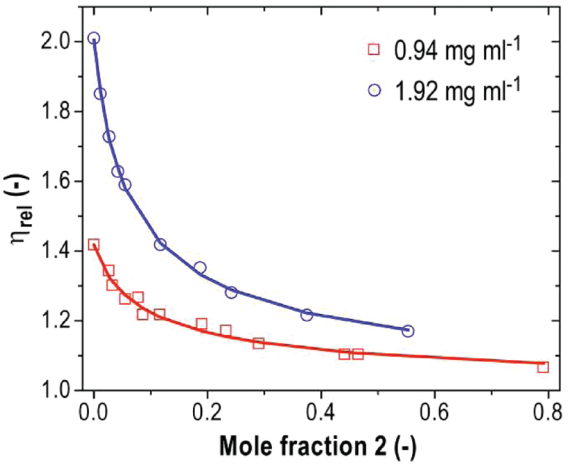
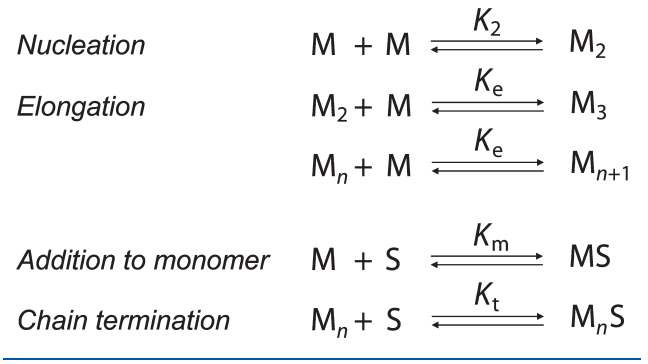


Figure 3. Relative viscosity as a function of mole fraction **2** added for two concentrations of **1** in MCH. Concentration: 0.94 mg mL^{-1} (red) and 1.92 mg mL^{-1} (blue).

Scheme 2. Schematic Model for the Cooperative Self-Assembly of a BTA Monomer (M) in the Presence of a Monotopic Monomer S



polymeric species of **1**. The concentration-dependent model in Scheme 2 assumes a cooperative dimerization-elongation model (K_2−K_e model[9]) for the self-assembly of **1**, which implies a nucleus size of 2. This model is the simplest model to describe a cooperative supramolecular polymerization.[53] From independent spectroscopic measurements (Figure 1A) the values for K_2 and K_e were found to be 3.9 × 10^2 and 5.3 × 10^5 M^{-1}, respectively, at room temperature.[42,54]

As the affinity of the monotopic derivative to the end of a polymer is not necessarily identical to that of a "normal" ditopic monomer, we introduced a new binding constant K_t for the equilibrium between monotopic derivative and polymer. Moreover, we included the possibility of binding between a monotopic and a ditopic monomer, which equilibrium was governed by a binding constant K_m.

Using the above model, the mass balances could be solved (using Matlab[55]), from which the DP_N is calculated, which can be equated to the specific viscosity ($\eta_{sp} = \eta_{rel} - 1$) via[16,56]

$$\eta_{sp} = pDP_N^{\,a} \quad (1)$$

In the above equation, the parameter p is only introduced as a scaling parameter, while a relates to the scaling of the viscosity

Table 1. Results from Fitting the Data in Figure 3 with the Model in Scheme 2

parameter	0.94 mg mL^{-1}	1.92 mg mL^{-1}
K_t (M^{-1})	$2.85 \times 10^4 \pm 0.06 \times 10^4$	$2.22 \times 10^4 \pm 0.0003 \times 10^4$
K_m (M^{-1})	21 ± 0.04	16 ± 0.002
K_e (M^{-1})	5.3×10^5[a]	5.3×10^5[a]
K_2 (M^{-1})	3.9×10^2[a]	3.9×10^2[a]
p	$1.3 \times 10^{-5} \pm 0.6 \times 10^{-5}$	$4.4 \times 10^{-5} \pm 0.8 \times 10^{-5}$
a	1.76 ± 0.09	1.57 ± 0.03

[a] Value was not fitted but used as a constant input parameter.

with the stack length. The data for the two concentrations in Figure 3 were subjected to a nonlinear least-squares analysis using the above model. Initially, nonlinear least-squares analysis of the data was performed with a model in which K_m and K_t were both allowed to be varied independently from each other.[42] However, these conditions lead to rather high uncertainties for the parameter value of K_m. This is mainly caused by the relatively low concentration of free BTA monomers in solution, which is a result of the cooperative nature of the supramolecular polymerization. Hence, we tried to fit the data assuming no interaction between the monotopic derivative and the monomer, i.e., K_m = 0, which leads to one parameter less to be fitted.[42] Under this assumption, it was possible to obtain an agreeable fit. However, it was also possible to obtain a good fit of the experimental data, assuming that the ratio K_2/K_e is equal to K_m/K_t, which means that the degree of cooperativity is identical for both monomers. This can be rationalized considering the similarity in molecular structure between the monotopic and ditopic monomer. That is, the electronic and structural effects that cause K_2 to be much smaller than K_e (i.e., the origin of cooperativity) are also expected to be operative for the monotopic derivative. Under these conditions a good fit of the data was obtained, the results of which are tabulated in Table 1.

The most relevant parameter obtained from the modeling is the equilibrium constant K_t, which was found to be $(2-3) \times 10^4$ M^{-1}, which is considerably smaller than the equilibrium constant $K_e = 5.3 \times 10^5$ M^{-1}. Even when considering that the monotopic monomer can only bind to one side of the stack (which theoretically reduces K_e by a factor 2), the binding constant K_t is still a factor 10 smaller than K_e. Similarly, the K_m value is an order of magnitude smaller than K_2, which results from the assumption that that the ratio K_2/K_e is equal to K_m/K_t. The low K_t value suggests that monotopic monomer **2** does not have a high affinity for the end of the stacks of molecules of **1**. This prompted us to study the influence of an *N*-methylated benzene- and cyclohexane-based monoamide on the self-assembly behavior of **1**. Also for these non-C_3-symmetrical derivatives a decrease in relative viscosity could be observed, albeit the effect is not as strong as for **2**.[42] In fact, also addition of dimethylformamide (DMF) leads to a reduction in viscosity, which was not observed when adding ACN.[42] The results for the latter solvent exclude that changes in solvent polarity are causing the decrease in viscosity, since DMF and acetonitrile have a similar dipole moment (3.82 D vs 3.87 D) and dielectric constant (38.25 vs 36.64). Apparently, additives containing a (tertiary) amide functionality are capable of reducing the viscosity, which implies that the interaction between monotopic monomer **2** and the stacks of **1** is not highly specific. That is, other compounds containing hydrogen bond accepting groups also have a reducing effect on the DP.

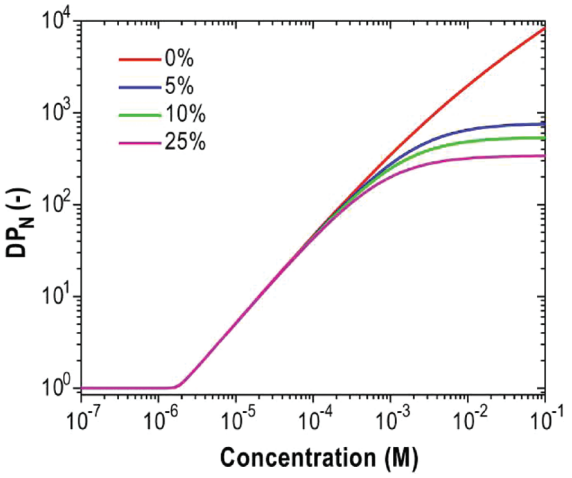


Figure 4. Predicted degree of polymerization, DP_N, for **1** in MCH as a function of concentration, for four different mole fractions of monotopic monomer **2**. Mole fractions of **2** were 0 (red), 0.05 (blue), 0.10 (green), and 0.25 (purple).

To understand the differences in the effect of the monotopic monomer **2** at different concentrations of **1**, the DP_N was calculated for four different mole fractions of **2** (Figure 4). It is clear from these predictions that no effect of the monotopic monomer on the DP_N is present below 10^{-4} M, which is the result of the rather low K_t value. It is only at high concentration (above 10^{-4} M) of monomer **1** that monotopic monomer **2** is able to attach to the end of the stacks of **1** and reduce the length of the stacks, as measured with viscometry. In fact, above 10^{-2} M the DP_N reaches a plateau value, indicating that the viscosity no longer depends on concentration.[57]

The origin of the low K_t and K_m value can be related to the antiparallel arrangement of the amide groups of **2** (Figure 2C). To attach to the end of a stack of **1** (or to a monomer of **1**), all amide groups need to be aligned parallel in one direction to allow for the 3-fold hydrogen-bonding. As a result, **2** is an unfavorable conformation for binding to the end of the stack, which could explain the low K_t value. These results demonstrate that for electronically coupled monomers the design of a monotopic chain stopper is not trivial. Because of *N*-methylation of the C_3-disk, the binding strength of the monotopic monomer **2** was reduced by more than a factor 10 as compared to the ditopic analogue (**1**).

When reconsidering the design of a monotopic monomer, it is perhaps better to modify the structure of the C_3-symmetrical molecule such that it is sterically blocked on one side of the disk. The synthesis of these so-called capped structures has already been extensively reported for porphyrin derivatives, which were applied to inhibit binding of small molecules (like O_2 and CO) to the porphyrin's active site.[58−60] Alternatively, a monotopic BTA derivative in which the three amide groups are preorganized in a parallel fashion would result in a monotopic monomer with a strong affinity for the ends of the BTA stacks.

CONCLUSION

Using optical spectroscopy and viscometry in combination with mathematical modeling and DFT calculations, we were able to understand in detail the consequence of addition of a second monotopic component in the self-assembly of BTA monomers

into long supramolecular polymers. Using viscometry, it was possible to observe the characteristic features of a cooperative supramolecular polymerization process in solution for C_3-symmetrical discotic **1**. Furthermore, *N*-methylated BTA **2** was successfully synthesized and characterized and was evaluated as a chain stopper in the supramolecular polymerization of **1**. It was only at high concentrations ($\sim 10^{-3}$ M) that we could observe a decrease in DP upon addition of the monotopic monomer, as was evidenced from solution viscometry. DFT calculations revealed that this weak binding is related to the connectivity of the three amide groups of the monotopic BTA monomer **2**.

Nonlinear curve-fitting to a model to describe the cooperative supramolecular polymerization in the presence of a monotopic monomer revealed that, compared to the monomer **1**, the association constant of the monotopic monomer **2** with the end of stack of **1** was an order of magnitude smaller. This shows that care should be taken when designing a monotopic analogue of a ditopic monomer with electronically coupled binding sites.

Our binary self-assembly model can be more generally applied to other cooperative supramolecular polymers to which a second component is added that can interact with the monomers and/or polymers. This will open up the route to a better understanding—and predicting—of the properties of such binary systems.

■ ASSOCIATED CONTENT

Supporting Information. Experimental conditions, synthetic procedures, details of DFT calculations, modeling procedures, and supporting figures and tables. This material is available free of charge via the Internet at http://pubs.acs.org.

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■ REFERENCES

(1) Ajayaghosh, A.; Praveen, V. K. *Acc. Chem. Res.* **2007**, *40*, 644.
(2) Brunsveld, L.; Folmer, B. J. B.; Meijer, E. W.; Sijbesma, R. P. *Chem. Rev.* **2001**, *101*, 4071.
(3) Drain, C. M.; Varotto, A.; Radivojevic, I. *Chem. Rev.* **2009**, *109*, 1630.
(4) Hoeben, F. J. M.; Jonkheijm, P.; Meijer, E. W.; Schenning, A. P. H. J. *Chem. Rev.* **2005**, *105*, 1491.
(5) Würthner, F. *Chem. Commun.* **2004**, 1564.
(6) Schenning, A. P. H. J.; Meijer, E. W. *Chem. Commun.* **2005**, 3245.
(7) Bouteiller, L. *Adv. Polym. Sci.* **2007**, *207*, 79.
(8) Chen, Z.; Lohr, A.; Saha-Möller, C. R.; Würthner, F. *Chem. Soc. Rev.* **2009**, *38*, 564.
(9) Zhao, D.; Moore, J. S. *Org. Biomol. Chem.* **2003**, *1*, 3471.
(10) Douglas, J. F.; Dudowicz, J.; Freed, K. F. *J. Chem. Phys.* **2008**, *128*, 224901.
(11) van der Schoot, P. In *Supramolecular Polymers*, 2nd ed.; Ciferri, A., Ed.; Taylor & Francis: London, 2005; p 77.
(12) Ciferri, A. *Macromol. Rapid Commun.* **2002**, *23*, 511.
(13) 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.
(14) Palmans, A. R. A.; Meijer, E. W. *Angew. Chem., Int. Ed.* **2007**, *46*, 8948.
(15) Lortie, F.; Boileau, S.; Bouteiller, L.; Chassenieux, C.; Lauprêtre, F. *Macromolecules* **2005**, *38*, 5283.
(16) Sijbesma, R. P.; Beijer, F. H.; Brunsveld, L.; Folmer, B. J. B.; Hirschberg, J. H. K. K.; Lange, R. F. M.; Lowe, J. K. L.; Meijer, E. W. *Science* **1997**, *278*, 1601.
(17) Furutsu, D.; Satake, A.; Kobuke, Y. *Inorg. Chem.* **2005**, *44*, 4460.
(18) Abbel, R.; Grenier, C.; Pouderoijen, M. J.; Stouwdam, J. W.; Leclère, P. E. L. G.; Sijbesma, R. P.; Meijer, E. W.; Schenning, A. P. H. J. *J. Am. Chem. Soc.* **2009**, *131*, 833.
(19) Wang, X.; Guerin, G.; Wang, H.; Wang, Y.; Manners, I.; Winnik, M. A. *Science* **2007**, *317*, 644.
(20) de Greef, T. F. A.; Meijer, E. W. *Aust. J. Chem.* **2010**, *63*, 596.
(21) Xu, H.; Rudkevich, D. M. *Chem.—Eur. J.* **2004**, *10*, 5432.
(22) Berl, V.; Schmutz, M.; Krische, M. J.; Khoury, R. G.; Lehn, J.-M. *Chem.—Eur. J.* **2002**, *8*, 1227.
(23) Castellano, R. K.; Rudkevich, D. M.; Rebek, J., Jr. *Proc. Natl. Acad. Sci. U. S. A.* **1997**, *94*, 7132.
(24) Yebeutchou, R. M.; Tancini, F.; Demitri, N.; Geremia, S.; Mendichi, R.; Dalcanale, E. *Angew. Chem., Int. Ed.* **2008**, *47*, 4504.
(25) Knoben, W.; Besseling, N. A. M.; Bouteiller, L.; Cohen Stuart, M. A. *Phys. Chem. Chem. Phys.* **2005**, *7*, 2390.
(26) As a result, the authors could approximate the polymerization by an isodesmic model; i.e. the binding constant between monomer and growing polymer is independent of the polymer length.
(27) Helmich, F.; Lee, C. C.; Nieuwenhuizen, M. M. L.; Gielen, J. C.; Christianen, P. C. M.; Larsen, A.; Fytas, G.; Leclère, P. E. L. G.; Schenning, A. P. H. J.; Meijer, E. W. *Angew. Chem., Int. Ed.* **2010**, *49*, 3939.
(28) Hermans, T. M.; Broeren, M., A. C.; Gomopoulos, N.; van der Schoot, P.; van Genderen, M. H. P.; Sommerdijk, N. A. J. M.; Fytas, G.; Meijer, E. W. *Nature Nanotechnol.* **2009**, *4*, 721.
(29) Hanabusa, K.; Koto, C.; Kimura, M.; Shirai, H.; Kakehi, A. *Chem. Lett.* **1997**, 429.
(30) Matsunaga, Y.; Miyajima, N.; Nakayasu, Y.; Sakai, S.; Yonenaga, M. *Bull. Chem. Soc. Jpn.* **1988**, *61*, 207.
(31) Brunsveld, L.; Schenning, A. P. H. J.; Broeren, M. A. C.; Janssen, H. M.; Vekemans, J. A. J. M.; Meijer, E. W. *Chem. Lett.* **2000**, 292.
(32) van Gorp, J. J.; Vekemans, J. A. J. M.; Meijer, E. W. *J. Am. Chem. Soc.* **2002**, *124*, 14759.
(33) Smulders, M. M. J.; Schenning, A. P. H. J.; Meijer, E. W. *J. Am. Chem. Soc.* **2008**, *130*, 606.
(34) Smulders, M. M. J.; Stals, P. J. M.; Mes, T.; Paffen, T. F. E.; Schenning, A. P. H. J.; Palmans, A. R. A.; Meijer, E. W. *J. Am. Chem. Soc.* **2010**, *132*, 620.
(35) Smulders, M. M. J.; Filot, I. A. W.; Leenders, J. M. A.; van der Schoot, P.; Palmans, A. R. A.; Schenning, A. P. H. J.; Meijer, E. W. *J. Am. Chem. Soc.* **2010**, *132*, 611.
(36) Wilson, A. J.; Masuda, M.; Sijbesma, R. P.; Meijer, E. W. *Angew. Chem., Int. Ed.* **2005**, *44*, 2275.
(37) Cantekin, S.; Balkenende, D. W. R.; Smulders, M. M. J.; Palmans, A. R. A.; Meijer, E. W. *Nature Chem.* **2011**, *3*, 42.
(38) Paramonov, S. E.; Jun, H.-W.; Hartgerink, J. D. *J. Am. Chem. Soc.* **2006**, *128*, 7291.
(39) Clark, T. D.; Buriak, J. M.; Kobayashi, K.; Isler, M. P.; McRee, D. E.; Ghadiri, M. R. *J. Am. Chem. Soc.* **1998**, *120*, 8949.
(40) Yu, T.-B.; Bai, J. Z.; Guan, Z. *Angew. Chem., Int. Ed.* **2009**, *48*, 1097.
(41) Lanning, J. D.; Hawk, A. J.; Derryberry, J.; Meredith, S. C. *Biochemistry* **2010**, *49*, 7108.

(42) See Supporting Information.
(43) Filot, I. A. W.; Palmans, A. R. A.; Hilbers, P. A. J.; van Santen, R. A.; Pidko, E. A.; de Greef, T. F. A. *J. Phys. Chem. B* **2010**, *114*, 13667.
(44) Jonkheijm, P.; van der Schoot, P.; Schenning, A. P. H. J.; Meijer, E. W. *Science* **2006**, *313*, 80.
(45) A similar increase in relative viscosity could be observed upon lowering the temperature for relatively concentrated solutions of **1**. For more information see Supporting Information.
(46) Knoben, W.; Besseling, N. A. M.; Cohen Stuart, M. A. *J. Chem. Phys.* **2007**, *126*, 024907.
(47) Assuming slow-breaking and/or flexible polymers yields exponents larger than 3 in each case.
(48) Shikata, T.; Kuruma, Y.; Sakamoto, A.; Hanabusa, K. *J. Phys. Chem. B* **2008**, *112*, 16393.
(49) Stals, P. J. M.; Everts, J. C.; de Bruijn, R.; Filot, I. A. W.; Smulders, M. M. J.; Martín-Rapún, R.; Pidko, E. A.; de Greef, T. F. A.; Palmans, A. R. A.; Meijer, E. W. *Chem.—Eur. J.* **2010**, *16*, 810.
(50) ^{1}H NMR spectroscopy in $CDCl_3$ revealed that the tertiary amide in **2** is present as mixture of the *cis* and *trans* isomers.
(51) Cannon, A. S.; Foxman, B. M.; Guarrera, D. J.; Warner, J. C. *Cryst. Growth Des.* **2005**, *5*, 407.
(52) Also, sergeant-and-soldiers experiments at 10^{-5} M concentration in the presence of **2** revealed that the affinity of **2** was rather weak. See Supporting Information for more details.
(53) Although the nucleus size is not determined, using the more general K_n-K model (where n represents the nucleus size) yields similar concentration-dependent behavior for the degree of aggregation and degree of polymerization. For more information, see: Goldstein, R. F.; Stryer, L. *Biophys. J.* **1986**, *50*, 583.
(54) Smulders, M. M. J.; Nieuwenhuizen, M. M. L.; de Greef, T. F. A.; van der Schoot, P.; Schenning, A. P. H. J.; Meijer, E. W. *Chem.—Eur. J.* **2010**, *16*, 362.
(55) Matlab, version 7.5.0 (R2007b).
(56) Due to their relatively low concentration and dimensions (compared to the polymers), the contribution of monomers to the viscosity was neglected. The polydispersity of the polymers was not explicitly addressed but was included indirectly by taking the average degree of polymerization DP_N. Second, due to the highly dynamic nature of the BTA supramolecular polymers, we assume that the shear rate is smaller than the reciprocal relaxation time so that the zero shear rate viscosity is measured.
(57) Due to the limited solubility of **1** in MCH, it was not possible to expermentally verify this prediction.
(58) Boitrel, B.; Guilard, R. *Tetrahedron Lett.* **1994**, *35*, 3719.
(59) Johnson, M. R.; Seok, W. K.; Ma, W.; Slebodnick, C.; Wilcoxen, K. M.; Ibers, J. A. *J. Org. Chem.* **1996**, *61*, 3298.
(60) Garcia, B.; Lee, C. H.; Blasko, A.; Bruice, T. C. *J. Am. Chem. Soc.* **1991**, *113*, 8118.