Time-dependent amplification of helical bias in self-assembled dye nanorods directed by the sergeants-and-soldiers principle†

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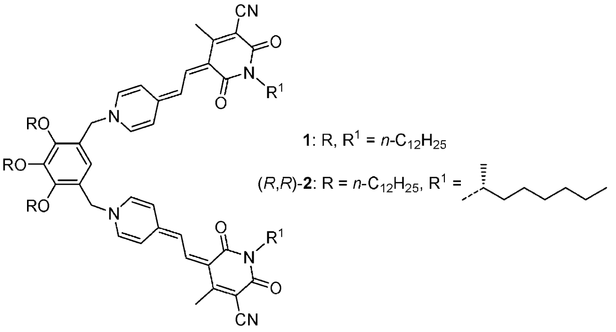
A pronounced sergeants-and-soldiers directed chiral amplification is observed for the self-assembly of merocyanine dye nanorods and the amplification process is shown to become slower for decreasing fraction of sergeant molecules.

Chiral amplification phenomena have attracted much attention not only due to their implication for the emergence of homochirality in nature[1] and ongoing interest in chromophore-based chiral assemblies for (opto)electronic applications,[2] but also because of their significance to chemical reactions and technical processes leading to enantiomerically enriched organic compounds.[3] A mode of chiral amplification commonly referred to as the "sergeants-and-soldiers" principle has been found in macromolecules[4] and supramolecular assemblies[5] that implies a dominant effect of a small fraction of chiral co-monomers on the helical sense of a polymeric backbone or aggregate.[6] Such strong amplification ensues from the event that the major achiral components (soldiers) "follow" the helicity dictated by the chiral components (sergeants). In the past, the sergeants-and-soldiers principle had been studied mostly on thermodynamically equilibrated systems, and reports on the time dependence of such chiral amplification are rather scarce.[7,8] In particular, the progression of a sergeants-and-soldiers principle directed chiral amplification process in supramolecular aggregates that are directly co-assembled from achiral and chiral monomers has not been investigated so far. Here we present the kinetics of such an amplification process in nanorods co-assembled from achiral and chiral bis(merocyanine) dyes **1** and **2**.[9–11]



In our study we have recorded the time-dependent circular dichroism (CD) of aggregates that have been co-assembled from achiral **1** and chiral (*R*,*R*)-**2** monomers employed in different ratios. An increasing helical sense excess, as indicated by a growing bisignate CD effect, with increasing time reveals the kinetics of a chiral amplification process directed by the sergeants-and-soldiers principle. A schematic illustration of this process is shown in Fig. 1.

The co-assembly experiments were performed by mixing stock solutions of **1** and (*R*,*R*)-**2** in THF (3.33×10^{-5} M) in different volumetric ratios (for details, see the ESI†). In THF stock solutions, the bis(merocyanine) dyes are present predominantly in the monomeric form owing to the high polarity of this solvent. Subsequently, nonpolar methylcyclohexane (MCH) was added to give solutions with a total monomer concentration of 10^{-5} M in a mixture of THF–MCH = 30 : 70 (vol%). Upon addition of nonpolar MCH, the monomers aggregate very rapidly owing to the increased Coulomb forces between the dipolar dyes.[9] Afterwards, the solutions were heated to 47 °C to allow for sufficiently fast formation of nanorod aggregates (previously we have denoted these aggregates as **H2** nanorods, for details see the ESI† and ref. 11).

Fig. 2 shows CD spectra of aggregates containing 5% chiral "sergeant" molecules that are recorded at different time intervals (20 min–39 h) after initiation of aggregation and heating to 47 °C.[12] The wavelengths of the maxima/minima of the *P*-helical bisignate Cotton effect of the major UV/Vis absorption band at 442 nm, as well as the isodichroic points at 442 and 470 nm observed from the CD spectra recorded during this time, remain constant and are in very good accordance with those previously observed for **H2** nanorods formed from pure (*R*,*R*)-**2** monomers at room temperature.[11] Importantly, these spectral features reveal the completed formation of **H2** nanorods after only 20 min at elevated temperature.‡

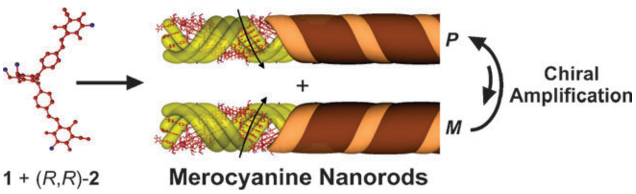


Fig. 1 Co-assembly of achiral and chiral bis(merocyanine) dyes **1** and (*R*,*R*)-**2** leads to dye nanorods with left- (*M*) and right-handed (*P*) helicity. The helical sense excess of these aggregates increases (chiral amplification) with time directed by the sergeants-and-soldiers principle.

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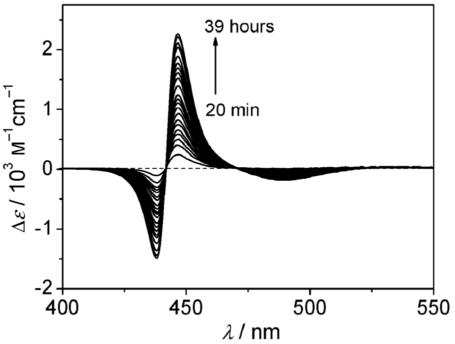

Fig. 2 Time-dependent CD spectra of nanorods formed from dyes **1** and (*R*,*R*)-**2** (95 : 5 mol%) ($c_{tot} = 10^{-5}$ M, THF–MCH = 30 : 70 vol%, 47 °C). The arrow indicates spectral changes with increasing time.

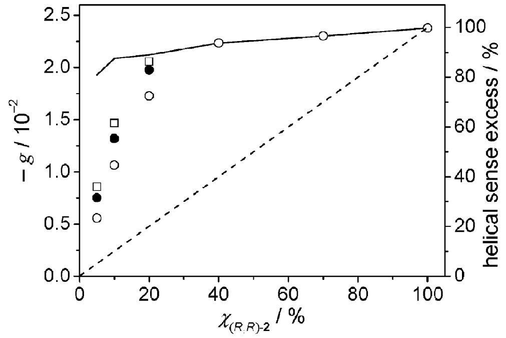

Fig. 3 Dependence of the anisotropy factor *g* at 437 nm on the mole fraction $\chi_{(R,R)\text{-}2}$ of chiral (*R*,*R*)-**2** after 6 h (○), 12 h (●), and 18 h (☐) of equilibration at 47 °C as well as the final values obtained from the stretched exponential fit of the time-dependent CD data (solid line). The dashed line represents the expected *g* values in the absence of any chiral amplification.

Thus, the subsequent and for all wavelengths uniform increase of the CD intensity (recorded for up to 39 h) can be attributed to a reconstruction of coexisting **H2** nanorod aggregates with energetically disfavoured left-handed (*M*) helicity into such with the preferred right-handed (*P*) helicity. Such a process is clearly expressed in a rise of the helical sense excess. Notably, the nanorods of opposite helical sense (*M* and *P*) are energetically different due to co-assembly of achiral and chiral components.

The final anisotropy factors *g* of this process (obtained by extrapolation) for the 95 : 5 mol% and other ratios of **1** : (*R*,*R*)-**2** are represented by the solid line in Fig. 3. This dependence of *g* on the mole fraction of chiral co-monomers reveals a strong nonlinearity and provides evidence for a sergeants-and-soldiers principle directed chiral amplification process. It is interesting to see that almost the same final helical bias is realized for all mixtures studied, *i.e.*, one sergeant can direct almost 20 soldiers in the present experiments.

An unprecedented feature observed in our study is a pronounced impact of the fraction of (*R*,*R*)-**2** sergeants on the time required for this chiral amplification process. Thus, already after 6 h (Fig. 3, open circles), the anisotropy factors of nanorods containing 40% or more chiral sergeants are almost the same as those observed for nanorods assembled from pure chiral monomers (*R*,*R*)-**2**. In these cases the helical sense excess, which can be directly derived from the *g* values, reaches more than 93% during the first 6 h (Fig. 3, right scale).§ However, the kinetics of this chiral amplification becomes considerably slower for decreasing fraction of co-monomer (*R*,*R*)-**2**, as revealed by the increasing *g* factors of nanorods containing 5 to 20% chiral sergeants in the time period from 6 to 18 h. In the case of 20% chiral sergeants, a helical sense excess of 73% is obtained after 6 h, while 87% are reached after 18 h. Finally, the helical sense excess reached by nanorods containing 10 and 5% chiral sergeants is only 62 and 36%, respectively, after 18 h.

For the evaluation of the kinetics of this chiral amplification process, the anisotropy factors *g* at the minima of the Cotton effect at 437–438 nm are plotted *versus* time in Fig. 4. The kinetics of this chiral amplification process on the basis of time-dependent *g* values could properly be described by applying a stretched exponential relaxation function (for details see the ESI†). As the data in ESI† Table S1 show, for a decrease of chiral sergeants from 20 to 5%, the relaxation time increases from 3 to 69 h. This result pinpoints that the chiral amplification drastically slows for a smaller fraction of chiral sergeants.

Though the detailed molecular mechanism of the present amplification process is not yet known, it is important to note that the chiral amplification process observed here is directly related to a reconstruction of co-aggregates with improper helical sense and thereby markedly distinguished from previous reports on time-dependent sergeants-and-soldiers directed chiral amplification. In previous studies, the time dependence of the sergeants-and-soldiers effect was either due to a slow exchange of achiral and chiral building blocks among the respective pre-assembled racemic and homochiral aggregates,[7]¶ or based on the induction of homochirality into racemic helical assemblies formed from achiral building blocks by addition of chiral guest molecules that bound to the assembly.[8]

Our present study relates, at least in part, to the "majority-rules"-directed chiral amplification process of (*R*,*R*)-**2** and (*S*,*S*)-**2** monomers that we have reported recently.[13] However,

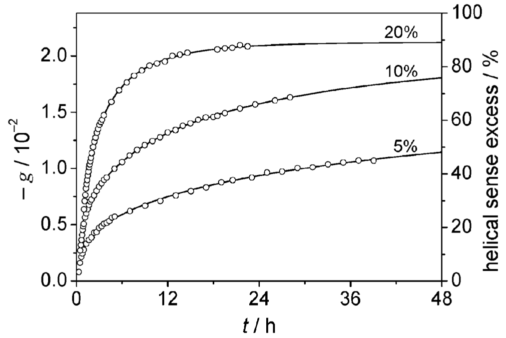

Fig. 4 Time-dependent anisotropy factors *g* at 437 nm of nanorods formed from dyes **1** and (*R*,*R*)-**2** with various mole fractions of chiral (*R*,*R*)-**2** (5–20%) as indicated ($c_{tot} = 10^{-5}$ M, THF–MCH = 30 : 70 vol%, 47 °C). The solid lines represent the stretched exponential curve fits (details are given in the ESI†).

the grave difference between the present and previous studies is that our previous work[13] concerns the early stage of nanorod formation, *i.e.*, the self-assembly of the monomers into kinetical nanorods (denoted as **H1**), while the present study reveals the time-dependent development of helical bias as a self-ordering phenomenon of pre-assembled **H2** nanorods with statistical $M : P$ ratio. These complementary studies reveal that chiral amplification mechanisms can operate at different stages of self-assembly to afford an energetically favoured structure,[14] and highlight the complexity of self-assembly pathways in artificial systems that is of course omnipresent in nature.

To summarize, our present work shows that the sergeants-and-soldiers principle is operative in the self-assembly of bis(merocyanine) dye nanorods. The chiral amplification process observed in this system can be interpreted in terms of a reconstruction of an initially formed **H2** nanorod mixture with statistical helicity into such with the helical sense favoured by the sergeant molecules. The rate of this process decreases strongly with the decreasing fraction of chiral sergeant molecules, but high excess of helical sense can still be reached with a small sergeants fraction after an extended period of time. In other words, a small number of sergeants do manage to direct a substantial number of soldiers (~20) but require longer to convince them to follow.

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Notes and references

‡ The CD spectra recorded in the first 20 min show the inversion of the CD spectrum during the stereomutation from **H1** into **H2** nanorods as previously reported (see ref. 10). During this process a shift of the CD maxima and different isodichroic points are observed. Notably, a close comparison of the CD spectrum of **H2** nanorods formed from pure (*R*,*R*)-**2** and those of the here studied co-aggregates (see ESI†) reveals a slight hypsochromic shift of the co-aggregates (about 1 nm). This small difference indicates their co-aggregated nature and can be attributed to a slightly different packing in the co-aggregates.

§ The *g* value of aggregates formed from pure (*R*,*R*)-**2** monomers corresponds to a helical sense excess of 100%, see ref. 10.

¶ We have also conducted such type of experiments by adding a small amount of homochiral **H2** nanorods pre-assembled from (*R*,*R*)-**2** to the racemic mixture of **H2** nanorods pre-assembled from achiral **1**. In this case slow amplification of helical bias could be observed owing to the exchange of chiral and achiral monomers among the pre-assembled aggregates.

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