J|A|C|S
COMMUNICATIONS

Chiral Memory via Chiral Amplification and Selective Depolymerization of Porphyrin Aggregates

Floris Helmich,[||] Cameron C. Lee,[||] Albertus P. H. J. Schenning,* and E. W. Meijer*

Laboratory of Macromolecular and Organic Chemistry, Eindhoven University of Technology, P.O. Box 513, 5600 MB Eindhoven, The Netherlands

Received August 28, 2010; E-mail: a.p.h.j.schenning@tue.nl; e.w.meijer@tue.nl

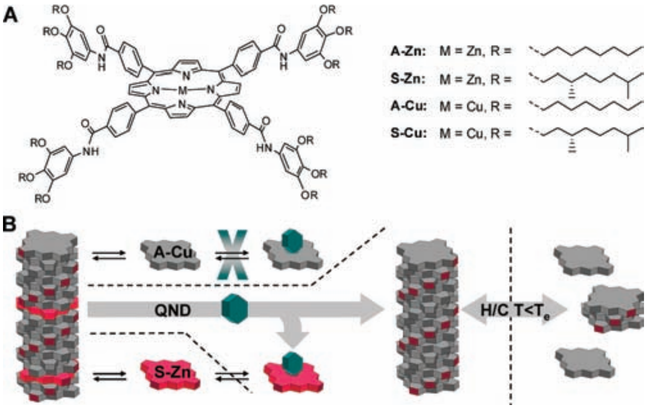
Abstract: Chiral memory at the supramolecular level is obtained via a new approach using chiral Zn porphrins and achiral Cu porphyrins. In a "sergeant-and-soldiers" experiment, the Zn "sergeant" transfers its own chirality to Cu "soldiers" and, after chiral amplification, the "sergeant" is removed from the coaggregates by axial ligation with a Lewis base. After this extraction, the preferred helicity observed for the aggregates containing achiral Cu porphyrins reveals a chiral memory effect that is stable and can be erased and partially restored upon subsequent heating and cooling.

The transfer, amplification, and storage of chirality in supramolecular architectures is of great interest.[1] Within this area, the formation of an assembly constructed from achiral building blocks but containing an imprinted homochiral memory is a real challenge. A few examples of such systems in which chiral auxiliaries are employed to bias the chirality of racemic covalent polymers,[2] discrete supramolecular systems,[3] and porphyrin-based aggregates[4] are known. Even more remarkable examples disclose the combination of storage and amplification of supramolecular chirality, as shown for porphyrins[5] and calixarene-based rosettes.[6] These so-called memory approaches[7] are based on a temporary diastereomeric relationship in which the conformational inertness of the kinetically trapped chiral architecture is sufficient to overcome the removal or substitution of the auxiliary. The latter examples inspired us to investigate chiral memory at the supramolecular level by the selective depolymerization of porphyrin aggregates, which are found in the class of self-assembled, helical, one-dimensional dye polymers that show tunable dynamic stability and amplification of chirality.[8] In our approach, it is important that (1) chiral and achiral building blocks mix in order to allow the amplification of chirality, (2) molecular recognition guarantees the selective and complete removal of the chiral building block, and (3) the conformational stability of the remaining aggregate based on achiral building blocks is high enough to preserve the chirality.

We previously described the hydrogen-bond-assisted and highly cooperative self-assembly of the chiral Zn porphyrin **S−Zn** (Scheme 1A) in methylcyclohexane (MCH) and its remarkable behavior in the presence of a Lewis base.[9] Mechanistic insights revealed the prime role of monomers that coexist with the porphyrin aggregates at nanomolar concentration; axial ligation occurs predominantly with monomers, and this scavenging leads to depolymerization. We now report the coaggregation of chiral base-sensitive **S−Zn** and the achiral base-insensitive Cu porphyrin **A-Cu** and subsequent treatment with the Lewis base quinuclidine (QND). We show that according to the "sergeant-and-soldiers" principle, **S−Zn** strongly amplifies the preferred helicity of the coaggregates with **A-Cu** and that we can selectively extract this "sergeant" from these coaggregates by axial ligation with QND. The helicity observed in the remaining "soldier" supramolecular polymer indicates a chiral memory effect that is obtained by removing only the chiral building block from the helical amplified stacks *after* self-assembly. The supramolecular chiral memory is sufficiently stable under ambient conditions that it can be partially erased and restored by respectively heating and cooling the solutions of the aggregates.

Regardless of the metalation state or side-chain identity, **A-Zn**, **S−Zn**, **A-Cu**, and **S−Cu** (Scheme 1A)[10] formed the same H-type aggregates as reported previously[9] when prepared via injection of a concentrated chloroform solution in MCH at room temperature (RT).[11] The aggregates showed the characteristic sharp Soret band at $\lambda_{max} \approx 390$ nm in MCH that reveals the presence of extended cofacial aggregates,[9] which are circular dichroism (CD)-active or -silent for **S−Zn/Cu** or **A-Zn/Cu**, respectively. The injection method allowed the easy preparation of the identical type of supramolecular coaggregates consisting of porphyrins with mixed metals and/or mixed stereochemistry. Chloroform injection of premixed comonomers afforded thermodynamically stable coaggregates in a remarkably quicker and more efficient way than mixing preaggregated porphyrins in MCH (Figure S2).[12] In the latter case, the supramolecular dynamics for the monomer−aggregate equilibrium is too slow for the exchange of comonomers between aggregates.

Scheme 1. (A) Chiral/Achiral Amide-Functionalized Zinc/Copper Tetraphenylporphyrins Used in This Study; (B) Schematic Depiction of Selective Depolymerization with Chirality Retention and Temperature-Induced Switching of the Chiral Memory



Successful coaggregation was evidenced by chiral amplification via the "sergeant-and-soldiers" principle and energy-transfer studies. These two effects were studied simultaneously in the coaggregation of **S−Cu** and **A-Zn** with different feed ratios at a total porphyrin

---

[||] These authors contributed equally.

concentration of 1.0×10^{-6} M in MCH. As the fraction of **S−Cu** was increased, strong chiral amplification was observed in which the "sergeant" comonomer transferred its own chirality to the achiral **A-Zn** comonomers, yielding a helical aggregate with a single handedness (Figure 1A).[13] Modeling of these data revealed a large helix reversal penalty (HRP) of 14.3 kJ mol^{-1} versus a mismatch penalty (MMP) of 0.7 kJ mol^{-1}, which is on the same order as that found for stacks of benzene-1,3,5-tricarboxamides.[14,12] Similar results were observed for quenching of the fluorescence of **A-Zn** upon addition of nonemissive **S−Cu**, which acts as a trap in the coaggregate (Figure 1B).[15] Notably, the two processes seemed to follow the same nonlinear trend as shown for the composition 10% **S−Cu**, at which both the Cotton effect was saturated and the nonlinear quenching behavior ceased (Figure 1C).

The *reversed* **S−Zn**:**A-Cu** system was used for the selective removal of **S−Zn** and showed the same mixing with a slightly stronger chiral amplification (HRP = 19.4 kJ mol^{-1}, MMP = 0.10 kJ mol^{-1}),[12] while the aggregate fluorescence was fully quenched for all mixtures as a result of the high fraction of **A-Cu** (Figure 1C). By preparation of the 1:9 **S−Zn**:**A-Cu** coaggregate at 1.0×10^{-6} M, it was possible to selectively remove the **S−Zn** from the fully amplified stack by axial ligation with QND because of the difference in the sensitivities of Cu porphyrins[16,12] and Zn porphyrins [9,12] toward Lewis bases.

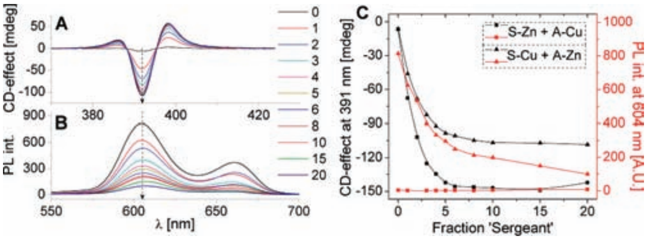


Figure 1. (A) CD and (B) emission spectra at different **S−Cu** "sergeant" fractions in the **S−Cu**:**A-Zn** coaggregate. (C) CD effect at 391 nm (left axis) and emission intensity at 604 nm with $\lambda_{ex} = 405$ nm (right axis) vs the "sergeant" fraction (■ = **S−Zn**:**A-Cu**, ▲ = **S−Cu**:**A-Zn**). All spectra were taken at 1.0×10^{-6} M in MCH at RT.

Addition of a 10 000-fold excess of QND to the 1:9 **S−Zn**:**A-Cu** coaggregates at 1.0×10^{-6} M pushed the extraction of **S−Zn** to completion, causing a decrease of ~10% in the aggregate Soret band at 390 nm while a new band appeared at 431 nm (Figure 2A). The latter originated from the **S−Zn**:QND monomer complex, as confirmed by a reference experiment.[17] The extraction process proceeded very slowly, according to time-dependent UV−vis measurements (Figure S7a).[12] This can be rationalized by the slow monomer exchange (see above) and the extremely low concentration of receptive **S−Zn** comonomers in the depolymerization mechanism we proposed previously.[9] From the UV−vis intensities at 390 and 431 nm, we estimate that at least 95% of **S−Zn** was extracted from the coaggregates after treatment with QND;[18] hence, the remaining aggregate contained no more than 0.5 mol % "sergeant".[12] The selective removal was also supported by an increase in the fluorescence of **S−Zn**:QND, revealing the liberation of **S−Zn** from the coaggregate (Figure 2B).

After treatment with QND, we observed only a 15% reduction of the CD intensity (Figure 2C), which was a little more than expected for the ~10% decrease of the aggregate Soret band but significantly less than the CD response expected from the highest estimate of the amount of **S−Zn** remaining in the aggregate.[19] After extraction, a considerable CD activity remained present for several months,[12] indicating that the rate of racemization in the remaining **A-Cu** aggregates was even lower than the rate of removal of **S−Zn** from the coaggregates. This lack of conformational dynamics is similar to the chiral memory effect observed for chiral porphyrin aggregates in water.[4]

Analogously,[4b] the remarkable inertness at RT prompted us to investigate the possibility of releasing and restoring the chiral memory by a series of heating and cooling experiments on solutions of imprinted chiral stacks containing **A-Cu**. First, heating and cooling of 1:9 **S−Zn**:**A-Cu** (1:9) coaggregates in the absence of QND resulted in a complete loss of optical activity above the elongation temperature (T_e). Subsequent slow cooling from the molecularly dissolved state above T_e resulted in a full recovery of the optical activity due to chiral amplification by **S−Zn** (Figure S9a).[12] Second, in the presence of QND and after removal of the **S−Zn** from the coaggregate, the CD effect was again lost upon heating the solution above $T_e \approx 68$ °C. In this case, however, slow cooling to RT did not result in recovery of the CD effect because of the erasure of the chiral memory and the absence of any chiral porphyrin in the self-assembled stack. Finally, heating to and subsequent cooling from 60 °C ($<T_e$), at which only a fraction of **A-Cu** was aggregated, produced a partial recovery of the chiral memory (Figure 2D).[20] At this relatively high temperature of 60 °C, the conformational inertness of the remaining assemblies was sufficient for these "**A-Cu** seeds" to maintain their imprinted chirality, allowing enantiospecific self-assembly of **A-Cu** upon cooling.

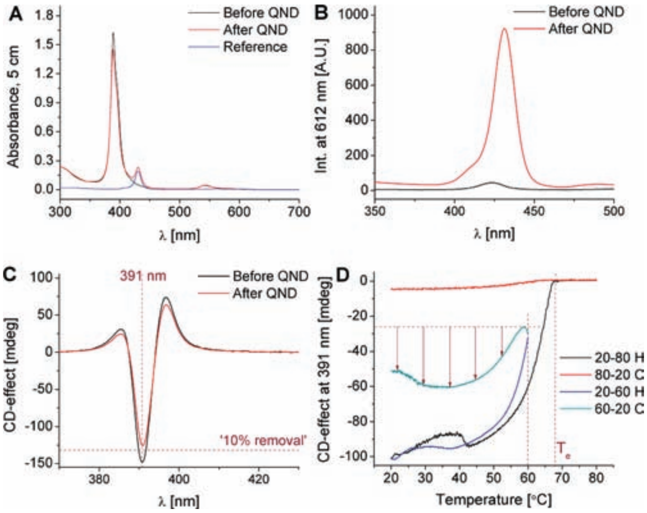


Figure 2. (A)UV−vis, (B) excitation, and (C) CD spectra before and after extraction with QND. (D) Temperature-dependent CD effect at 391 nm for heating (H) and cooling (C) of the "memorized" solutions at 6 °C/h below (20−60 H and 60−20 C, respectively) and above (20−80 H and 80−20 C, respectively) T_e. In all panels, [1:9 **S−Zn**:**A-Cu**] = 1.0×10^{-6} M with a 10 000-fold excess of QND in MCH at RT.

In summary, we have described a class of highly tunable porphyrin-based supramolecular copolymers that, by proper choice of the central metal and the side-chain identity, show chiral amplification, selective depolymerization, and chiral memory. The chiral information in the remaining aggregate was retained as a result of slow conformational dynamics, which also allowed temperature-induced switching of the chiral memory.

Acknowledgment. This work was supported by the Council of Chemical Sciences of The Netherlands Organization for Scientific Research (CW-NWO). We thank Dr. Maarten Smulders for modeling the "sergeants-and-soldiers" experiments and for discussions.

Supporting Information Available: Experimental details, synthetic procedures, characterization data, and modeling details. This material is available free of charge via the Internet at http://pubs.acs.org.

References

(1) Scarso, A.; Rebek, J., Jr. *Top. Curr. Chem.* **2006**, *265*, 1–46.

(2) Yashima, E.; Maeda, K.; Okamoto, Y. *Nature* **1999**, *399*, 449–451.

(3) (a) Furusho, Y.; Kimura, T.; Mizuno, Y.; Aida, T. *J. Am. Chem. Soc.* **1997**, *119*, 5267–5268. (b) Rivera, J. M.; Craig, S. L.; Martin, T.; Rebek, J., Jr. *Angew. Chem., Int. Ed.* **2000**, *39*, 2130–2132. (c) Kubo, Y.; Ohno, T.; Yamanaka, J.; Tokita, S.; Iida, T.; Ishimaru, Y. *J. Am. Chem. Soc.* **2001**, *123*, 12700–12701.

(4) (a) Bellacchio, E.; Lauceri, R.; Gurrieri, S.; Scolaro, L. M.; Romeo, A.; Purrello, R. *J. Am. Chem. Soc.* **1998**, *120*, 12353–12354. (b) Mammana, A.; D'Urso, A.; Lauceri, R.; Purrello, R. *J. Am. Chem. Soc.* **2007**, *129*, 8062–8063.

(5) Toyofuku, K.; Alam, M. A.; Tsuda, A.; Fujita, N.; Sakamoto, S.; Yamaguchi, K.; Aida, T. *Angew. Chem., Int. Ed.* **2007**, *46*, 6476–6480.

(6) Prins, L. J.; De Jong, F.; Timmerman, P.; Reinhoudt, D. N. *Nature* **2000**, *408*, 181–184.

(7) Cozzi, F.; Siegel, J. S. *Org. Biomol. Chem.* **2005**, *3*, 4296–4298.

(8) Lee, C. C.; Grenier, C.; Meijer, E. W.; Schenning, A. P. H. J. *Chem. Soc. Rev.* **2009**, *38*, 671–683.

(9) Helmich, F.; Lee, C. C.; Nieuwenhuizen, M. M. L.; Gielen, J. C.; Christianen, P. C. M.; Larsen, A.; Fytas, G.; Leclere, P.; Schenning, A. P. H. J.; Meijer, E. W. *Angew. Chem., Int. Ed.* **2010**, *49*, 3939–3942.

(10) Chiral and achiral metal porphyrins were synthesized from commercially available *meso*-tetrakis(4-carboxyphenyl)porphyrin and a chiral/achiral trialkoxyaniline wedge. After amidation and metal insertion, the porphyrins were purified by column chromatography and recycling size-exclusion chromatography and fully characterized.[12]

(11) $CHCl_3$ (0.5 vol %) did not affect the aggregation. We refrained from "traditional" dissolution in MCH with subsequent heating/cooling (as shown earlier for **S-Zn**)[9] because **A-Zn** forms a different aggregate type upon cooling..[12]

(12) See the Supporting Information.

(13) Palmans, A. R. A.; Vekemans, J.; Havinga, E. E.; Meijer, E. W. *Angew. Chem., Int. Ed.* **1997**, *36*, 2648–2651.

(14) 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*, 611–619.

(15) Schick, G. A.; Schreiman, I. C.; Wagner, R. W.; Lindsey, J. S.; Bocian, D. F. *J. Am. Chem. Soc.* **1989**, *111*, 1344–1350.

(16) Szintay, G.; Horvath, A.; Grampp, G. *J.Photochem. Photobiol., A* **1999**, *126*, 83–89.

(17) In the reference experiment performed with a **S-Zn** concentration of 10^{-7} M and a 100 000-fold excess of QND, hydrogen bonding was not particularly favored; complexed monomeric species (sharp Soret band at 431 nm) rather than complexed dimers were formed.[9] Moreover, no changes in the UV−vis spectra were observed when QND was added to **A-Cu** homoaggregates.[12]

(18) Extraction was performed by stirring for 24 h in the absence of light.

(19) On the basis of the *g* values from Figure 1C (Figure S7b),[12] the reduction of the CD intensity is estimated to be >75% when 0.5% **S-Zn** remains co-aggregated.

(20) The temperature-induced switching of the chiral memory was very sensitive to small differences in the experimental conditions (e.g., the heating and cooling rates). Unlike at RT, QND affected the H-type aggregation of **A-Cu** at higher temperatures (Figure S9b).[12]

JA1077602