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Helical Structures

Multicomponent Cylindrical Assemblies Driven by Amidinium–Carboxylate Salt-Bridge Formation

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The synthesis of supramolecular architectures has rapidly evolved into one of the major research areas in contemporary chemistry.[1] Although a variety of supramolecular arrays have been generated based on metal–ligand coordination or a hydrogen-bonding-driven self-assembly process,[2,3] the preparation of discrete, well-defined three-dimensional supramolecular assemblies is still a significant synthetic challenge. In particular, multicomponent cylindrical complexes are restricted to a few seminal examples,[2,4] owing to the difficulty of controlling the heteroleptic complexation in such a dynamic multicomponent self-assembly process.

Amidinium–carboxylate salt bridges have a well-defined geometry and exhibit high association constants even in polar solvents and have consequently been employed as useful modules for constructing supramolecular assemblies.[5] The key feature is the ability to use complementary pairs of molecules to generate well-defined supramolecular structures in a controlled fashion, and therefore the salt bridges can be employed as the structural motifs for the self-assembly of complementary acid–base organic modules. In addition, the nitrogen atoms can accommodate chiral substituents, which would enable the control over supramolecular chirality—a very important and challenging task.[6] We describe herein the synthesis of cylindrical complexes with a controlled helicity through multicomponent self-assembly that relies on amidinium–carboxylate salt-bridge formation and the guest-encapsulation-induced twist of a cylinder.

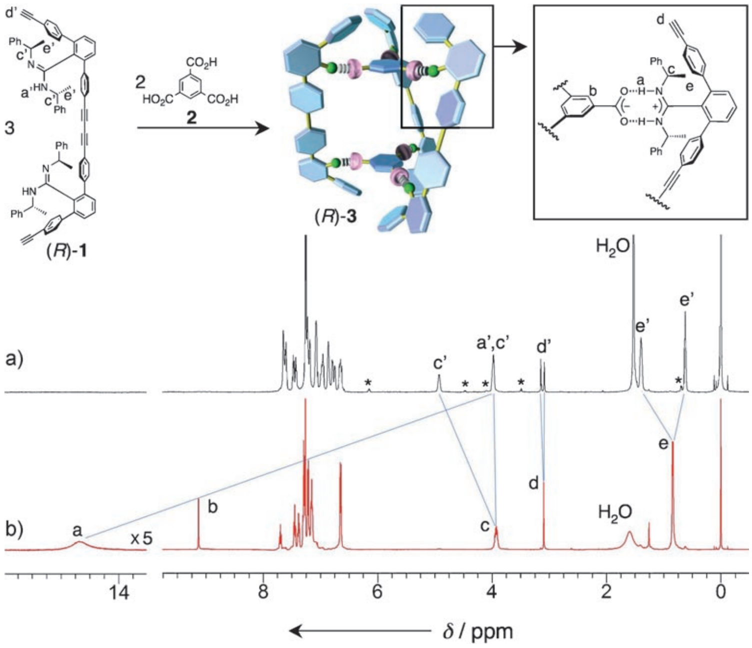

Figure 1. Partial ^{1}H NMR spectra (500 MHz, CDCl$_3$, 25 °C) of a) (*R*)-**1** (0.1 mM) and b) (*R*)-**3** (0.1 mM). The asterisks denote the signals for the corresponding *Z* isomer, that is, the geometrical isomer of the C=N bond, of (*R*)-**1**.[5c]

The cylindrical complex (*R*)-**3** was prepared by mixing a solution of the molecular strand (*R*)-**1**, which bears chiral amidine groups, in CHCl$_3$ and a solution of 1,3,5-benzenetricarboxylic acid **2** in THF in 3:2 molar ratio at ambient temperature (Figure 1).[7] The formation of the 3:2 complex (*R*)-**3** was confirmed by ESI-mass spectrometry (MS) measurements. The ESI-MS spectrum of a solution of (*R*)-**3** in CHCl$_3$ displayed signals at *m*/*z* 3587 and 1794 which correspond to $[M{+}H]^+$ and $[M{+}2H]^{2+}$, respectively. In the ^{1}H NMR spectrum of (*R*)-**3**, the resonance of the NH protons was observed as a broad singlet at a low magnetic field of $\delta = 14.69$ ppm, indicating the formation of salt bridges. The aromatic protons of **2** appeared as a singlet at $\delta = 9.13$ ppm and reflects the highly symmetrical structure of (*R*)-**3** (Figure 1).

Single crystals of (*S*)-**3** suitable for X-ray crystallography studies were obtained from a CHCl$_3$/hexane solution.[7] Crystallographic analysis revealed the cylindrical shape of (*S*)-**3**, in which the five components are connected through six salt bridges (Figure 2a).[8] A large cavity with a diameter of approximately 1 nm lies inside the cylindrical complex with a height of around 2.7 nm and a diameter of around 2.3 nm. The upper and lower tricarboxylate units are almost planar with average deviations from the mean planes of 0.12 and 0.13 Å, respectively. The two tricarboxylate units make an angle of

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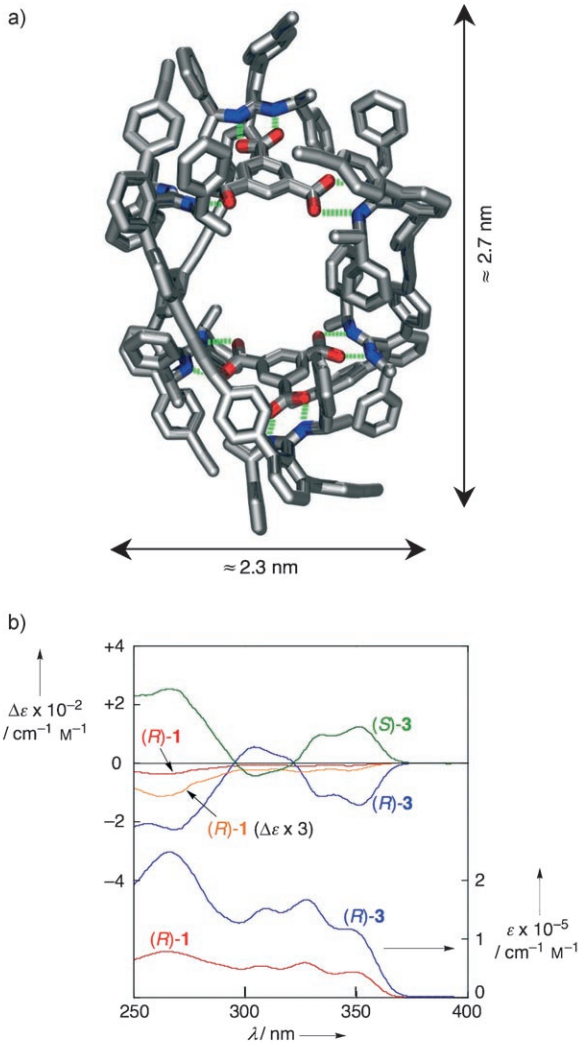

Figure 2. a) X-ray crystal structure of the cylindrical complex (*S*)-**3**. Hydrogen atoms are omitted for clarity; N blue, O red, C gray. The intercomponent hydrogen bonds between N and O with average N⋯O distances of 2.77 Å are shown by green dashed lines. b) CD (Δε) and absorption (ε) spectra (upper and lower sets of spectra, respectively) of (*R*)-**1**, (*R*)-**3**, and (*S*)-**3** in $CHCl_3$ (0.1 mM, 25 °C). The CD spectrum of (*R*)-**1** multiplied by a factor of 3 is shown for comparison.

10.8°, that is, they are almost parallel to each other. All the benzene rings of the *m*-terphenyl groups are twisted counterclockwise by about 45–60°, and each amidine strand is tilted in one direction by about 70° with respect to the tricarboxylate units. As a result, (*S*)-**3** adopts a left-handed, triple-stranded helical structure.

Next, we investigated the solution structure of the cylindrical complex using circular dichroism (CD) spectroscopy (Figure 2b). Both enantiomers of **3** showed intense mirror-image CD signals. Note that a remarkable increase in the intensities of the Cotton effect for (*R*)-**3** was observed in the regions corresponding to the diacetylene linker (300–370 nm) as well as the *m*-terphenyl chromophore, as compared to (*R*)-**1**, suggesting that (*R*)-**3** adopts a partial right-handed helical structure in solution.[9] The intensity of these Cotton effects further increased upon cooling, indicating the dynamic nature of the triple-stranded helical structure and that the bias in the helical sense increases with a decrease in temperature.[7]

One of the advantages of the multicomponent self-assembly is that modules can be employed to construct various desired superstructures, as long as they do not interfere with the recognition motifs for the self-assembly. For example, a 4:2 cylindrical complex should be formed if a tetratopic carboxylate is employed instead of the tritopic carboxylate **2**. In fact, the combination of (*R*)-**1** and zinc 5,10,15,20-tetrakis(4-carboxyphenyl)porphyrin **4** yielded the corresponding 4:2 cylindrical complex (*R*)-**5**[7] through specific amidinium–carboxylate salt-bridge formation as revealed by the appearance of the ^{1}H NMR signal for the NH hydrogen atom at $\delta = 14.32$ ppm and those for CHN at $\delta = 4.03$–4.08 ppm (Figure 3). The β-pyrrolic proton signals of the porphyrin moiety appeared at $\delta = 8.90$ and 9.20 ppm, reflecting the presumed D_4-symmetrical structure of the cylindrical complex. The formation of the 4:2 cylindrical complex (*R*)-**5** was also supported by the negative mode CSI-MS spectrum of (*R*)-**5** in $CHCl_3$/MeOH (10:1) which showed a signal at *m*/*z* 5959.61 corresponding to $[M{-}H{+}MeOH]^-$.[7] Molecular-mechanics (MM) calculations suggest that (*R*)-**5** most likely adopts an almost untwisted cylindrical structure in which each amidine column is nearly perpendicular to the two porphyrin units, which are separated by approximately 1.3 nm from each other (Figure 3). This modeling result is consistent with the CD measurement results: no remarkable increase in the intensity of the Cotton effect for (*R*)-**5** around the diacetylene absorption region (300–370 nm) was observed as

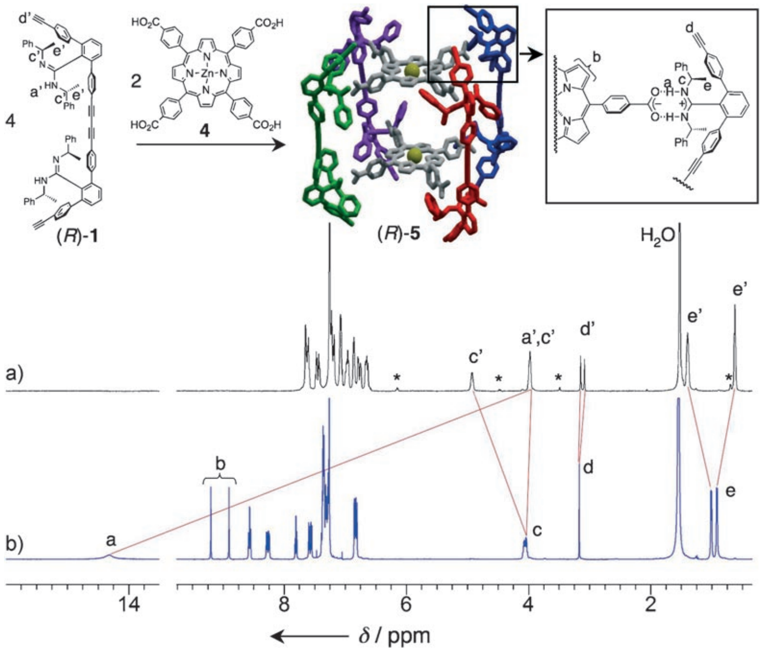

Figure 3. Partial ^{1}H NMR spectra (500 MHz, $CDCl_3$) of a) (*R*)-**1** (0.1 mM) and b) (*R*)-**5** (0.1 mM). The asterisks denote the signals for the corresponding *Z* isomer of (*R*)-**1**.[5c] The structure of (*R*)-**5** (top) was obtained by molecular-mechanics calculations.

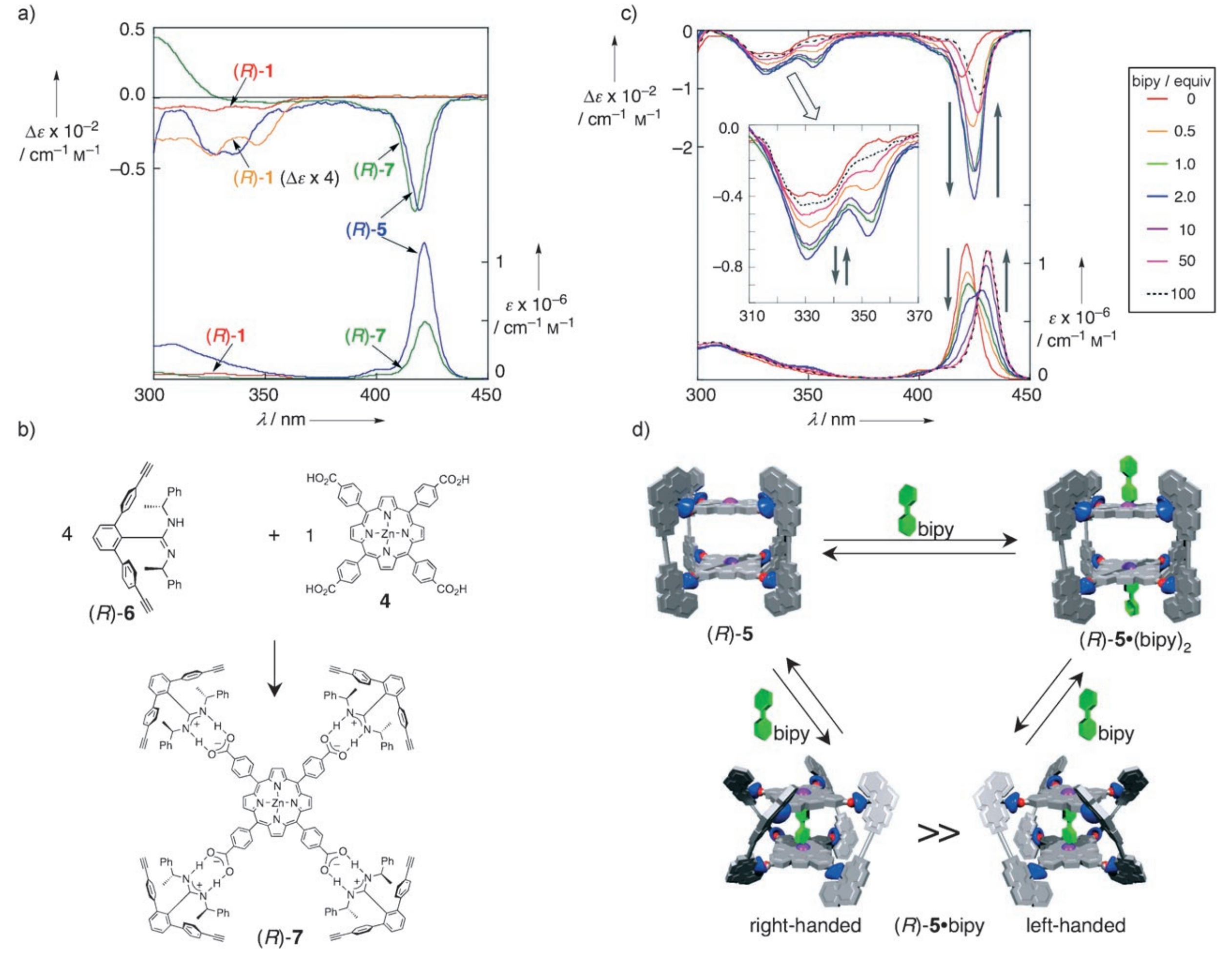

Figure 4. a) CD and absorption spectra of (*R*)-**1**, (*R*)-**5**, and (*R*)-**7** in $CDCl_3$ (0.1 mM) at 25 °C. The CD spectrum of (*R*)-**1** multiplied by a factor of 4 is shown for comparison. b) Synthesis of the quinary complex (*R*)-**7**. c) Changes in the CD and absorption spectra of (*R*)-**5** in $CDCl_3$ (0.1 mM) at 25 °C upon the addition of bipy (0–100 equiv). The inset shows expanded details of the changes in CD (310–370 nm). d) Schematic illustration of the formation of (*R*)-**5**·bipy and (*R*)-**5**·(bipy)$_2$.

compared to that of (*R*)-**1** (Figure 4 a), probably as a result of the untwisted cylindrical structure of (*R*)-**5**. The CD signals induced in the Soret band may be attributed to the perturbation from the chiral amidine groups, as a similar negative Cotton effect was observed around the same Soret band in the CD spectrum of the 4:1 complex (*R*)-**7**[7] that was prepared from **4** and (*R*)-**6** in 1:4 molar ratio as a model complex (Figure 4 a and b). This speculation was further supported by the fact that the intensity of the Cotton effect for (*R*)-**5** in $CDCl_3$ showed no temperature dependence between +30 and −10 °C.[7]

The zinc porphyrin based supramolecular cylinder (*R*)-**5** has a three-dimensional cavity and may be able to encapsulate guest molecules, in particular nitrogen bases of the appropriate size and shape.[10] We thus explored the complexation of 4,4′-bipyridine (bipy) into the internal cavity of (*R*)-**5** surrounded by the two zinc porphyrin components. Upon the addition of increasing amounts of bipy into a solution of (*R*)-**5**, a gradual red shift in the Soret band of the zinc porphyrin was observed as a result of the coordination of the bipy to the zinc centers, suggesting the formation of the sandwich complex (*R*)-**5**·bipy together with the octonary complex (*R*)-**5**·(bipy)$_2$ in which the two bipy molecules are bound to the zinc centers from the outside (Figure 4 c and d). The formation of (*R*)-**5**·bipy was clearly confirmed by ^{1}H NMR spectroscopy. The signals of the bound bipy units were considerably shifted upfield relative to the signals of free bipy ($\Delta\delta = -6.8$ and -2.7 ppm) owing to the ring-current effect of the porphyrin units, as is often the case with bipy–(zinc porphyrin) sandwich complexes.[7,10] In contrast, (*R*)-**5**·(bipy)$_2$ and free (*R*)-**5** underwent a fast exchange on the ^{1}H NMR timescale, thereby producing averaged ^{1}H NMR signals. The ^{1}H NMR titration experiments of (*R*)-**5** with bipy showed that the proportion of (*R*)-**5**·bipy to the total cylindrical complexes reached a maximum value of 20 % at 25 °C when two equivalents of bipy was added to the solution of (*R*)-**5**.[7] Such a low proportion of the (*R*)-**5**·bipy species may be attributed to the slightly longer distance between the two zinc centers of (*R*)-**5** (ca. 1.3 nm) than the optimal one for bipy of about 1.1 nm. This resulted in the deformation of the cylindrical frame of (*R*)-**5** upon binding bipy inside the cavity, thus generating a twisted structure with an excess onehandedness, as described below, because of the rigid amidine strands. The shrinkage of the cylindrical frame upon sandwiching a bipy molecule was supported by the upfield shifts of the ^{1}H NMR signals for pyrrole β hydrogen atoms due to the ring-current effect of the other porphyrin unit, which means that the distance between the two porphyrin units became shorter.[7,10a] This encapsulation process accompanied with a structural deformation may not be favored over the formation of (R)-**5**·(bipy)$_2$. Therefore, the further addition of bipy caused a decrease in the amount of (R)-**5**·bipy, and consequently (R)-**5**·(bipy)$_2$ predominantly formed at higher concentrations of bipy.[7]

A titration studied by CD using bipy was then performed. The Cotton effect around the Soret band exhibited a red shift along with other changes in the absorption spectra (Figure 4c). In addition, the CD intensities around the Soret band and the diacetylene linker region (300–370 nm) significantly and cooperatively increased with an increasing proportion of (R)-**5**·bipy ([bipy]/[(R)-**5**] = 0–2). These results are in good agreement with the ^{1}H NMR titration results and suggest that (R)-**5**·bipy may adopt an excess right-handed helical structure assisted by the encapsulation of bipy.[11,12] That is, the 4:2 cylindrical frame is twisted in one direction upon encapsulation of bipy as a result of shortening of the distance between the two zinc centers followed by a helical deformation of the frame. A further increase in the relative concentration of bipy gradually led to a decrease in the overall CD intensity as a result of the formation of (R)-**5**·(bipy)$_2$. The CD spectral pattern and intensity finally became almost the same as those for (R)-**5** around the diacetylene region (Figure 4c, inset). The chemical shifts of the pyrrole β-hydrogen signals of (R)-**5**·(bipy)$_2$ were similar to those of free (R)-**5**, suggesting that the distances between the two porphyrin units in(R)-**5**·(bipy)$_2$ and (R)-**5** are approximately the same.[7] These results indicate that the 4:2 cylindrical frame of (R)-**5**·(bipy)$_2$ appears to take an almost untwisted cylindrical shape similar to that of (R)-**5**, as illustrated in Figure 4d.[13]

The complexation behavior of (R)-**5** with bipy was found to be highly temperature dependent. Upon cooling a solution of (R)-**5** in the presence of an equimolar amount of bipy in CDCl$_3$, the Soret band shifted to 425 nm, showing the predominant formation of (R)-**5**·bipy (Figure 5). The proportion of (R)-**5**·bipy to the total cylindrical complexes increased with decreasing temperature and reached 80% at −55 °C, as estimated by ^{1}H NMR spectroscopy.[7] The CD intensities also increased along with the increase of (R)-**5**·bipy, suggesting that sandwich formation is less entropically demanding than formation of the octonary (capped) complex.[11]

In summary, cylindrical complexes were effectively synthesized through a multicomponent self-assembly process driven by amidinium–carboxylate salt-bridge formation. The tricarboxylate-based 3:2 cylindrical complex **3** adopts an excess of one-handed helical structure in solution as well as in the solid state. The porphyrin-based cylindrical complex **5**, which has an almost untwisted cylindrical frame, further twists in one direction with an excess of one-handed helical supramolecular structure upon formation of the sandwich complex with bipy. Thus, we have for the first time achieved control of the helicity of multicomponent cylindrical complexes. This strategy utilizing amidinium–carboxylate salt bridges in combination with metal coordination may provide a means to construct a wide variety of discrete supramolecular assemblies with controlled helicity.

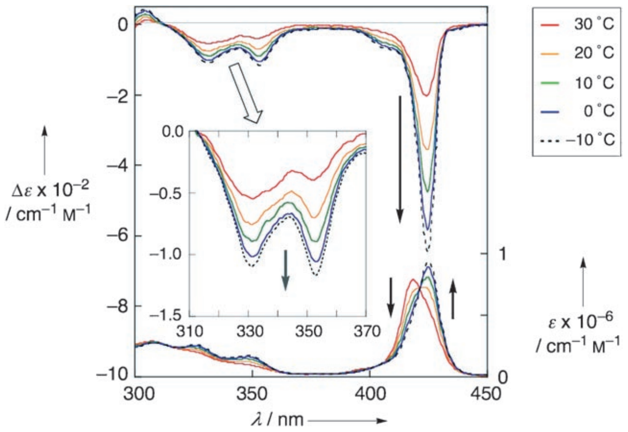

Figure 5. CD and absorption spectra of (R)-**5** in CDCl$_3$ (0.1 mM) in the presence of bipy (1.0 equiv) at various temperatures. The inset shows expanded details of the CD changes (310–370 nm).

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[7] See Supporting Information for details of the synthesis, structures, and characterization of the cylindrical complexes (*R*)- or (*S*)-**3**, **5**, and **5**·bipy.

[8] Crystal data for (*S*)-**3** ($C_{252}H_{198}N_{12}O_{12}\cdot 10(H_2O)$): $M_r = 3766.57$, crystal dimensions $0.30 \times 0.15 \times 0.05$ mm^3, triclinic, space group $P1$, $Z = 1$, $\rho_{calcd} = 0.993$ g cm^{-3}, $\mu(Mo_{K\alpha}) = 0.063$ mm^{-1}, $F(000) = 1970$, $2\theta_{max} = 50.7°$ were $a = 17.395(2)$, $b = 18.235(3)$, $c = 22.228(3)$ Å, $\alpha = 88.211(2)°$, $\beta = 87.456(3)°$, $\gamma = 63.587(3)°$, and $V = 6307.9(15)$ Å^3. A total of 32965 reflections were collected of which 27637 reflections were independent ($R_{int} = 0.1056$). The structure was refined to final $R_1 = 0.1177$ for 27637 data [$I > 2\sigma(I)$] with 2589 parameters, $wR_2 = 0.3738$ for all data, GOF = 0.757, and residual electron density max/min = 0.656/−0.380 e Å^{-3}. CCDC-621220 contains the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.

[9] Some multicomponent cylindrical complexes constructed through metal–ligand coordination were found to be twisted in the solid state.[4] However, the helicity was not controlled in the solid state nor in solution.

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[11] The helical sense of (*R*)-**5**·bipy is assigned to be right-handed based on the CD spectral pattern of the region corresponding to the diacetylene linker for (*R*)-**3** in solution (Figure 2b). Similar changes in the formation of sandwich and capped forms depending on the concentrations of bidentate amines and temperatures were observed for zinc linear and cyclic porphyrin dimers; see Ref. [10a,c] and: a) C. A. Hunter, M. N. Meah, J. K. M. Sanders, *J. Am. Chem. Soc.* **1990**, *112*, 5773–5780; b) H. L. Anderson, C. A. Hunter, M. N. Meah, J. K. M. Sanders, *J. Am. Chem. Soc.* **1990**, *112*, 5780–5789; c) P. Ballester, A. I. Oliva, A. Costa, P. M. Deyá, A. Frontera, R. M. Gormilia, C. A. Hunter, *J. Am. Chem. Soc.* **2006**, *128*, 5560–5569.

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[13] When pyridine was used instead of bipy, we observed monotonic changes in the absorption spectra of (*R*)-**5** with a clear isosbectic point at 426 nm, but CD enhancement in the region corresponding to the diacetylene linker was hardly observed at all.[7]