Temperature Effect on Supramolecular Chirality Induction in Bis(zinc porphyrin)

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Received October 15, 1999. Revised Manuscript Received December 28, 1999

Abstract: The achiral syn folded conformer (face-to-face) of the ethane-bridged bis(Zn porphyrin) gradually transforms into the chiral extended anti form in the presence of enantiopure guest molecules (alcohols or amines) upon lowering the temperature from 293 to 183 K. The mechanism of the supramolecular chirality induction is based upon the formation of right- or left-handed screw diastereomers of the anti form. The split absorption maxima which are caused by the exciton coupling of the corresponding *B* transitions match the bisigned Cotton effects. The amplitude of the CD bands is found to be dependent on the bulk and ligation strength of the chiral guest, while the sign of the couplets is observed to be determined by the absolute configuration of the external ligand. The formation of the screw structure in the anti conformation is also confirmed by ^{1}H NMR.

Introduction

Supramolecular chirality forms an integral part of natural systems, examples of which include the DNA double helix and the secondary α-helical structure of proteins assembled by noncovalent interactions. Furthermore, it plays an important role in the fields of asymmetric catalysis and autocatalysis,[1] nonlinear optics,[2] polymer science,[3] molecular recognition, and self-assembly[4] and in molecular device design.[5] In addition, this phenomenon has proved to be a useful tool in the determination of the absolute configuration of chiral compounds.[6] In general, the chirality of supramolecular systems can be produced through direct synthetic modifications and/or by external asymmetric induction via self-assembly, axial ligation, or aggregation processes. The latter approach offers more possibilities to control chirality induction via fine-tuning of the intramolecular interactions by changing the physicochemical properties of the surrounding media, such as temperature, pressure, pH, etc. Here we describe the temperature effect on the chirality transfer process from single enantiopure molecules to the whole supramolecular system. The major advantage of this approach is the application of a lipophilic system that can operate over a wide range of temperatures, and thus offers a great possibility for employing even weakly interacting ligands as a result of low-temperature binding enhancement.

Recently porphyrins and related chromophores have been shown to be well-suited host molecules for studying the processes involved in supramolecular chirality induction.[4a,5,6b] Porphyrinoids have many desirable attributes for acting as effective host molecules of supramolecular systems. They possess well-resolved and intense absorption spectra which are in the red-shifted spectral region where the majority of the prospective chiral guest molecules do not absorb. Also their synthetic modifications are both facile and versatile, particularly formation of various metallocomplexes that expand significantly the possible range of guest compounds, utilizing the well-known coordination properties of metalloporphyrins. Moreover, porphyrinoids are molecules of great biological importance owing to their role in natural enzymatic reactions, oxygen transport, and photosynthesis and are intensively used in artificial catalytic, electron- and energy-transfer systems, thus opening a wide range of potential applications. These attractive features prompted us to apply porphyrin compounds as achiral host molecules for studying the processes of supramolecular chirality induction.

Experimental Section

Materials. The syn conformer of the ethane-bridged bis(Zn porphyrin) (see syn structure in Figure 1) was synthesized according to previously reported methods.[7] Chiral alcohols and amines were purchased from Fluka Chemica AG and were used as received. Anhydrous CH_2Cl_2 for VT UV−vis and CD measurements and $CDCl_3$ for VT ^{1}H NMR studies were purchased from Aldrich Chemical Co. and used without further purification.

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10.1021/ja9936971 CCC: $19.00
Published on Web 04/21/2000

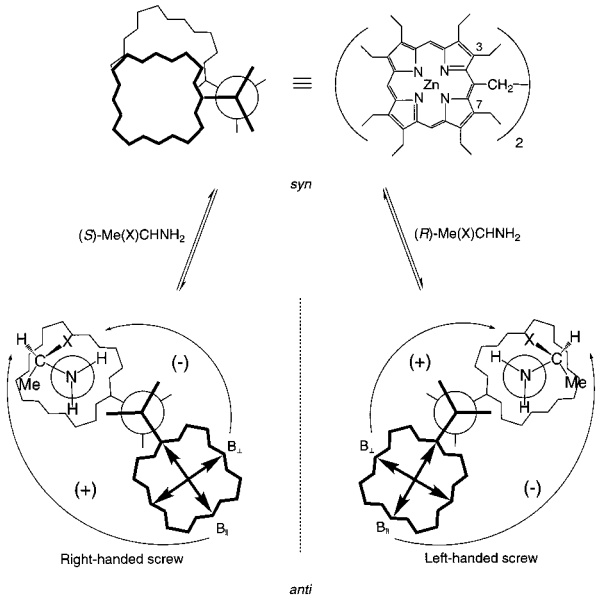

Figure 1. Mechanism of the thermally induced supramolecular chirality in bis(Zn porphyrin).

Spectroscopic Measurements. UV and CD spectra were measured simultaneously on a J-720 spectropolarimeter (Jasco, Japan) equipped with a liquid nitrogen-controlled quartz cell (path length = 5 mm) in a cryostat, at temperatures ranging from 23 to −104 °C. Scanning conditions were as follows: scanning rate = 100 nm per min, bandwidth = 2 nm, response time = 0.5 s. The solution temperature in the cryostat was monitored directly by immersing a thermocouple into the solution.

^{1}H NMR spectra were recorded at 400 MHz on a JEOL JNM-EX 400 spectrometer. Chemical shifts were referenced to the residual proton resonance in $CDCl_3$ (δ 7.25 ppm).

Results and Discussion

Our recent studies reveal that a temperature decrease induces the syn-anti conformational switching of two bis(Zn porphyrins) in achiral alcohol containing solvents, resulting in the formation of a linear coplanar anti isomer.[8] The driving force for this process is the low-temperature enhancement of the strength of alcohol ligation. Expanding this concept to chiral guest compounds, a new, thermally driven supramolecular chirality induction is observed in the symmetrical ethane-bridged bis(Zn porphyrin)[7] (see syn structure in Figure 1) in the presence of enantiopure chiral alcohols and amines (Table 1) when the temperature is lowered.

This unique phenomenon has been monitored by variable-temperature (VT) UV−vis, CD, and ^{1}H NMR spectroscopy and these methods reveal dramatic transformations in the initial spectral pattern of the bis(Zn porphyrin) in the syn conformation over the temperature range investigated (Figures 2, 4, 5, and 6). The VT UV−vis changes (Figure 2b) are the result of the same syn-anti conformational switching that has been described for achiral alcohols.[8] The anti conformer, formed upon lowering the temperature from 293 to 183 K, shows two bathochromically shifted and well-resolved $B_\perp$ and $B_\parallel$ transitions[9] for all of the chiral ligands studied (see Table 1). The low-energy shift observed for both *B* transitions of the anti conformer, caused by coordination of the amine, is larger than that caused by coordination of the corresponding alcohol by 5−6 nm. This is a result of a greater affinity of amine ligands for Zn porphyrins, leading to better p_z-a_{2u} ligand−porphyrin orbital mixing. The observed energy splitting (ΔE_{UV} = 10−13 nm), which is caused by a nonequivalent coupling of the two degenerate *B* transitions, is in good agreement with exciton coupling theory[10] and previously reported data for linear bis-porphyrin structures.[11] This is indicative of a gradual conformational change from the folded syn form that occurs at higher temperatures to the extended anti form observed at lower temperatures.[8] The driving force for this process is the enhanced binding of the chiral ligands to the zinc porphyrin at lower temperature, because no conformational changes are observed in ligand free solutions, where the bis-porphyrin adopts the syn conformation over the whole temperature range.

VT CD monitoring of the conformational change shows the appearance of bisigned Cotton effects that gradually increase as the temperature falls (Figure 2a). The maxima and minima positions of the induced CD couplets correspond to the split $B_\perp$ and $B_\parallel$ absorption transitions, indicating a good match between the observed CD splitting (ΔE_{CD} = 12−14 nm) and the Davydov splitting, which is sharply defined in the UV−vis spectrum of the anti conformer (Table 1). Similar results have been observed for sugar-based bis-cyanine chromophores.[12] This clearly demonstrates that the achiral syn form transforms into the optically active supramolecular anti form in the presence of chiral ligands at low temperatures. Although the detailed mechanism of this phenomenon is not fully understood the nature of this supramolecular chiral induction can be rationalized as follows (Figure 1). After the temperature has been lowered and the subsequent formation of the anti species has occurred due to the first ligation,[8] another (*S*)- or (*R*)-enantiopure ligand can approach the second zinc porphyrin moiety to form the bis-ligated complex, in which both chiral ligands are positioned on the same side of the porphyrin planes in the anti structure.[13] This triggers a conformational turn of the neighboring porphyrin ring of the bis-porphyrin, thus forming the corresponding right- or left-handed screw in the anti conformers. Examination of CPK molecular models reveals that there is a steric interaction between the substituent (X) on the asymmetric carbon of the chiral amine or alcohol and the ethyl group at either the 3- or 7-position of the neighboring porphyrin ring (depending on the absolute configuration of the ligand), resulting in a conformational turn in the anti form (see Figure 3). It is therefore reasonable that the bulk of X and the coordination strength of the ligand are the major factors contributing to the intensity of the CD signals. Guests with bulkier (X) groups on the asymmetric carbon and with stronger binding affinities lead to greater supramolecular chirality induction, rotating the neighboring porphyrin ring to a greater extent about the axis connecting them, resulting in an enhancement of the Cotton effects (Table 1). Indeed, the amplitudes of the CD couplets induced by ligands with the more bulky aromatic substituents are greater than those with less bulky aliphatic substituents by a factor of 4 for alcohol guests and 7 for amine guests (see Figure 4). The amine ligands also lead to more intense CD signals in the temperature range

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(13) This process is apparently enthalpically driven, if the same solvation−desolvation factor is assumed for both possible approaches of the second ligand.

Table 1. UV−Vis and CD Spectral Data of the Resulting Supramolecular System with Different Chiral Guests at 193 K[a]

	UV−vis data λ_{max} (nm) ($\epsilon/10^5$ (M^{-1} cm^{-1}))		CD data λ_{max} (nm) ($\Delta\epsilon_n$ (M^{-1} cm^{-1}))			
chiral guest, L	$B_{\parallel}$ transition	$B_{\perp}$ transition	first Cotton ($n = 1$)	second Cotton ($n = 2$)	third Cotton ($n = 3$)[b]	A[c]
(*R*)-(−)-2-BuOH	432 (1.93)	419 (2.44)	432 (−3.5)	420 (+8.3)		−11.8
(*S*)-(+)-2-BuOH	432 (2.14)	420 (2.34)	433 (+10.7)	419 (−1.1)		+11.8
(*R*)-(+)-1-PhEtOH	431 (1.86)	419 (2.21)	431 (−25.4)	417 (+23.9)		−49.3
(*S*)-(−)-1-PhEtOH	432 (2.10)	420 (2.41)	431 (+32.0)	417 (−20.1)		+52.1
(*R*)-(−)-2-$BuNH_2$	436 (2.22)	425 (2.63)	438 (−16.2)	426 (+31.9)		−48.1
(*S*)-(+)-2-$BuNH_2$	436 (2.15)	425 (2.63)	438 (+21.6)	425 (−25.2)		+46.8
(*R*)-(+)-1-$PhEtNH_2$	436 (2.31)	425 (2.72)	437 (−151.3)	424 (+180.0)	410 (−20.7)	−331.3
(*S*)-(−)-1-$PhEtNH_2$	436 (2.23)	425 (2.68)	437 (+148.0)	424 (−176.5)	411 (+14.3)	+324.5
(*R*)-(+)-1-(1-Naphthyl)$EtNH_2$	436 (2.37)	426 (2.71)	437 (−115.0)	425 (+154.6)	412 (−21.7)	−269.6
(*S*)-(−)-1-(1-Naphthyl)$EtNH_2$	436 (2.29)	426 (2.67)	438 (+117.0)	425 (−143.9)	411 (+21.9)	+260.9

[a] $C_{bis(Zn\ porphyrin)} = (3.3-3.8) \times 10^{-6}$ M, $C_{alcohol} = (3.3-3.9) \times 10^{-1}$ M, $C_{amine} = (2.5-4.1) \times 10^{-4}$ M in CH_2Cl_2. [b] The relatively small third Cotton effect observed for systems with aromatic amines is likely to be the result of an excitonic coupling between porphyrin *B* and the ligand's aromatic dipoles. [c] $A = \Delta\epsilon_1 - \Delta\epsilon_2$. This value represents the total amplitude of the CD couplets.

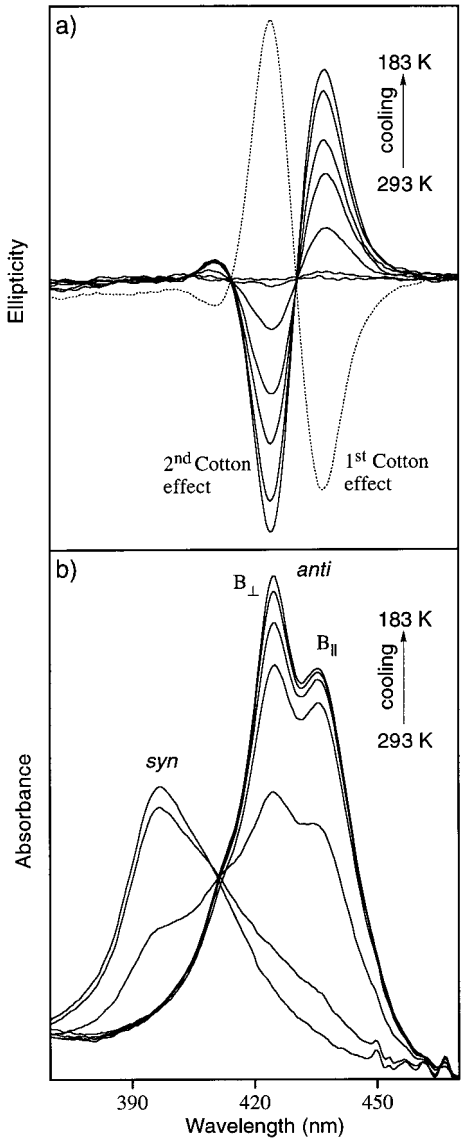

Figure 2. Temperature-induced changes in (a) the CD spectrum and (b) UV−vis spectrum of the bis(Zn porphyrin) in CH_2Cl_2 containing (*S*)-(−)-1-$PhEtNH_2$ upon cooling from 293 to 183 K (solid lines) or (*R*)-(+)-1-$PhEtNH_2$ at 183 K (dotted line in the CD spectrum, the UV−vis spectrum is coincident to that of the (*S*)-enantiomer).

studied than the corresponding alcohols due to their greater binding affinities.[14] Thus, aromatic amines give a (6.2−6.7)-

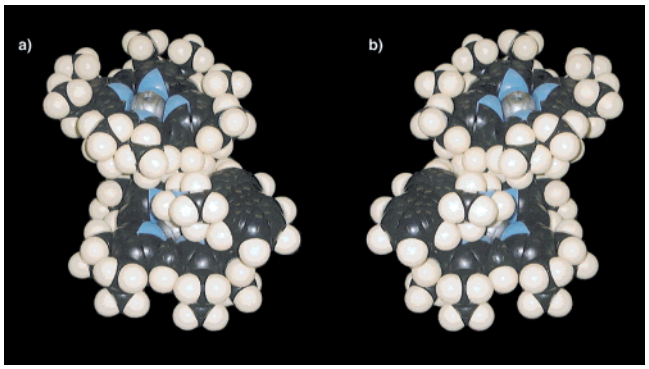

Figure 3. CPK models of bis(Zn porphyrin) with (a) (*R*)-(+)-1-(1-Naphthyl)$EtNH_2$ and (b) (*S*)-(−)-1-(1-Naphthyl)$EtNH_2$.

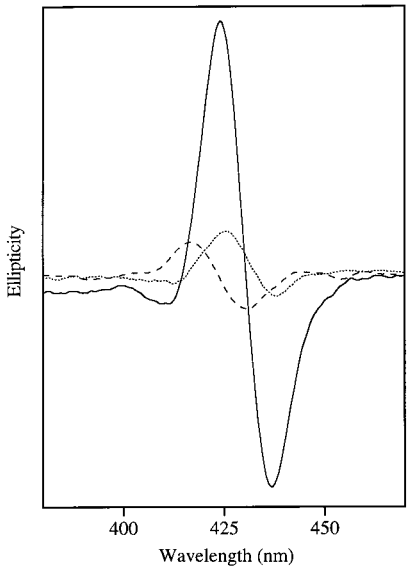

Figure 4. CD spectra of bis(Zn porphyrin) in CH_2Cl_2 containing (*R*)-(+)-1-$PhEtNH_2$ (solid line), (*R*)-(−)-2-$BuNH_2$ (dotted line), and (*R*)-(+)-1-PhEtOH (dashed line) at 193 K.

-fold enhancement in comparison to the aromatic alcohols (see Figure 4), while aliphatic amines give a (4.0−4.1)-fold enhancement when compared to aliphatic alcohols.

The sign of the induced Cotton effect is determined by the absolute configuration of the external ligand. According to the CD exciton chirality method,[15] a clockwise orientation of two

(14) ΔG_{293} (kcal·mol^{-1}) = 0.43−0.87 for alcohols and −7.30 to −8.51 for amines.

Table 2. ^{1}H NMR Spectral Data of the Resulting Supramolecular System with Different Amines at 213 K[a]

	chemical shift δ (ppm) (no. of protons, multiplicity)		
chiral guest, L	10,20-*meso*-H	15-*meso*-H	$-CH_2CH_2-$ bridge
(*R*)-(−)-2-BuNH$_2$	9.97 (4H, s)	9.85 (2H, s)	5.11 (4H, s)
(*R*)-(+)-1-PhEtNH$_2$	10.03 (2H, s), 9.96 (2H, s)	9.84 (2H, s)	5.30 (2H, m), 5.10 (2H, m)
(*S*)-(−)-1-PhEtNH$_2$	10.03 (2H, s), 9.96 (2H, s)	9.84 (2H, s)	5.29 (2H, m), 5.09 (2H, m)
rac-1-PhEtNH$_2$	10.00 (4H, s)	9.84 (2H,s)	5.16 (4H, s)
(*R*)-(+)-1-(1-Naphthyl)EtNH$_2$	10.10 (2H, s), 9.98 (2H, s)	9.87 (2H, s)	5.30 (2H, m), 5.02 (2H, m)

[a] $C_{\text{bis(Zn porphyrin)}} = (1.57-1.62) \times 10^{-3}$ M, $C_{\text{amine}} = (3.14-3.24) \times 10^{-3}$ M in $CDCl_3$.

interacting electronic transition dipoles produces positive chirality, while a counterclockwise orientation leads to negative chirality. Since ligands with (*S*) absolute configuration induce a right-handed turn in the anti conformer, the corresponding pairs of the coupling $B_{\parallel}$ and $B_{\perp}$ transitions should form clockwise and counterclockwise twists respectively (Figure 1).[16] In the case of the (*R*) enantiomer, the dipole's directions will be exactly opposite. These predictions are in complete agreement with the observed signs of CD bands that are associated with the interacting porphyrin transitions for all of the supramolecular systems studied here (Table 1).

The results of a VT ^{1}H NMR study of the conformational switching behavior and formation of the chiral screw structures in the anti conformer of bis(Zn porphyrin) are in good agreement with VT UV−vis and CD spectral data. The general tendencies of VT ^{1}H NMR changes (Figures 5 and 6) are the same as those caused by an achiral alcohol.[8] Decreasing the temperature from 293 to 213 K leads to a significant downfield shift of the 10,20-*meso* protons ($\Delta\delta = 0.38-0.69$ ppm), no change in the position of the 15-*meso* protons, and the transformation of the eight well-resolved signals of the CH_2CH$_3$ protons ($\delta = 4.26-2.38$ ppm) into two broad multiplets located at a more downfield region ($\delta = 4.24-3.44$ ppm). These changes arise from the syn-anti conformational change. The 10,20-*meso* protons are strongly shielded by the ring current effect of the neighboring porphyrin, and thus are the most affected by conformational switching. Also, the CH_2CH$_3$ protons become more equivalent due to their easier rotation in the anti form in comparison to the more rigid syn conformer. Similar changes have been observed for cis and trans ethylene-bridged bis-porphyrin.[17]

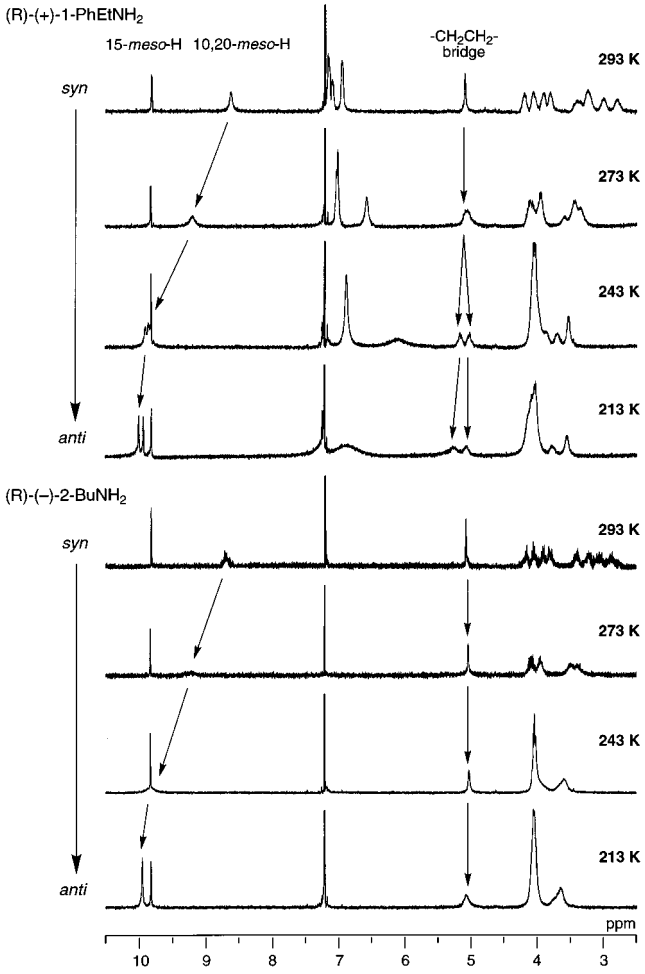

Figure 5. Temperature-induced changes in the ^{1}H NMR spectra of bis(Zn porphyrin) in $CDCl_3$ in the presence of (a) (*R*)-(+)-1-PhEtNH$_2$ and (b) (*R*)-(−)-2-BuNH$_2$ upon cooling from 293 to 213 K.

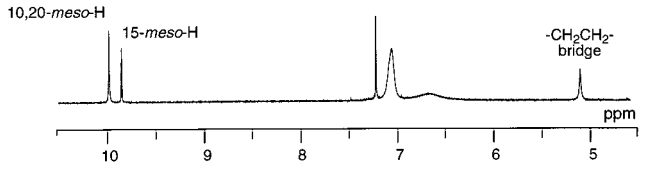

Figure 6. ^{1}H NMR spectrum of bis(Zn porphyrin) in $CDCl_3$ in the presence of racemic 1-PhEtNH$_2$ at 243 K.

The most remarkable differences in the low-temperature ^{1}H NMR spectra were found for chiral aromatic amines (Figure 5a, Table 2). In contrast to achiral alcohol or chiral alkylamine, the 10,20-*meso* protons and $-CH_2CH_2-$ bridge protons are split into two signals of equal intensity at 213 K with differences in chemical shift of 0.07−0.12 ppm and 0.2−0.28 ppm, respectively (Figure 5a). The nonequivalence of these protons resulted

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(16) A reviewer suggested another interpretation of the induced CD signals, that they are a result of two interacting electric transition moments (one for each porphyrin ring in bis(Zn porphyrin)) rather than four interacting electric transition moments (two for each porphyrin ring in bis(Zn porphyrin)). Recently such a simplification was applied to describe chirality induction in several bis-porphyrins (see ref 6a and: Matile, S.; Berova, N.; Nakanishi, K.; Fleischhauer, J.; Woody, R. W. *J. Am. Chem. Soc.* **1996**, *118*, 5198−5206). In this model only $B_{\parallel}$ transitions were assumed to be the interacting "effective" transitions. Although this approximation can rationalize the induction and sign of the CD couplets considering the porphyrin as an aromatic ring having only one electric transition dipole, we are cautious to use it. The reason is a failure to explain or address the well-resolved split of the Soret band observed in the UV−vis spectra of all the supramolecular systems studied regardless of the ligand structure (this split was found even in the case of such ligands as ethanol),[8] as well as the good match found between the transitions observed in UV−vis and CD spectra. Therefore, the more realistic approach is to consider both coupling $B_{\parallel}$ and $B_{\perp}$ transitions in each porphyrin ring. Certainly, such an "effective" transition moment is applicable for cases where no split Soret band is found, but in cases such as ours where this effect is observed it would be incorrect not to consider its implications. At present the detailed evaluation of all eight allowed transitions (in the screw structure of bis(Zn porphyrin) there are no pure forbidden transitions) is difficult, therefore we consider the observed split of the Soret band to be a result of the major contributions from the coupling $B_{\parallel}$ and $B_{\perp}$ transitions as described previously (see ref 8 and references cited within).

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from their different location with respect to the neighboring porphyrin ring (Figure 3), leading to different exposure to the ring current effect. The appearance of this splitting correlates with the intense CD signals observed for aromatic amines, while alkylamines, which are less CD active, show no splitting in their ^{1}H NMR spectra at low temperature (Figure 5b). The corresponding racemic mixture of aromatic amines also shows no splitting in this region of the spectrum (Figure 6) due to the equimolar ratio of the resulted right- and left-handed screws in the anti conformation of bis(Zn porphyrin). This nonequivalence of the 10,20-*meso* protons and $-CH_2CH_2-$ bridge protons is an additional indication of the formation of an asymmetrical supramolecular anti species.

Conclusion

This work clearly demonstrates that temperature can serve as an effective tool for supramolecular chirality induction control in achiral host systems, proceeding via the considerable low-temperature enhancement of chiral ligand binding, and its role in the subsequent mechanism of asymmetry transfer. These observations should contribute greatly to the understanding of the supramolecular chirality phenomena in artificial and natural systems, and may have implications in the design of thermally driven chiroptical molecular devices because the observed spectral changes are completely reversible upon heating or cooling. Furthermore, the clear matching of the observed CD signals to the Davydov splitting and the non-interference of the bis-porphyrin absorption with absorption of chiral guests make this system well suited for determining the absolute configuration of chiral compounds.

Acknowledgment. We thank Prof. E. Yashima, Prof. T. Mizutani, and Prof. Y. Sakata for valuable comments, Dr. S. R. L. Everitt and Dr. G. A. Hembury for assistance in the preparation of this manuscript, and Ms. H. Takigawa for technical support.

JA9936971