The effect of complex stoichiometry in supramolecular chirality transfer to zinc bisporphyrin systems†

Juan Etxebarria,[a] Anton Vidal-Ferran*[ab] and Pablo Ballester*[ab]

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The self-assembly of Zn–bisporphyrin tweezers induced by coordination to enantiopure 1,2-diaminocyclohexane features supramolecular chirality induction and inversion processes that are exclusively controlled by the stoichiometry of the assembled complexes.

Porphyrins and metalloporphyrins have developed into versatile chirality induction reporter groups for structural studies by means of circular dichroism spectroscopy.[1] The ease with which these units take part in supramolecular self-assembly systems[2] and the role they play as chiroptical sensors[3] in the assignment of the absolute configuration of biologically relevant chiral guests,[4] as well as in chirality memory systems,[5] has converted them into very interesting chemical tools.

Studies on supramolecular chirality induction (chirogenesis) in Zn–bisporphyrin systems upon coordination with chiral guests are amply documented in the recent literature.[6] In contrast, examples of Zn–bisporphyrin systems experiencing stoichiometry controlled supramolecular chirogenesis phenomena followed by chirality inversion have been seldom observed. To the best of our knowledge, only one example, an ethane bridged Zn–bisporphyrin, capable of undergoing this type of process has been described to date.[7] Here, we present new examples of this rarely observed phenomenon using flexible 1,3-dicarbonylaryl-bridged bisporphyrins, **1a–b** and **2**, in the presence of enantiopure *trans*-1,2-diaminocyclohexanes (DACH: (1*R*,2*R*)-**4** or (1*S*,2*S*)-**4**) (Fig. 1).

The Zn–bisporphyrin receptors used in this work have been synthesized by following previously published procedures.[8] The ditopic coordination of DABCO to Zn–bisporphyrin **1b** induced the formation of intramolecular 1 : 1 sandwich complexes which were thermodynamically highly stable ($K_a > 10^7$ M^{-1} in CH_2Cl_2 or toluene). At micromolar concentration these 1 : 1 sandwich complexes proved to be stable in the presence of an excess of DABCO, although increasing the DABCO concentration induced the formation of a 2 : 1 open complex.[9] The calculated distances, using molecular modelling, for the cofacial arrangement of the porphyrin units in the 1 : 1 sandwich complex of **1b** with DABCO (7.0–9.0 Å) seemed to us to be highly suitable for binding enantiopure DACH through two Zn–N coordination interactions, hence allowing the investigation of the potential chirality induction phenomena.

The coordination of (1*R*,2*R*)-**4** to **1a**, **1b** and **2** was first probed using UV–visible titrations in CH_2Cl_2, maintaining the bisporphyrin concentration constant at *ca.* 10^{-5} M (Fig. 2, top). In all three cases, the addition of an excess of diamine (1*R*,2*R*)-**4** (*ca.* 100 equiv.) shifted the Soret absorption band from 422 nm to approximately 430 nm (430, 431 and 432 nm for **1a**, **1b** and **2**, respectively). A Soret absorption band centred at *ca.* 430 nm as a consequence of a red-shift of 10 nm is typical for 2 : 1 amine–bisporphyrin open complexes.[9] We analyzed the three sets of UV–visible titration data using multivariate factor analysis and considering a binding model with three colored stoichiometric states of the bisporphyrin: free, 1 : 1 complex and 2 : 1 complex.[10] In all cases, we fixed the UV–visible spectra of the free bisporphyrin and the stability constant of the 2 : 1 open complex ($K_{21} = 4K_m^2 = 1.0 \times 10^{10}$ M^{-2}).‡ We calculated the following values for the stability constants of the 1 : 1 sandwich complexes: K_{11}(**1a**) $= 1.2 \pm 0.4 \times 10^6$ M^{-1}; K_{11}(**1b**) $= 2.5 \pm 0.5 \times 10^5$ M^{-1} and K_{11}(**2**) $= 2.5 \pm 0.2 \times 10^5$ M^{-1}. The high values determined for the thermodynamic stability constants of the 1 : 1 complexes (K_{11}) are in support of a complex geometry having a ditopic interaction between the diamine and the bisporphyrin tweezers (Scheme 1). However, the low effective molarities (EM $= K_{11}/K_m^2 < 0.0005$ M) that can be determined for these complexes indicate that the conformation adopted by the bisporphyrin is not free of conformational strain. The UV–visible spectra obtained in the fitting procedures for the three 1 : 1 complexes displayed a 2 nm red-shift of the Soret band (see ESI†). This 2 nm red-shift is characteristic of 1 : 1

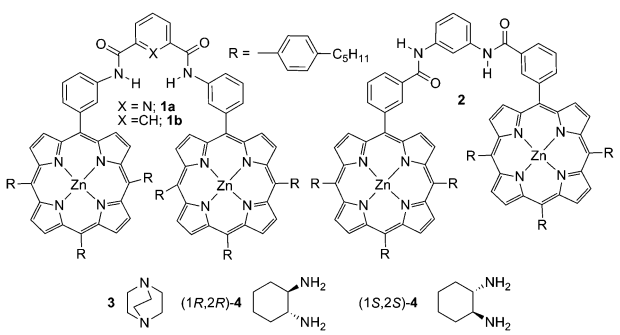


Fig. 1 Structural formulae of the Zn–bisporphyrins **1** and **2**, diazabicyclo[2.2.2]octane (DABCO) **3** and (1*R*,2*R*)- and (1*S*,2*S*)-diaminocyclohexane **4**.

[a] *Institute of Chemical Research of Catalonia (ICIQ), Avgda. Països Catalans 16, 43007 Tarragona, Spain. E-mail: pballester@iciq.es; E-mail: avidal@iciq.es; Fax: +34 977 920228; Tel: +34 977 920206*
[b] *Catalan Institution for Research and Advanced Studies (ICREA), Passeig Lluís Companys, 23, 08018 Barcelona, Spain*

† Electronic supplementary information (ESI) available: General procedures used for UV-Vis and CD titrations, additional titrations and corresponding curve fittings. See DOI: 10.1039/b812819g

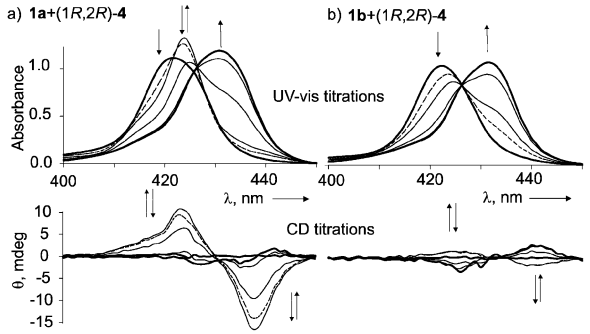
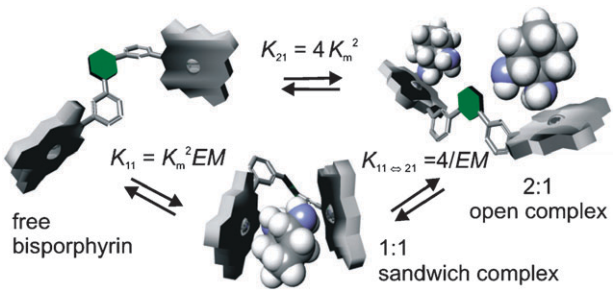


Fig. 2 Selected spectra of the UV–visible (top) and CD titrations (bottom) of **1a** (a) and **1b** (b) with (1*R*,2*R*)-**4** showing the Soret band region. Number of equivalents added: 0, 1, 2, 10, 50, 100.



Scheme 1 Complexation equilibria involved in the coordination of diamine (1*R*,2*R*)-**4** to Zn–bisporphyrins **1–2** and schematic representation of the species involved. The overall K_{21} and stepwise binding constants K_{11} and $K_{11\leftrightarrow 21}$, as well as their relationship with K_m (the microscopic binding constant) and EM (effective molarity) are also indicated.

amine–bisporphyrin sandwich complexes, in which the two porphyrin units of the tweezers are close in space being simultaneously bound to a ditopic ligand and experiencing strong excitonic coupling between their transitions.[9]

The 1 : 1 sandwich complexes formed by (1*R*,2*R*)-**4** with **1b** and **2** are one order of magnitude less stable than the (1*R*,2*R*)-**4@1a** complex. It is also worth noting that during the titration of **1a** with (1*R*,2*R*)-**4** we observed an initial isosbestic phase with a

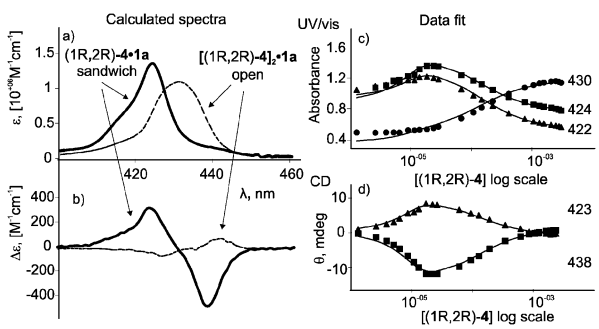


Fig. 3 Calculated UV–visible spectra (a) and CD spectra (b) of the 1 : 1 (bold line) and 2 : 1 (dashed line) complexes formed between **1a** and (1*R*,2*R*)-**4**. Fits of the titrations data at selected wavelengths to the theoretical binding model considering the bisporphyrin in three different stoichiometric states (free, 1 : 1 and 2 : 1 complexes; see text for details): UV–visible at 422, 424 and 430 nm (c) and CD at 423 and 438 nm (d).

concomitant shift of the Soret band to 424 nm (Fig. 3a). On the contrary, we did not observe any initial isosbestic phase for the titration of **1b** and **2**. The explanation for this dissimilar behaviour of the titrations resides in the fact that, in the latter cases, the formation of the 1 : 1 sandwich complexes and their destruction yielding 2 : 1 open complexes occurred simultaneously, that is, in the same range of ligand concentrations *vide infra*. In the former case, however, the (1*R*,2*R*)-**4@1a** (1 : 1) complex due to its higher thermodynamic stability is exclusively formed in solution in the initial phase of the titration.

The interaction of (1*R*,2*R*)-**4** with bisporphyrins **1a**, **1b** and **2** was also monitored using CD spectroscopy (Fig. 2, bottom). The initial addition of (1*R*,2*R*)-**4** to solutions of **1a**, **1b** and **2** in CH_2Cl_2 led to the appearance and stepwise enhancement of a negative bisignate Cotton effect in the porphyrin Soret band. Nevertheless, upon increasing the concentration of (1*R*,2*R*)-**4** the ellipticity (θ) values of the samples decreased. This change is associated with the destruction of the 1 : 1 sandwich complex and the formation of the 2 : 1 open complex for which we anticipated a silent CD.§ However, for **1a** and **1b** the increase in the concentration of **4** transformed the negative CD couplet assigned to the 1 : 1 sandwich complex into a new weak but detectable positive CD couplet. This result implies the existence of exciton coupling also in the 2 : 1 open complexes derived from **1a** and **1b** which must have an opposite spatial orientation of the coupling electronic transitions to those present in the 1 : 1 sandwich complexes. To verify the proposed binding model and to obtain spectral parameters of the chirality induction and inversion processes, the CD titration data of (1*R*,2*R*)-**4** with the three bisporphyrins were also analyzed using multivariate factor analysis.[10] The whole series of experimental CD spectra recorded at intervals of 1 nm were fitted to a binding model considering that the bisporphyrin is involved in three different stoichiometric states but only two of them are CD active. Fixing the stability constant of the 1 : 1 sandwich and the 2 : 1 open complexes to the values obtained from the UV–visible titration experiments, the only variables to be optimized during the fitting procedure were the CD spectra in the molar circular dichroism scale ($\Delta\varepsilon$) of the two active species, 1 : 1 and 2 : 1 complexes. For the three bisporphyrins, we obtained a remarkably good fit of the CD titration data to the corresponding theoretical curves at all the wavelengths. The fitting procedure returned the calculated CD spectra for the complexes (Fig. 3b for **1a**).

Table 1 summarizes the calculated spectral parameters for the different complexes. The CD optical activity observed for the 1 : 1 and 2 : 1 complexes of the bisporphyrins is due to the asymmetric twist experienced by the two porphyrin units upon coordinating to (1*R*,2*R*)-**4** and to the existence of exciton coupling between their electronic transitions. In the 1 : 1 sandwich complexes, the co-facial arrangement and short distance between the centres of the interacting electric dipoles results in two energy exciton states [higher energy homocouplings $B_\perp(+)$ and $B_\parallel(+)$ and lower energy homocouplings and $B_\perp(-)$ $B_\parallel(-)$] being well separated in the CD spectra.[6g] Nonetheless, as a consequence of the strong exciton interactions, these pairs of energy states become optically allowed and partially forbidden transitions in the absorption spectra (UV–visible). Thus, the position of the first Cotton effect in these 1 : 1 complexes matches a bathochromically shifted weak absorption band of the UV–visible spectra that arises from the

Table 1 Determined CD spectral data (CD sign, peak position/nm, A total amplitude/M^{-1} cm^{-1}) of the complexes (1:1 and 2:1) of bisporphyrin **1a**, **1b** and **2** upon coordination with (1*R*,2*R*)-**4**

		1 : 1 Sandwich complex			2 : 1 Open complex		
Ligand	Host	FC[a]	SC[a]	A^a/M^{-1} cm^{-1}	FC	SC	A/M^{-1} cm^{-1}
(1*R*,2*R*)-**4**	**1a**	−438	+423	783	+441	−427	139
	1b	−440	+425	185	+441	−426	135
	2	−443	+428	176	[b]	[b]	

[a] FC: 1st Cotton effect; SC: 2nd Cotton effect; A: total amplitude, $A = |\Delta\varepsilon_1 - \Delta\varepsilon_2|$. [b] Too small CD signal to be significant. A silent CD is assigned.

lowest energy $B_{\perp}(-)$ and $B_{||}(-)$ homocoupling transitions. The chirality sign associated with the first Cotton effect depends on the absolute configuration of **4**. In accordance with the CD exciton chirality method, the negative chirality observed for the (1*R*,2*R*)-**4@1a** complex should be produced by an anticlockwise coupling of the $B_{||}(-)$ transitions corresponding in turn to a left-handed chiral twist of the porphyrin units.[6g] The opposite sign of the CD spectra of the 2 : 1 complexes with (1*R*,2*R*)-**4** is due to a different twist direction of the porphyrin units. The two energy exciton states are also well separated in the CD spectra of the 2 : 1 complexes.

The A value of 783 M^{-1} cm^{-1} calculated for the (1*R*,2*R*)-**4@1a** complex is extremely high. To the best of our knowledge, this is one of the largest A values reported for a chirality induction process involving bis-porphyrin tweezer receptors. The key factors influencing the magnitude of the A value are the intertransition distances and angles. Most likely the four-fold increase observed for the A value of the (1*R*,2*R*)-**4@1a** when compared to the other two sandwich complexes originates from its higher thermodynamic stability which can be related to a closer spatial proximity of the porphyrin units in combination with the presence of internal hydrogen bonds in the 2,6-dicarboxamidopyridine spacer conferring an additional conformational rigidity to the porphyrin twist. The spectral and binding parameters evaluated for (1*S*,2*S*)-**4** are identical to those for (1*R*,2*R*)-**4** within experimental error, while the sign of the A value is opposite.

In summary, this work demonstrates that the properties of both chirality induction and inversion are expressed and stoichiometrically controlled in the self-assembly induced by coordination with enantiopure *trans*-1,2-diaminocyclohexane of Zn–bisporphyrin tweezer receptors having aromatic spacers. A full and unambiguous rationalization of the observed chirality transfer processes requires the detailed characterization of the structures of the complexes and we hope to be able to report on this subject in due time.

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Notes and references

‡ $K_m = 5 \times 10^4$ M^{-1}. This value was calculated from the titration of tetraphenylmonoporphyrin and cyclohexylamine.
§ A silent CD was obtained for the 2 : 1 complex of **1a** with (*R*)-1-cyclohexylethylamine (ESI†).§ A silent CD was obtained for the 2 : 1 complex of **1a** with (*R*)-1-cyclohexylethylamine (ESI†).

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