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Optically active supramolecular systems based on porphyrins

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Abstract. The published data on supramolecular complexes of porphyrins with optically active organic molecules are systematised. The key principles, mechanisms and driving forces of complexation and factors responsible for effective control over formation of supramolecular systems are considered. The bibliography includes 105 references.

I. Introduction

Among the immense diversity of 'host – guest' interactions, complexation of tetrapyrrole chromophores with chiral organic molecules has recently received considerable attention.[1 – 27] The interest in these processes is largely determined by the necessity of identification and separation of chiral biologically active substrates. Porphyrins with rigid macrocycles and predetermined arrangement of substituents that specifically interact with different types of 'guest' molecules are ideally suited for the solution of this problem.

Mutual arrangement of porphyrin fragments in a supramolecular system can be controlled by chemical modifications of the macrocycle or by change in the solvent polarity. The relative positions of tetrapyrrole chromophores change during host – guest complex formation, exciton interactions appear between their π-electronic systems, which is accompanied by the corresponding spectral changes. This allows the successful use of diverse spectral analytical methods for the study of intermolecular interactions.

The examples of porphyrin-based host – guest systems documented in the literature illustrate the broad potential of their practical applications. However, no adequate rationale for the electronic or structural factors that control the complexation is available so far.

This review is the first generalisation and analysis of the results of investigations into porphyrin-based optically active supramolecular systems published over the past decade. The main principles, mechanisms and driving forces involved in the formation of supramolecular systems and factors that efficiently control this process are considered.

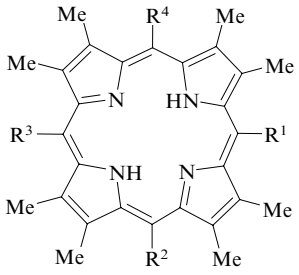
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II. 'Host – guest' systems based on monomeric porphyrins

Optically active host – guest systems based on monomeric porphyrins are conventionally divided into two main types, *viz*., systems with achiral or racemic porphyrins ('hosts') that interact with optically active guest molecules and systems based on chiral porphyrins. The formation of supramolecular systems can be detected by various spectral analytical methods.

Host – guest systems based on monomeric porphyrins possess interesting properties. Thus fully substituted porphyrins **1** – **3** with a saddle-shaped structure of the macrocycle as a result of steric repulsion between neighbouring substituents exist in the form of two enantiomers; their interconversions yield a racemic mixture. This equilibrium can be shifted towards the formation of a particular structure (*de* > 98%) upon interaction with mandelic acid enantiomers.[28, 29] This interaction involves the formation of H-bonds between the carboxy groups of the acid and the nitrogen atoms in the pyrrole fragments of the porphyrin macrocycle. The supramolecular host – guest complexes formed (1 : 2) possess a strong induced circular dichroism (CD) signal in the region of the Soret band. The sign of the CD signal correlated with the absolute configuration of the chiral centre of the guest. An interesting property of porphyrins **1** – **3** is their ability to retain the induced optical activity upon substitution of achiral acetic acid for chiral mandelic acid.

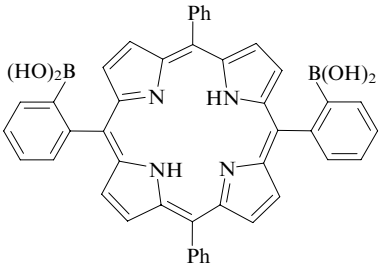


1 – **3**

1: R^1 = 2,6-$(MeO)_2C_6H_3$, $R^2 = R^3 = R^4$ = Ph;
2: $R^1 = R^3$ = 2,6-$(MeO)_2C_6H_3$, $R^2 = R^4$ = Ph;
3: $R^1 = R^2 = R^3$ = 2,6-$(MeO)_2C_6H_3$, R^4 = Ph.

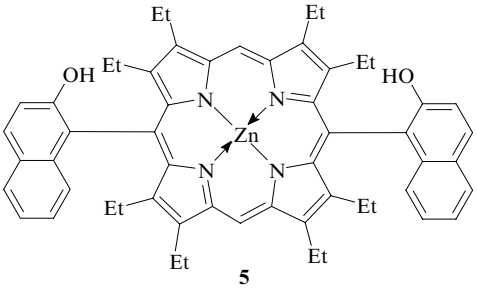
Among ten disaccharides tested, only lactulose is selectively bound to the porphyrin receptor **4**. The position of the hydroxy groups of the carbohydrate matches that of two boronic acid

residues in the phenyl rings of substituted porphyrin, which is the reason for the selective binding. This results in the formation of a 1 : 1 complex with a positive CD signal in the region of the Soret band.[30]

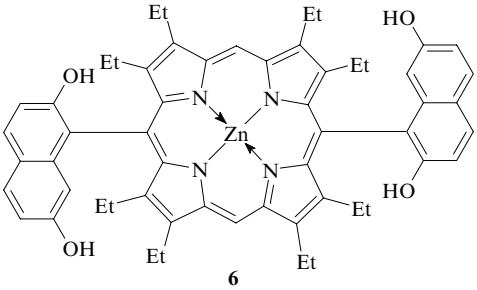


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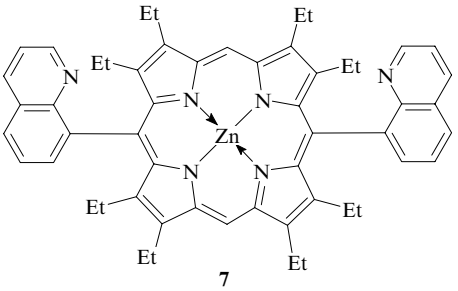
The interactions of metalloporphyrins **5**–**8** with carbohydrates [31, 32] and the recognition of alkaloids by the porphyrin sensor **9** have been described.[33]



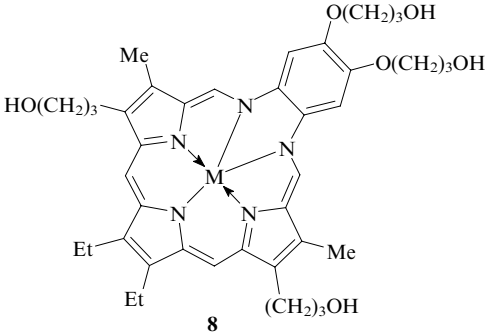
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6

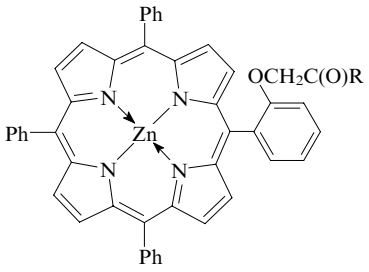


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8

M = $LuNO_3$, $Gd(NO_3)Cl$.

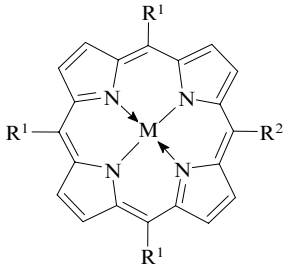


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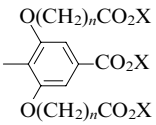
R = OH, NH_2.

An amino acid receptor based on the *trans*-isomer of porphyrin **6** possessed high selectivity with respect to dimethyl L-aspartate (the binding constant $K_a = 6.98 \times 10^4$ M^{-1}), which exceeded that with respect to L-leucine and L-glutamic acid esters.[34] In this case, host–guest complexes are stabilised by three-point binding, *i.e.*, coordination interaction between the Zn atom and the NH_2 groups and two hydrogen bonds formed by the OH groups in the opposite naphthalene rings of porphyrin and the carbonyl groups of the amino acid. All the systems under study manifested a split induced CD signal at the Soret band region; the latter was due to through-space electronic interactions between the porphyrin and the carbonyl group of the amino acid, although the effects of other factors should not be excluded either.

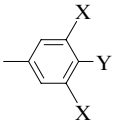
Porphyrin receptors **10** were designed [35] for specific binding of amines and amino acid esters. They should be used as esters in non-polar organic solvents and as acids in aqueous media. In organic solvents, the complexation is achieved due to coordination of the amino group of the amino acid by Zn of the porphyrin macrocycle (the enthalpy factor). In aqueous media, competitive binding of solvent molecules to Zn weakens the coordination interactions between host and guest molecules. Under these conditions, dispersion interactions between the long methylene chains of the host and the hydrophobic side substituent of the guest favour the complexation (the enthalpy factor). Dehydration of the interacting surfaces of the host and guest molecules is the principal factor that governs complexation in aqueous media (the entropy factor).



10–**12**

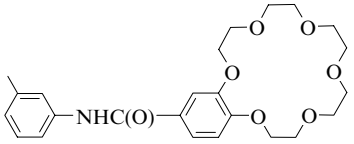
10: M = Zn; $R^1 = R^2 =$ 

(X = H, Me; *n* = 1, 4, 10);

11: M = Gd(acac), $R^1 = R^2 =$ 

(X = Me, Bu^t, OMe, F, Cl, Br; Y = H, OMe);

12: M = Er(acac), Gd(acac), Yb(acac); R^1 = Ph,

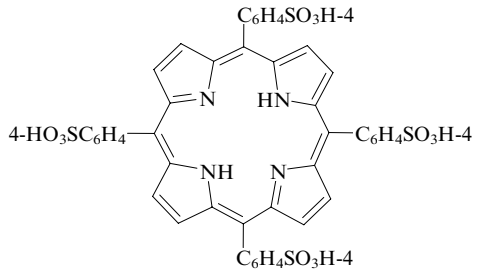
$R^2 =$  ;

acac is acetylacetonate.

The recognition of optically active zwitter-ionic amino acids was studied in a two-phase system 'organic solvent – water'.[36] The amino acids were extracted from the aqueous phase using porphyrins **11**, which formed (1 : 1) complexes with the amino acids. The CD spectra of the resulting complexes manifested two well-resolved signals corresponding to the split Soret band. The magnitude of the molar amplitude of CD (*A*) strongly depended on the nature of the solvent and the substituents in the porphyrin and amino acid molecules, while the sign of the induced CD signals was determined by the chirality of the amino acid. The porphyrin containing di-*tert*-butylphenyl groups manifested the highest sensitivity in aromatic solvents. This method was proposed for determination of absolute configurations of α-amino acids.

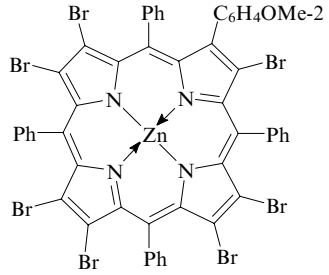
Later, the sensitivity of the method was increased through incorporation of a crown-ether fragment into the porphyrin receptor **12**.[37] Simultaneous coordination of the CO_2^- group of the amino acid in the lanthanide reaction centre of porphyrin, the interaction of the NH_3^+ group with the crown-ether fragment and the adequate choice of the coordinating metal increase significantly the extraction potential of the receptor and, as a consequence, the magnitude of the molar amplitude *A*.

Solid-phase optical detection based on the registration of the hypsochromic shifts in the visible region of the absorption spectrum of porphyrin **13** immobilised as a monolayer on a cellulose film was used for the recognition of amino acids.[38] The magnitude of the hypsochromic shift depends on the structure of the amino acid, which makes it possible to quantitatively determine amino acids in solutions.



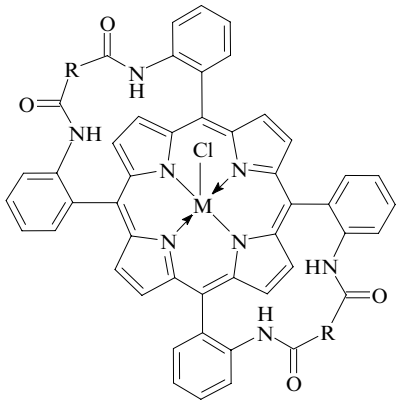
13

There is an ample body of data on supramolecular systems in which both hosts and guests possess optical activities. Chiral recognition in such systems is based on three-dimensional structural matching of both molecules according to the 'key – lock' principle and intermolecular binding usually involves three centres. Ideally, only one out of two enantiomeric forms of the guest is bound efficiently to the host molecule to form a stable complex, whereas binding of the other enantiomeric form is much weaker. The difference in the binding strength can be established by different spectral methods. For example, two diastereomeric complexes formed by chiral non-planar porphyrin **14** and (*S*)-2-pyrrolidinemethanol owing to coordination and hydrogen bonds could be identified by ^{1}H NMR spectroscopy.[39]

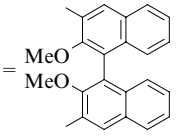


14

A direct correlation was found[40] between the enantioselectivities of complexation and catalytic oxidation. The chirality of the metal complexes of the 'strapped' porphyrin derivatives **15a**,**b** studied was due to steric hindrance to rotation of two binaphthyl fragments around the C(1)–C(1′) bonds. The aluminium complex **15a** bound chiral epoxides and alcohols. Distinct differences between the electronic absorption spectra of complexes upon binding of enantiomers enabled determination of the complexation constants by spectrophotometric titration. The corresponding iron complex **15b** catalysed, with high efficiency and enantioselectivity, the epoxidation of non-functionalised alkenes. A linear relationship between the changes in the free energies of complexation and catalytic epoxidation suggests that both processes follow similar stereoselective mechanisms.

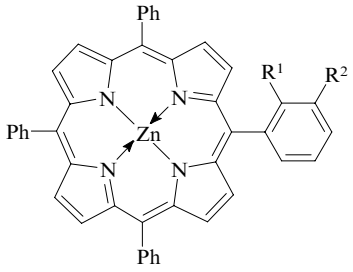


15a,**b**

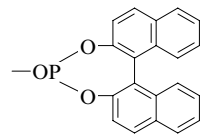
R = 

; M = Al (**a**), Fe (**b**).

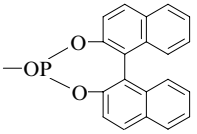
Porphyrins **16** – **18** possessing optical activities due to the 1,1′-binaphthyl fragments react with various phosphorus-containing chiral and achiral ligands. The complexes formed were used as



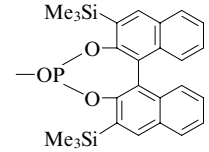
16 – **18**

16: R^1 = 

, R^2 = H;

17: R^1 = H, R^2 = 

;

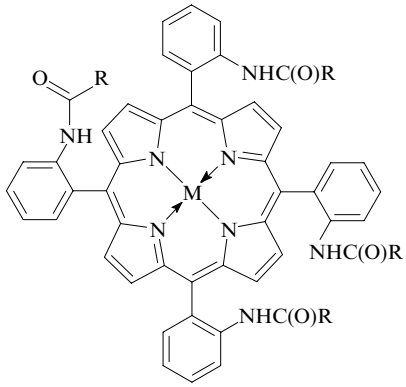
18: R^1 = 

, R^2 = H.

supramolecular bidentate templates in the palladium-catalysed asymmetric allylic alkylation of racemic 1,3-diphenylpropen-2-yl acetate with dimethyl malonate as a nucleophile. It was found[41] that the enantioselectivity of alkylation was determined not only by absolute configurations of porphyrin receptors and ligands, but also by structural features of the porphyrins, *e.g.*, bulkiness (the introduction of the $SiMe_3$ groups into porphyrin **18**) and arrangement of the binaphthyl substituent in the *ortho*- and *meta*-positions of porphyrins **16** and **17**.

5,10,15,20-Tetraphenylporphin derivatives **19** containing L-amino acids in the *ortho*-positions of the phenyl substituents formed (1 : 2) complexes with carbohydrates.[42] The fact that these porphyrins did not exceed tetrakis(decyl)-substituted receptors (**19**, R = $NHC_{10}H_{21}$-n) in binding capacity suggests the predominant contribution of urea fragments to H-bonding with the OH groups of carbohydrates.

A chiral derivative of ruthenium tetraphenylporphin complex **20** with optically active groups on both sides with respect to the porphyrin plane (the α,β,α,β-isomer) recognises enantiomers of amino acid esters. The binding of valine methyl ester by the ruthenium complex **20** occurred with the highest enantioselectivity and it was the L-enantiomer that was predominantly bound (*ee* 66%).[43, 44]

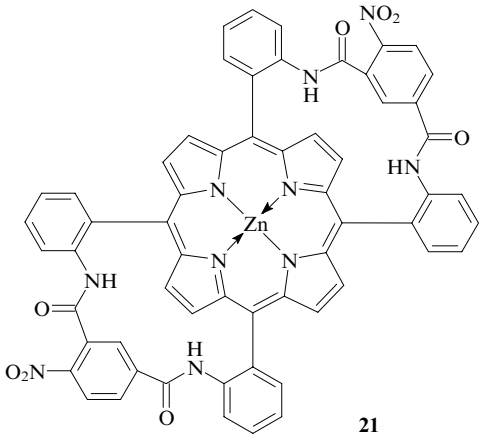


19, **20**

19: M = 2H, Zn; R = L-ValOMe, L-ThrOMe, L-TrpOMe, $NHC_{10}H_{21}$-n; **20**: M = RuO_2, Zn; R = C(OMe)(CF_3)Ph.

The zinc complex of the α,β,α,β-isomer of porphyrin **20** efficiently recognised the *S*-enantiomer of bulky 1-(1-naphthyl)ethylamine; the ratio of the binding constants was $K_S/K_R = 2.4$.[45]

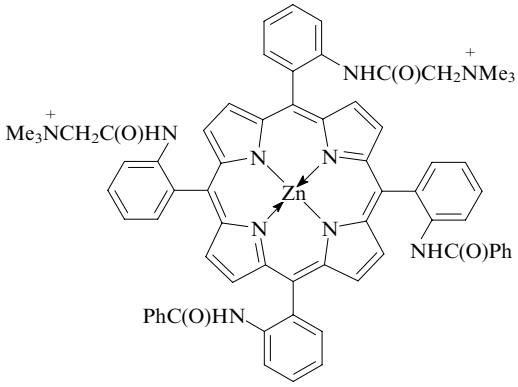
The stereoselectivity of the binding of D-valine methyl ester reached $K_D/K_L = 7.5$ when bridged chiral metalloporphyrin **21** was used. The preferential supramolecular complex was stabilised due to coordination and H-bonding of the carbonyl group of the guest with the amide group in the isophthalyl fragment of the host.[46]



21

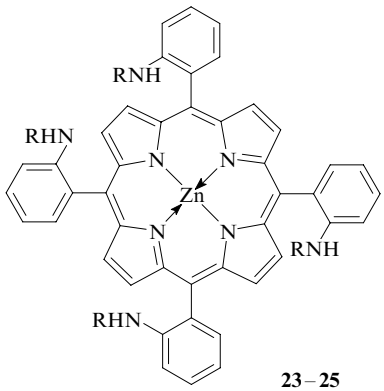
Thermodynamic analysis of the complexation revealed that the conformational freedom of the guest was largely lost as early as in the coordination step. The enthalpy factor that takes into account the formation of hydrogen bonds was suggestive of stabilisation of the complex as a whole.[46]

Both enantiomers of C_2-symmetric chiral water-soluble porphyrin **22** were used for enantioselective recognition of a series of amino acids and dipeptides in alkaline aqueous solutions. The stereoselectivity was effected by virtue of coordination of the NH_2 group by the Zn atom, Coulomb attraction between the carboxylate anion and the cationic ammonium group and steric interactions between the side group of the amino acid and the phenyl group of the *ortho*-substituent of porphyrin.[47]



22

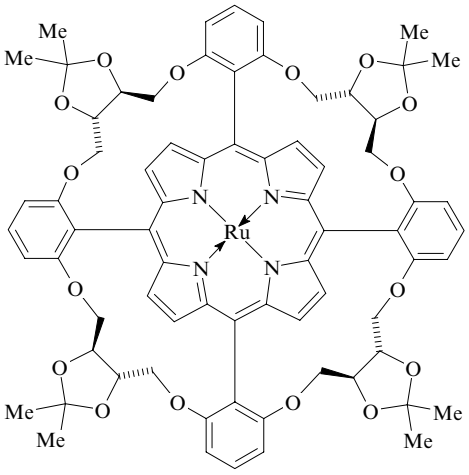
The most efficient recognition of amino acid esters by porphyrins modified by amino acids (complexes **23**–**25**) has been described.[48] Thus the enantioselectivity of binding of D-phenylalanine methyl ester reached the value of $K_D/K_L = 21.54$ and showed an exponential dependence on temperature. Diastereomeric complexes exhibited different CD spectra. Thus the CD spectrum of porphyrin **23** weakly bound to L-alanine methyl ester was similar to that of free porphyrin **23** and contained a single negative Cotton effect in the Soret band region. On the other hand, the strong complex with D-alanine methyl ester possessed a split signal owing to exciton interactions between porphyrin and the carbonyl group of the amino acid.



23–**25**

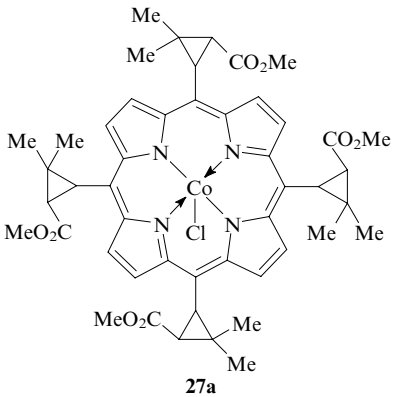
R = BocAla (**23**), BocPro (**24**), BzGln (**25**); Boc = $Bu^tOC(O)$.

The crucial importance of the three-centre model in chiral recognition was corroborated by low (*ee* 15%) binding stereoselectivity of racemic isocyanides by the Ru porphyrin complex **26**. This receptor was able to coordinate ligands, but had no additional centres for H-bonding.[49]

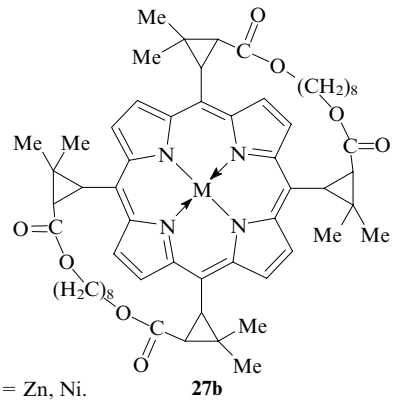


26

X-Ray diffraction analysis and ^{1}H NMR spectroscopy of chiral cobalt porphyrin complex **27a** revealed that the combination of one coordination interaction and two hydrogen bonds enabled efficient enantioselective recognition of amino alcohols and amino acid esters.[50–54] Moreover, cobalt porphyrin complex **27a** can be used for determination of enantiomeric excess in primary amines and aziridines by ^{1}H NMR spectroscopy.[53] A dependence of the conformation of the macrocycle on the nature of the central metal ion was established for metalloporphyrins **27b**; the α,α,α,α-conformation was changed to the α,β,α,β-conformation upon substitution of Ni for Zn.[54]

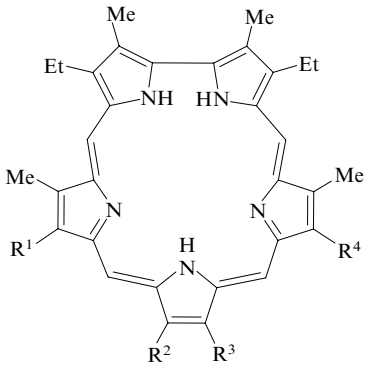


27a



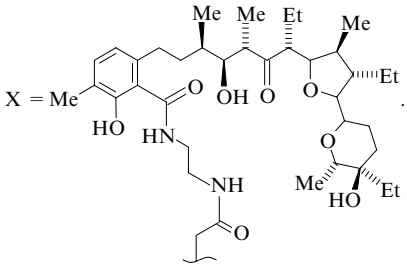
M = Zn, Ni. **27b**

Different chiral porphyrin derivatives are also used for binding of optically active compounds. Thus the lasalocid–sapphyrin conjugates **28**–**30** were used for the transfer of aromatic amino acids from one aqueous phase to another through an organic layer.[55] The mechanism of this reaction includes formation of a stable supramolecular ensemble of the host molecule with the zwitterionic form of the amino acid by virtue of electrostatic interaction of the carboxylate anion with protonated sapphyrin and formation of H-bonds between the NH_3^+ group of the amino acid and the ionophore fragment of lasalocid.



28–**30**

28: $R^1 = R^4 = Et$, $R^2 = Me$, $R^3 = CH_2X$;
29: $R^1 = X$, $R^2 = R^3 = Et$, $R^4 = CH_2C(O)PheOBu^t$;
30: $R^1 = X$, $R^2 = R^3 = Et$, $R^4 = CH_2C(O)PheOH$;

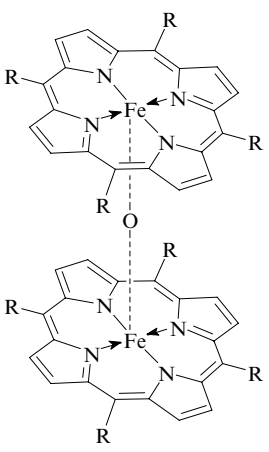


III. 'Host–guest' systems based on dimeric and oligomeric porphyrins

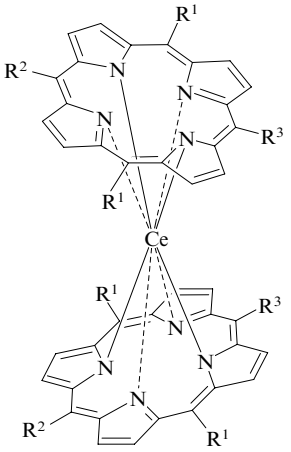
The above-cited examples of host–guest systems based on monomeric porphyrins demonstrate broad potential for their practical application. However, very often efficient functioning of monomeric porphyrin receptors is impossible without a synergetic support by one or several porphyrins. This stimulates the construction of novel chirogenic host–guest ensembles based on dimeric and oligomeric porphyrins. Such systems are classified according to the presence of a chiral fragment and the number of porphyrin macrocycles in the host molecule and the type of the covalent bridge.

First, let us consider the ensembles consisting of achiral or racemic bisporphyrin hosts and optically active guests. An achiral bisporphyrin molecule should possess at least two reaction sites and a flexible covalent bridge in order to adopt a stereospecific three-dimensional conformation upon interaction with chiral guest molecules. Then a supramolecular chiral ensemble is formed.

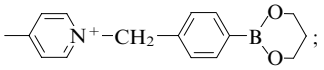
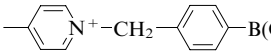
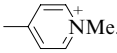
Double-decker bisporphyrins **31**–**38** linked 'centre-to-centre' were designed for binding of miscellaneous guest molecules.[56–61]



31, **32**



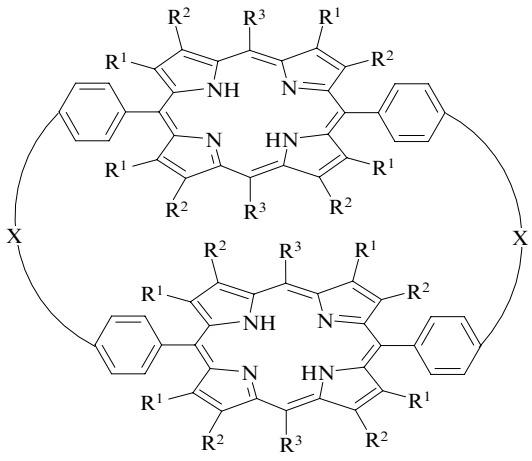
33 – **38**

31: R = $C_6H_4B(OH)_2$-3; **32**: R = $C_6H_4B(OH)_2$-4;
33: $R^1 = R^2 = R^3$ = 4-Py;
34: R^1 = Ph, $R^2 = R^3$ = 4-Py;
35: R^1 = 3,5-$(MeO)_2C_6H_3$, $R^2 = R^3$ = 4-Py;
36: R^1 = 4-$MeOC_6H_4$, $R^2 = R^3$ = ;
37: $R^1 = R^2$ = 4-$MeOC_6H_4$, R^3 = ;
38: R^1 = 4-$MeOC_6H_4$, $R^2 = R^3$ = .

The association mechanism involves the interaction of a bidentate guest with two complex-forming groups of adjacent porphyrins, which brings about twist of the porphyrin macrocycles around the central axis to the left or to the right depending on the stereochemistry of the guest molecule. This asymmetric twist results in changes in the interporphyrin exciton interactions and induction of optical activity in the region of absorption of the porphyrin. The induced optical activity retained for 3 days at 0 °C and over one year at −37 °C. The host–guest complexation occurred with a high degree of cooperativity, manifesting a positive allosteric effect; the characteristics of the CD signals strongly depended on the structure of the guest molecule,[56, 57] the nature of the solvent [61] and pH.[60]

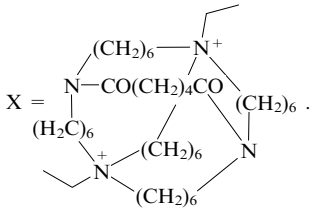
Bisporphyrin systems **31**, **32**, **36** and **37** containing boronic acid were successfully employed for the recognition of carbohydrates; the dimers containing pyridyl substituents (**33** – **35**) were used for the binding of chiral dicarboxylic acids, while cationic bisporphyrin **38** interacted with dianions. Bisporphyrin receptor **35** possessed an ability of memorising chirality. Interestingly, bisporphyrin **36** interacts with glucose oligomers as guests, and the sign of optical activity of the complex changes depending on the number of monosaccharide units.[59]

'Face-to-face' bisporphyrins **39** and **40** linked by covalent cryptand-containing bridges between the opposite positions of the macrocycles efficiently bind trisaccharides in aqueous solutions, predominantly by encapsulation.[62] Very weak induction of CD in the region of the Soret band is observed due to the inability of bisporphyrins to change their conformations depending on the stereochemistry of guest molecules because of structural rigidity of the cryptand-containing bridges.

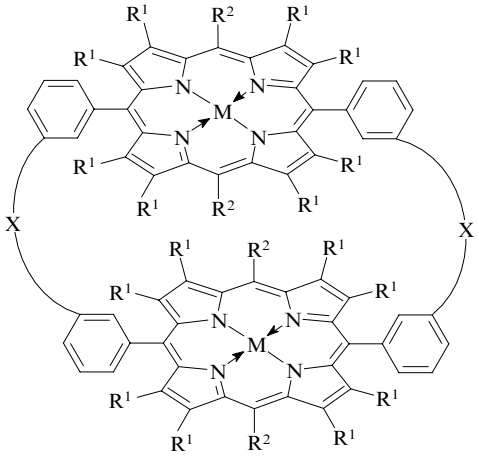


39, **40**

39: $R^1 = R^2$ = H, R^3 = C_6H_4Me-4;
40: R^1 = Me, R^2 = Pr^n, R^3 = H;

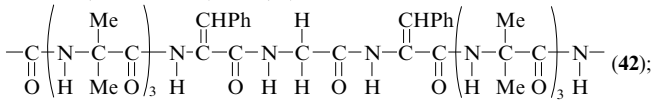
X = .

Dimers **41** and **42** containing flexible covalent bridges manifested good structural matching to bidentate pyridyl-anchored chiral peptides of appropriate lengths. As a result, stable inclusion complexes (1 : 1) with association constants of the order of 2.3×10^6 M^{-1} are formed. It was found that the helical structure of the guest plays a key role in the transcription of chiral information by inducing strong exciton interactions in the Soret absorption band region.[63]



41 – **43**

M = Zn, R^1 = H, R^2 = 2,4,6-$Me_3C_6H_2$:
X = $CO(NHCMe_2CO)_9NH$ (**41**),

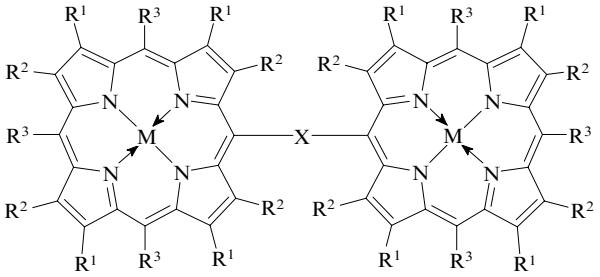
 (**42**);

M = 2H, R^1 = Me, R^2 = 2,6-$(MeO)_2C_6H_3$,
X = 4-$OCH_2C_6H_4CH_2O$-4 (**43**).

Bisporphyrin **43** with shorter *para*-xylylene bridges was used for the complexation with mandelic acid. This resulted in a significant (more than sevenfold) enhancement of a CD signal ($A = 260$ cm^{-1} M^{-1}) in comparison with the complex based on monomeric porphyrin. This effect is due to induction of helical chirality upon forced changes in mutual arrangement of both porphyrin rings in the course of formation of the supramolecular ensemble. Increasing concentrations of guest molecules triggered complex changes in the CD spectra manifested as multistep equilibrium. Such systems present interest as candidate chirality sensors for the study of stereochemistry of interacting guest molecules.[64]

Yet another structural type of bisporphyrins is based on combination of two chromophores linked through a single bridge. In this case, the mutual arrangement of the porphyrin macrocycles is less predictable because of lesser rigidity of the system. The complexation with a bidentate guest molecule can favour approach of the porphyrin moieties to each other and their fixation in the 'face-to-face' mode.

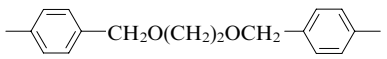
Lanthanide-containing bisporphyrins **44** and **45** linked through ether bridges of various lengths provide examples of such systems. These dimers were obtained as potential host molecules for binding cystine polyions.[65] The selectivity of recognition is largely determined by the size of the optically active guest molecules. Thus ytterbium bisporphyrin complex **44** with a short bridge effectively extracted cystine from aqueous solutions into the organic phase, but not cystathionine, homocystine or methionine. In contrast, bisporphyrin **45** effected preferential extraction of more extended homocystine. The formation of 'tweezers'-like 1 : 1 complexes was accompanied by the appearance of a complex CD signal in the Soret band region; its intensity was notably increased in comparison with the signal of the monomeric complex.

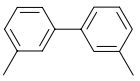


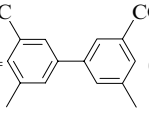
44 – 47

M = Yb(acac), Gd(acac); $R^1 = R^2 = H$; R^3 = Ph:

X =  (**44**),

 (**45**);

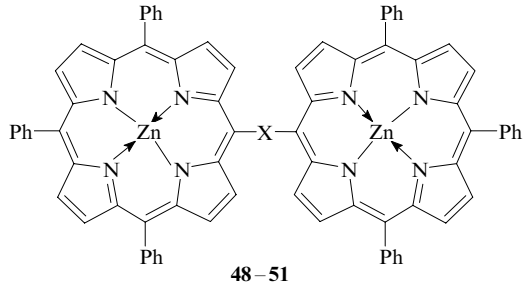
M = Zn, R^1 = Me, R^2 = n-C_6H_{13}, $R^3 = H$, X =  (**46**);

M = Zn, $R^1 = R^2 = H$, R^3 = 3,5-$Bu^t_2C_6H_3$, X =  (**47**).

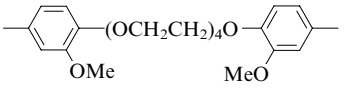
High binding selectivity of chiral diamines by bisporphyrins **46** and **47** linked through rigid bridges was reported.[66] The matching of the distance between the zinc atoms of the porphyrin macrocycles to the length of the chain linking two NH_2 groups of the guest is a prerequisite for efficient complexation. The highest association constant ($K_a = 2.4 \times 10^6$ M^{-1}) was found for the pair dimer **47** – cystine ethyl ester. The induced CD signal strongly depended on the bulkiness of the peripheral substituents in the porphyrin macrocycles and temperature. Thus the molar amplitude A increased 1.5-fold with a decrease in temperature down to -45 °C.

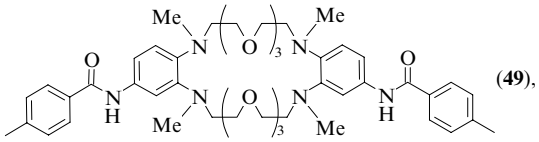
The feasibility of control over bisporphyrin conformation increased substantially upon introduction of a crown-ether-type linkage into the host molecule by virtue of specific binding of the crown-ether fragment to alkali metal ions.[67–69] Thus the addition of Na^+ ions to the bisporphyrin **48** – *trans*-1,2-diaminocyclohexane system caused a nearly twofold increase in the association constant due to the change in the bisporphyrin geometry and a concomitant significant increase in the molar amplitude A of the induced CD signal.[67]

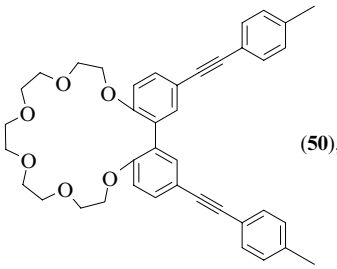
A similar effect was observed in the interaction of bisporphyrin **49** with *N*-alkyl-1,2-diaminocyclohexane.[68] However, in this case the formation of a complex with a larger crown-ether cavity required larger K^+ ions. Bisporphyrin **49** recognised the chirality of potassium camphorates and mandelates.

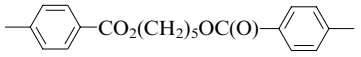


48 – 51

X =  (**48**),

 (**49**),

 (**50**),

 (**51**).

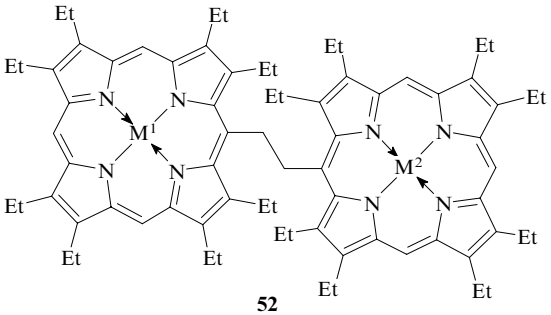
The chirality of porphyrin **50** in a 'tweezers' conformation which is conferred on it by its interaction with an optically active diamine, is retained after replacement of the chiral ligand by an achiral one in the presence of Ba^{2+} ions. The intensity of the CD signal in this particular system decreased only slightly within 24 hours.[69]

The 'tweezers'-like systems discussed above manifest high optical activities due to asymmetric spatial arrangement of two porphyrin chromophores. However, no detailed interpretation of electronic and structural factors responsible for this phenomenon has been given so far. In a series of studies,[70–80] attempts were undertaken to solve this problem using flexible bisporphyrin **51** that adopts 'tweezers'-like conformation upon complexation with bidentate ligands.

Presumably,[70–80] optical activity observed in the formation of supramolecular systems results from the stereospecific differentiation of the relative bulkiness of substituents at the chiral carbon atom of the guest owing to the ability of bisporphyrin to adopt the sterically least hindered conformation. The factors that influence the geometry of the ensemble, *e.g.*, H-bonding, the presence of

heteroatoms, the nature of the solvent, *etc*., should also be taken into consideration. The sign of the induced CD signal upon exciton interactions of two chiral tetrapyrrole fragments of bisporphyrin **51** can be used for determination of absolute configurations of bidentate guest molecules. In the case of discrepancies between the predicted and experimental chirality, conformational analysis was carried out using the molecular mechanics method. Some dependences of induced CD signals on the nature of the guest molecule, the solvent and temperature were given.[70–80]

The complexation of bisporphyrins **52** in which the tetrapyrrole fragments are linked through C_2-bridges was studied in order to get a deeper insight into the mechanism of induction of optical activities of supramolecular systems based on bisporphyrins.[8,81–95]



52

$M^1 = M^2 = Zn, Mg$; $M^1 = Zn$, $M^2 = 2H$.

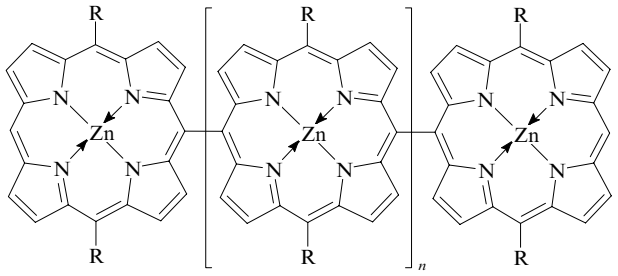
In contrast with the bisporphyrin systems considered above, this host molecule recognises chiralities of both bidentate and monodentate guests due to a limited number of conformations adopted by bisporphyrin with a short covalent bridge. Absorption, CD and ^{1}H NMR spectra suggest that bisporphyrin **52** interacts with primary amines by a cooperative mechanism to yield stable host–guest complexes (1 : 2) where bisporphyrin is in the *anti*-conformation. The Gibbs free energy for this complexation varies from -6.7 to -8.4 kcal mol^{-1}. The specific mechanism of induction of the optical activity in bisporphyrin **52** upon complexation with chiral monodentate guests stems from the difference in the repulsion forces of two bulkiest substituents at the asymmetric centre of the ligand and the ethyl groups of the neighbouring porphyrin fragment. The mutual repulsion of these groups forces the tetrapyrrole macrocycles to move away from one another and to twist, which results in generation of an intensive CD signal in the Soret band region, which is characteristic of exciton interactions. The correlation between the sign of the signal and induced helicity of the system enables determination of absolute configurations of monodentate guest molecules.

The effects of various factors on induction of chirality have been studied in detail.[81–95] It was found[81,82,84] that the value of the molar amplitude, A, in the CD spectra was proportional to the size of the bulkiest substituent at the asymmetric centre in homologous ligands. The crucial role of the solvent as an active component of the supramolecular system was determined[89,90] based on the analysis of solvent–solute interactions in the boundary zones where the difference between the complexation involving competing chiral ligands was small and the guest could be replaced by the solvent molecule. Temperature is yet another factor that governs chirogenic processes. Thus a drop in temperature, which diminished the mobility of the system, was accompanied by a significant increase in the molar amplitude A.[85–87] In this case, chirality could be induced as a result of binding of optically active alcohols despite their low affinities for zinc porphyrins. The ability of chiral alcohols to induce optical activity is significantly enhanced upon substitution of the Mg^{2+} ion for the central Zn^{2+} ion in the porphyrin macrocycle.[88] Phase transition is yet another important factor that controls optical activities of bisporphyrin complexes **52** with monodentate amines.[95] Phase transition in a system caused a significant (1.6–9-fold) increase in the anisotropy factor together with solid-phase 'switch' of chirality due to formation of intermolecular aggregates of opposite helicity.

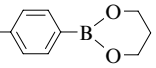
The interaction of bisporphyrin **52** with bidentate guests yielded extremely stable 'tweezers'-like complexes (1 : 1) with binding constants reaching 10^7 M^{-1}. In the majority of cases, further increase in the concentration of bidentate guests shifts the equilibrium towards the formation of supramolecular host–guest complexes (1 : 2) where bisporphyrin adopts the *anti*-conformation.[91–94] An interesting effect, *viz*., switchover of chirality, which was controlled exclusively by the stoichiometry of the supramolecular system as a result of opposite mutual spatial arrangement of its porphyrin components in 1 : 1 and 1 : 2 complexes, was characteristic of enantiopure 1,2-diphenylethylenediamine used as a guest.

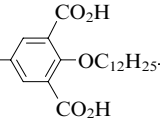
A more detailed rationale for induced optical activity in supramolecular systems based on bisporphyrins was gained with chiral 1,2-diaminocyclohexane as a guest. Based on X-ray data on the structure of bisporphyrin **52**–(*R*,*R*)-1,2-diaminocyclohexane complex and the Kuhn–Kirkwood mechanism of coupled-oscillator interaction, the intense bisigned CD signal ($A = -590$ cm^{-1} litre mol^{-1}) was rationalised as a combination of two $B_{\|}-B_{\|}$ and $B_{\perp}-B_{\perp}$ counter-clockwise electronic homointeractions, whereas the contribution of the corresponding $B_{\|}-B_{\perp}$-heterointeractions was insignificant.[94] Thus, high sensitivity and the ability of bisporphyrin **52** to recognise optical activities of different guest molecules, together with a deep insight into complexation mechanisms, make it a worthy candidate for versatile chirality sensors.

Bisporphyrin **53** with rigidly linked macrocycles was recommended for selective binding of oligosaccharides by a cooperative mechanism.[60,96] The fixed distances between the porphyrin fragments correspond closely to the size of maltotetraose, which results in stable host–guest complexes (1 : 2). This is concomitant with the appearance, in the CD spectrum in the region of the Soret band, of a complex chiroptic response consisting of three nonequivalent and asymmetric Cotton effects probably due to superposition of two or more CD signals.

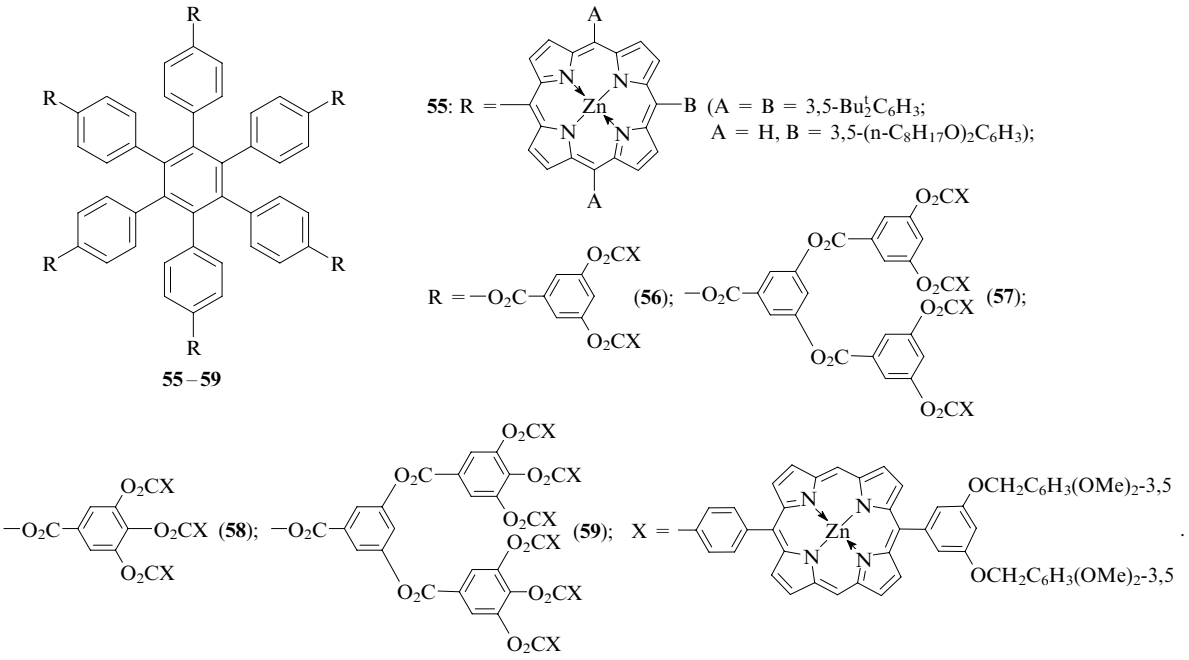


53, **54**

53: R =  , $n = 0$;

54: R =  , $n = 0, 1, 2, 6$.

The increase in the number of porphyrin macrocycles in *meso*,*meso*-linked oligomers **54** brought about significant enhancement of the effect of induced chirality.[97] In the presence of tetrahydropyrimidinone, these oligomers formed helical structures due to H-bonding of the carboxy groups in the *meso*-aryl substituents of porphyrin and the urea nitrogen atoms. The direction of helix formation was controlled by complexation with chiral diamino-1,1′-binaphthyl derivatives resulting in the appearance of induced CD signals. The intensity of the latter increased with the increase in the number of porphyrin units from



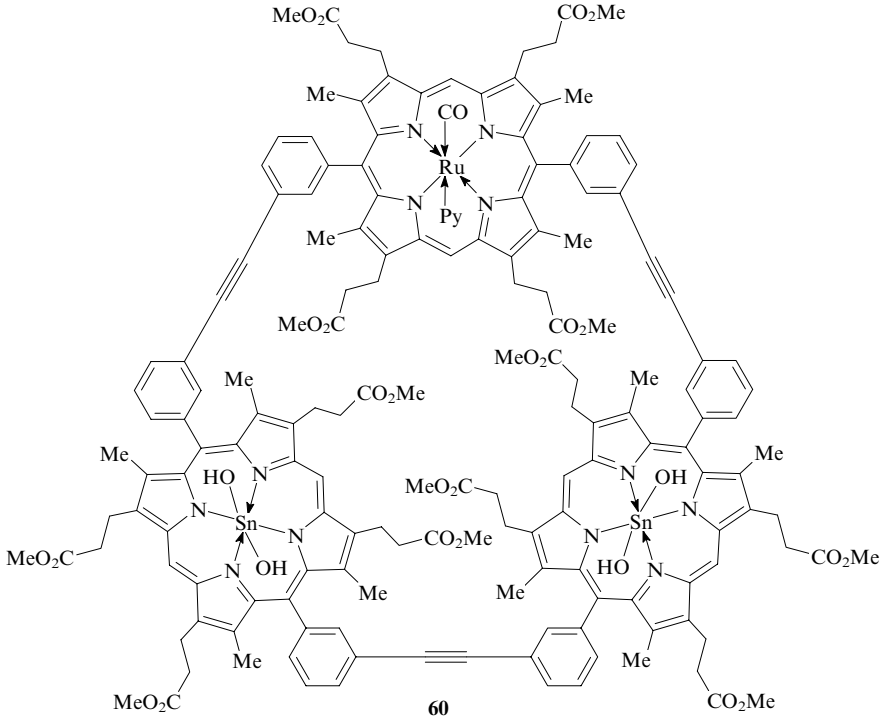
2 to 8. An interesting chirality memory effect was observed for octaporphyrin **54** ($n = 6$): the addition, to a helix formed by octaporphyrin and an optically active guest, of an opposite enantiomer caused a decrease in the induced chirality value, but not its complete cancel or switching the sign.

Yet another type of multiporphyrin systems was investigated.[98,99] In the presence of enantiomerically pure 1-(1-naphthyl)ethylamines, hexamers **55** manifested intense CD signals in the Soret band region; other chiral amines induced weak Cotton effects.

High stereoselectivity was observed for a series of dendritic porphyrins **56**–**59** in their complexation with bidentate chiral guests. The induced CD signal strongly depended on the number of porphyrin fragments; the maximum value of A (2693 $cm^{-1}\ M^{-1}$) was found for dendritic complexes **57**. However, this effect has not been comprehensively investigated yet.

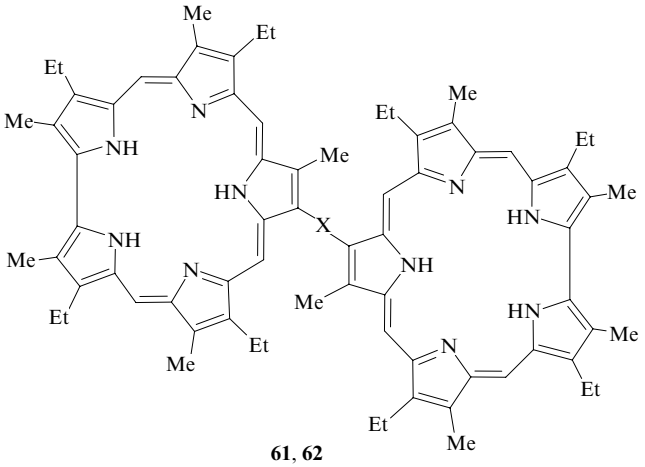
An attempt to develop a supramolecular system for chiral recognition and enantioselective catalysis based on heterometallic trimer **60** was undertaken.[100] In the first step, optically active carboxylic acids bind to tin-containing porphyrin fragments of the trimer **60** in a hexacoordination mode with formation of a host–guest ensemble (1 : 4) with a chiral cavity. However, further attempts to use this ensemble for separation of a racemic mixture of chiral substituted pyridines with subsequent catalytic asymmetric epoxidation were unsuccessful, apparently due to the loss of rigidity of the chiral cavity.

Host–guest systems in which both components possess optical activities can find wide application. Thus a series of chiral sapphyrin dimers **61**–**63** were used for the recognition of dicarboxylate anions by virtue of Coulomb attraction and formation of hydrogen bonds.[101] Dimers **61** and **62** formed stable complexes with *N*-benzyloxycarbonylaspartic and *N*-benzyloxycarbonylglu-



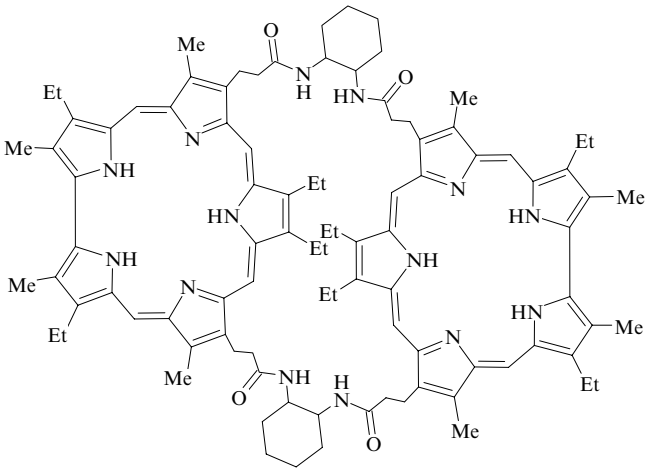
tamic acids ($K_a \sim 10^4 - 10^5$ M^{-1}), the binding of glutamic acid being more preferable.

Despite its low affinity for the guest molecules considered above, the cyclic dimer **63** also possesses the ability for chiral recognition. Presumably, this is due to high structural matching of the host and guest molecules as a result of rigid fixation of sapphyrin fragments by two covalent bridges. The detailed recognition mechanism demands additional investigation.



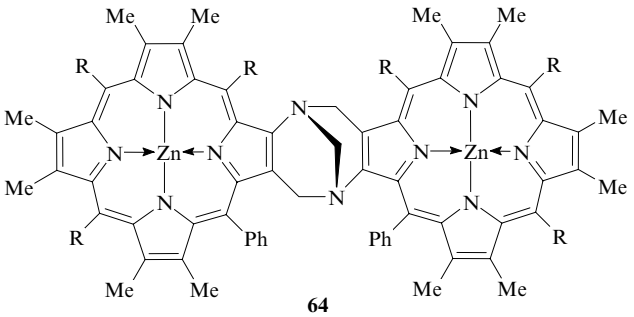
61, **62**

X = $(CH_2)_2C(O)HN$ / $(CH_2)_2C(O)HN$ (**61**), $(CH_2)_2C(O)HN$ / $(CH_2)_2C(O)HN$ (**62**).



63

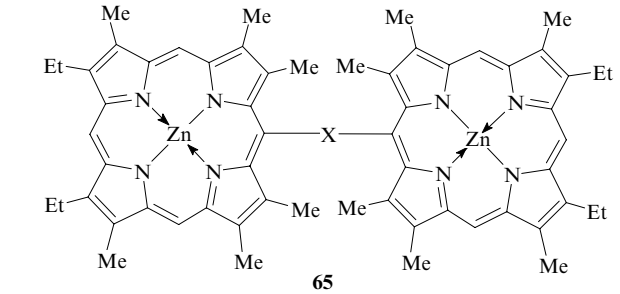
Bisporphyrin **64** with spatially fixed macrocycles was used for enantioselective binding of histidine and lysine esters (*ee* 80%–86% and 48%, respectively). The complexation was achieved through two-site interaction between two nitrogen atoms of the guest and two zinc ions of the host; this yielded 'tweezers'-like structures.[102]



64

R = 3,5-$Bu^t_2C_6H_3$.

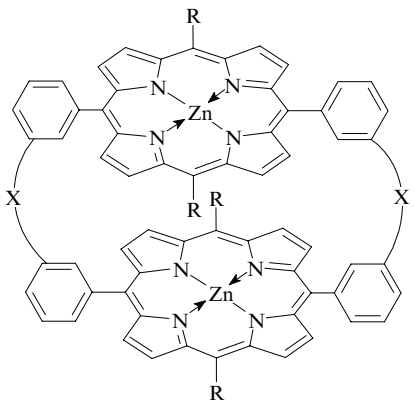
Bisporphyrin **65** rigidly bridged by a 1,1′-binaphthyl fragment was used for chiral recognition of various amino acid derivatives.[66] This host molecule manifested especially high affinity for lysine derivatives due to formation of 'tweezers'-like complexes. The stereoselectivity of binding is determined by steric repulsion of two methoxy groups of the bridge and the amide group of the amino acid derivative in the less favourable diastereomeric complex.



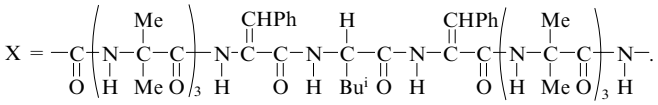
65

X = MeO / MeO

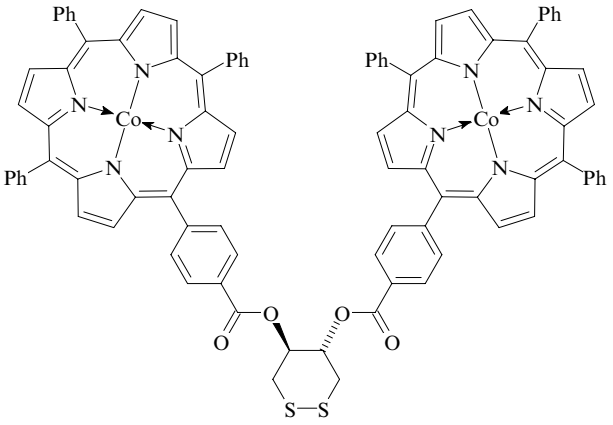
Chiral dimeric porphyrin **66** was used for stereoselective separation (*ee* 80%) of bidentate ligands of various lengths. Guest molecules contained an optically active leucine unit and two terminal pyridine fragments enabling two-site binding.[103] The formation of the preferential 'tweezers'-like complex was accompanied by a significant increase in the CD signal intensity in the Soret band region. The observed effect is due to stabilisation of the twisted conformation of the host molecule as a result of its binding to the helical guest molecule.



66

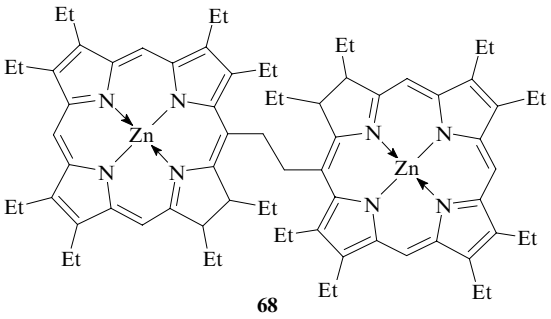


On the contrary, the intensity of a negative single signal in the CD spectrum of bisporphyrin **67** decreased dramatically in the presence of limonene.[104] This was accompanied by a hypsochromic shift the magnitude of which depended on the configuration of the enantiomer bound.



67

A similar decrease in the signal intensity in the CD spectrum of chiral bischlorin **68** was observed upon its interaction with optically active ligands.



68

The effect observed is also due to conformational changes in the host molecule. The significant differences between the chiroptical responses of the complexes with enantiomers suggests possible application of bischlorin **68** for chiral recognition.[105]

* * *

The published data considered in this review suggest that optically active supramolecular systems based on porphyrins and their derivatives present indubitable interest for both determination of absolute configurations of different organic molecules and in-depth studies of transcription of optical activity. Recent progress in this area is an important prerequisite to the development of advanced molecular technologies, such as chiral nanotechnology, design of 'smart' molecular tools to memorise chirality and optical activity sensors.

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