



## Enantioselective Complexation of Amino Acids by 6<sup>A</sup>-Deoxy-6<sup>A</sup>-hydroxyethylamino- $\beta$ -Cyclodextrin and its Metallo-Derivatives in Aqueous Solution

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**Abstract.** Enantioselectivity towards several amino acids by metallo-6<sup>A</sup>-deoxy-6<sup>A</sup>-hydroxyethylamino- $\beta$ -cyclodextrins (metallo- $\beta$ CD<sub>ea</sub>'s) was investigated by potentiometric titration of the various amino acid/metallo- $\beta$ CD<sub>ea</sub> systems with NaOH solution. It was shown that the cyclodextrin derivative is capable of distinguishing between enantiomers of amino acid species in the presence of certain metal ions (Co<sup>2+</sup>, Ni<sup>2+</sup>, Cu<sup>2+</sup> and Zn<sup>2+</sup>). Ni<sup>2+</sup>- $\beta$ CD<sub>ea</sub> complexes show the most enantioselectivity, whereas for Cu<sup>2+</sup>- and Co<sup>2+</sup>- $\beta$ CD<sub>ea</sub> complexes less selectivity is observed. As expected, Zn<sup>2+</sup>- $\beta$ CD<sub>ea</sub> complexes exhibit no enantioselectivity. Stability and selectivity, however, do not go hand in hand, since the most stable complexes are formed with Cu<sup>2+</sup>. Several factors play a role in determining stability and selectivity in binary and ternary complexes and further study is required to gain a more comprehensive understanding of these.

**Key words:** metallo-cyclodextrin, enantioselectivity, amino acid, binary complex, ternary complex.

### 1. Introduction

The presence of a hydrophobic cavity in cyclodextrin molecules renders them efficient hosts for a variety of guests. The most stable complexes are usually formed with hydrocarbon type (hydrophobic/lipophilic) species. Since cyclodextrins are composed of D-(+)-glucopyranose units and are chiral, it is expected that they can be used as agents for enantiomeric separation. However, native CDs are poor chiral discriminating agents [1]. To improve their chiral recognition, it is desirable to have a metal ion centre present as well as the chiral cavity in the molecule [2–7]. Native cyclodextrins are also inefficient coordinating ligands because of intramolecular hydrogen bonding. Both of these functions can be enhanced by functionalising the  $\beta$ CD at C(6) with a chelating moiety, in this case ethanolamine, to form 6<sup>A</sup>-deoxy-6<sup>A</sup>-hydroxyethylamino- $\beta$ -cyclodextrin ( $\beta$ CD<sub>ea</sub>).

Determination of stability constants for the formation of binary metallo- $\beta$ CD<sub>ea</sub> and metallo-substrate complexes and ternary metallo-substrate- $\beta$ CD<sub>ea</sub> complexes

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affords a mechanism to investigate the role of the metal ion centre and the cyclodextrin cavity interactions on the stability and enantioselectivity of these complexes. Previous work by Lincoln *et al.* [2–3] on enantioselectivity by M- $\beta$ CDpn ( $\beta$ CDpn = 6<sup>A</sup>-(3-aminopropylamino)-6<sup>A</sup>-deoxy- $\beta$ CD) (M = Co<sup>2+</sup>, Ni<sup>2+</sup>, Cu<sup>2+</sup>, Zn<sup>2+</sup>) towards phenylalanine (Phe), tryptophan (Trp) and histidine (His) showed that enantioselectivity was largest for Ni<sup>2+</sup> complexes and that Zn<sup>2+</sup> complexes possessed no ability for chiral recognition. They also concluded that stabilising interactions of the guest amino acid with the metal ion centre and with the hydrophobic CD cavity do not reinforce each other. The work presented here looks at the enantioselectivity of corresponding systems using 6<sup>A</sup>-deoxy-6<sup>A</sup>-hydroxyethylamino- $\beta$ -cyclodextrin ( $\beta$ CDea) as the functionalised CD. This deserves investigation because of the important role of aminoalcohols in hormone activity [8–9] and in the biochemistry of aminosugars [10–11]. In many respects, the results mainly support those of the previous authors, however, some differences were also noted and are described later. The various roles of the cyclodextrins, divalent metal ions and amino acids in affecting complexation are discussed.

## 2. Experimental

### 2.1. INSTRUMENTATION

Potentiometric titrations were carried out using a Mettler DL25 automatic titrator equipped with a Mettler DG-111-SC-pH electrode that was filled with 3 mol dm<sup>-3</sup> KCl (AgCl saturated). All titration solutions were degassed with nitrogen for at least 10 minutes before each titration. During all titrations, a similar stream of nitrogen gas was passed through the solution to prevent CO<sub>2</sub> adsorption from the atmosphere, which would cause an extensive drift in EMF. The titration solution was mechanically stirred in a 100 mL titration vessel closed to the atmosphere except for the nitrogen outlet and thermostatted in a waterbath at 25 °C (except where otherwise stated).

Magnetic moment determinations were performed on a Sherwood Scientific magnetic susceptibility balance, standardised with mercury(II)tetrathiocyanatocobaltate(II). Infrared spectra of solids (KBr-disc) were recorded using a Perkin Elmer Paragon 1000 FT-IR spectrometer. NMR spectra were measured by a Varian Gemini 2000 instrument (200 MHz). Atomic Absorption (AA) experiments were conducted on a Shimadzu AA-670 spectrophotometer.

### 2.2. PREPARATION OF MATERIALS

The 6<sup>A</sup>-deoxy-6<sup>A</sup>-hydroxyethylamino- $\beta$ -cyclodextrin was prepared as follows, by a modification of a previous method [12]. 6<sup>A</sup>-deoxy-6<sup>A</sup>-*O*-*p*-toluenesulphonyl- $\beta$ -cyclodextrin [13] ( $\beta$ CDOTs) (2.7 g, 2 mmol) and potassium iodide (0.8 g, 4 mmol) in aqueous solution (500 mL) were stirred for one hour on a steambath. Ethanolamine (1.44 mL, 20 mmol) was added and the reaction continued for 5

hours under atmospheric pressure until the solution was evaporated to 40 mL. This solution was cooled to room temperature and acetone (200 mL) was gradually added. The resulting precipitate was collected by filtration and washed with acetone. The resultant off-white solid was recrystallised from water and dried in vacuo for 4 hours at 50 °C. Anal. Calcd for  $\beta$ CDea: C. 39.23, H. 7.43, N. 1.04; found: C. 38.97, H. 6.92, N. 1.35.  $^1\text{H-NMR}$  (200 MHz, DMSO):  $\delta$  4.80, 4.00–2.85, 2.05, 1.02.  $^{13}\text{C-NMR}$  (200 MHz, DMSO):  $\delta$  102.05, 81.61, 73.15–72.10, 60.00, 56.11, 39.44, 30.73, 18.53 [14–16]. FTIR-spectra were recorded for  $\beta$ CD,  $\beta$ CDOTs and  $\beta$ CDea. Two new bands appear in the  $\beta$ CDOTs spectrum due to the asymmetric and symmetric  $\text{SO}_2$ -stretches at  $1375\text{ cm}^{-1}$  and  $1182\text{ cm}^{-1}$  respectively [17]. As expected, these bands are absent in the spectrum of  $\beta$ CDea.

(R)- and (S)-amino acids (Sigma) were dried to constant weight prior to use. Metal perchlorates (Aldrich) were purchased and used without further treatment. Stock  $0.100\text{ mol dm}^{-3}$   $\text{Ni}(\text{ClO}_4)_2$ ,  $\text{Cu}(\text{ClO}_4)_2$ ,  $\text{Co}(\text{ClO}_4)_2$  and  $\text{Zn}(\text{ClO}_4)_2$  solutions were standardised by EDTA titration. Deionised water was used in the preparation of all solutions.

### 2.3. POTENTIOMETRIC TITRATIONS

In all titrations, standardised  $0.100\text{ mol dm}^{-3}$  NaOH was titrated against the species of interest in solutions which were  $0.010\text{ mol dm}^{-3}$  in  $\text{HClO}_4$  and  $0.090\text{ mol dm}^{-3}$  in  $\text{NaClO}_4$ . Thus, the protonation constants for  $\beta$ CDea and the amino acids were determined from titrations of 25 mL aliquots of  $0.001\text{ mol dm}^{-3}$   $\beta$ CDeaH $_2^+$  or  $0.001\text{ mol dm}^{-3}$  amino acid solutions respectively. The stability constants for the binary metallo-cyclodextrin or metal-amino acid complexes were determined by titration of 25 mL aliquots of  $0.001\text{ mol dm}^{-3}$   $\beta$ CDeaH $_2^+$  or  $0.001\text{ mol dm}^{-3}$  amino acid solution to which 0.240 mL and 0.120 mL of  $0.100\text{ mol dm}^{-3}$   $\text{M}(\text{ClO}_4)_2$  solution had been added, respectively. The stability constants for the formation of complexes between  $\beta$ CDea and the (R)- or (S)-amino acid were determined by titration of 10 mL of  $0.001\text{ mol dm}^{-3}$  solutions of either (R)- or (S)-amino acid and 10 mL of  $0.001\text{ mol dm}^{-3}$  of  $\beta$ CDeaH $_2^+$  solution. The stability constants for the ternary complexes between the metals,  $\beta$ CDea and (R)- or (S)-amino acid were determined by titration of 10 mL of  $0.001\text{ mol dm}^{-3}$  solutions of either (R)- or (S)-amino acid and 10 mL of  $0.001\text{ mol dm}^{-3}$   $\beta$ CDeaH $_2^+$  solution with  $0.100\text{ mL}$  of  $0.100\text{ mol dm}^{-3}$   $\text{M}(\text{ClO}_4)_2$  solution added.  $\text{pK}_w$  values were determined by titration of  $0.010\text{ mol dm}^{-3}$   $\text{HClO}_4$  ( $0.090\text{ mol dm}^{-3}$  in  $\text{NaClO}_4$ ) against  $0.100\text{ mol dm}^{-3}$  NaOH. Derivations of the stability constants were carried out using the program SUPERQUAD [18]. At least three runs were performed for each system, and at least two of these runs were averaged; the criterion for selection for this averaging being that  $\chi^2$  for each run was  $<12.6$  at the 95% confidence level.

Several complexes exist in aqueous solutions of  $\beta$ CDea,  $\text{M}^{2+}$  and amino acids in the pH-range 2.0–11.5. The stabilities of these complexes were calculated from the differences between the pH-profiles arising from titration against NaOH of

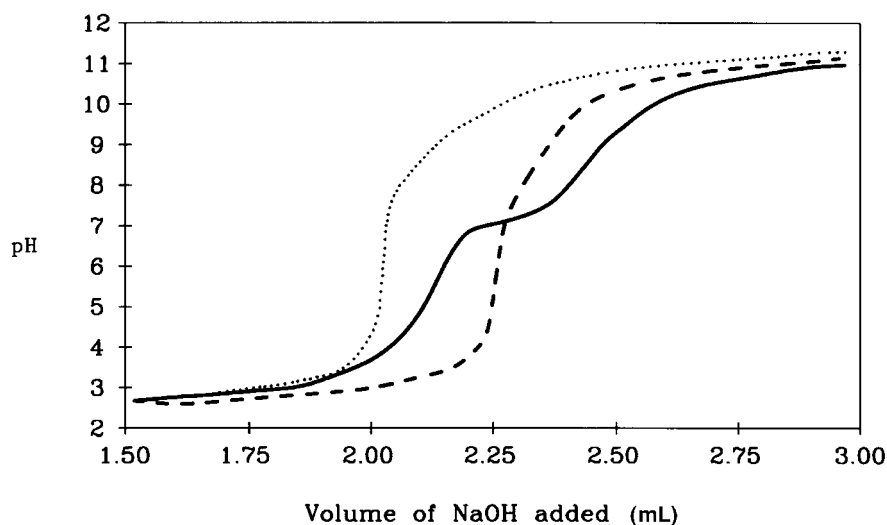


Figure 1. Titration profiles for (...)  $\beta$ CDeaH<sub>2</sub><sup>+</sup> ( $9.941 \times 10^{-4}$  mol dm<sup>-3</sup>, 25 mL), (- - -)  $\beta$ CDeaH<sub>2</sub><sup>+</sup> ( $1.003 \times 10^{-3}$  mol dm<sup>-3</sup>, 10 mL) and (R)-PheH<sub>2</sub><sup>+</sup> ( $1.010 \times 10^{-3}$  mol dm<sup>-3</sup>, 10 mL) and (—)  $\beta$ CDeaH<sub>2</sub><sup>+</sup> ( $1.003 \times 10^{-3}$  mol dm<sup>-3</sup>, 10 mL), (R)-PheH<sub>2</sub><sup>+</sup> ( $1.010 \times 10^{-3}$  mol dm<sup>-3</sup>, 10 mL) and Cu(ClO<sub>4</sub>)<sub>2</sub> ( $9.93 \times 10^{-2}$  mol dm<sup>-3</sup>, 0.100 mL), each in aqueous 0.010 mol dm<sup>-3</sup> HClO<sub>4</sub> and 0.090 mol dm<sup>-3</sup> NaClO<sub>4</sub> against 0.100 mol dm<sup>-3</sup> NaOH at 25 °C.

solutions containing different combinations of the complexing species. Three such pH-profiles are shown in Figure 1.

The sequence of these titrations was as follows: the determination of (i) the pK<sub>a</sub> values of the amino acids and  $\beta$ CDeaH<sub>2</sub><sup>+</sup>, (ii) the stability constants of the complexes in solution of (a)  $\beta$ CDeaH<sub>2</sub><sup>+</sup> and either (R)- or (S)-amino acid, (b) M<sup>2+</sup> and the amino acid, (c) M<sup>2+</sup> and  $\beta$ CDeaH<sub>2</sub><sup>+</sup> and (d) the ternary system M<sup>2+</sup>,  $\beta$ CDeaH<sub>2</sub><sup>+</sup> and either (R)- or (S)-amino acid. The pK<sub>a</sub> values determined in (i) were used as constants in the determination of stability constants in (ii). The stability constants determined in (ii-a)–(ii-c) were also employed as known values in the determination of stability constants in (ii-d). The titration data were fitted to equilibria containing the minimum number of species required for a good fit. A plot of the major Cu<sup>2+</sup> species present in the system Cu<sup>2+</sup>- $\beta$ CDea-(R)-phenylalanine is shown in Figure 2. This is typical of the other systems studied.

### 3. Results

The acid dissociations of TrpH<sub>2</sub><sup>+</sup> (pK<sub>a1</sub> =  $2.37 \pm 0.04$  and pK<sub>a2</sub> =  $9.39 \pm 0.02$ ), PheH<sub>2</sub><sup>+</sup> (pK<sub>a1</sub> =  $2.70 \pm 0.02$  and pK<sub>a2</sub> =  $9.19 \pm 0.01$ ) and HisH<sub>3</sub><sup>2+</sup> (pK<sub>a1</sub> =  $1.99 \pm 0.03$ , pK<sub>a2</sub> =  $6.11 \pm 0.01$  and pK<sub>a3</sub> =  $9.21 \pm 0.01$ ) were derived from data obtained in the pH-range 2.0–11.5. These pK<sub>a</sub> values compare favourably with

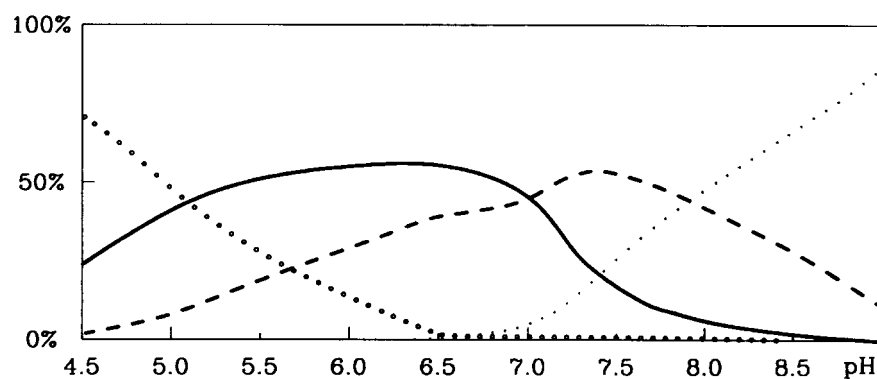
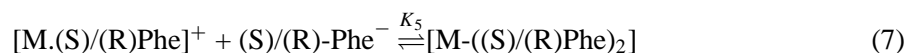
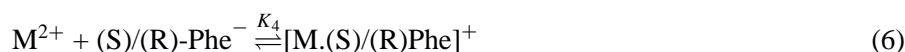
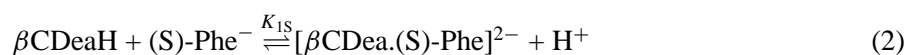
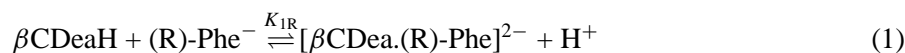


Figure 2. Percentage of  $\text{Cu}^{2+}$ -species in a solution containing 0.100 mL of  $9.93 \times 10^{-2} \text{ mol dm}^{-3} \text{ Cu}^{2+}$ , 10 mL of  $9.941 \times 10^{-4} \text{ mol dm}^{-3} \beta\text{CDeaH}_2^+$  and  $1.010 \times 10^{-3} \text{ mol dm}^{-3} \text{ R-PheH}_2^+$ , plotted against pH and relative to  $[\text{Cu}^{2+}] = 100\%$ . (R)-PheH (•••),  $\text{Cu} \cdot [(\text{R})\text{-Phe}]^-$  (—),  $\text{Cu} \cdot [(\text{R})\text{-Phe}]_2$  (- - -) and  $\text{Cu} \cdot \beta\text{CDea} \cdot (\text{R})\text{-Phe}$  (...).

literature values [19]. For  $\beta\text{CDeaH}_2^+$ ,  $\text{pK}_{a1} = 8.08 \pm 0.07$  and  $\text{pK}_{a2} = 10.69 \pm 0.05$  were derived from data obtained in the pH-range 5.0–8.5.

The constants determined for each system studied are defined here for the phenylalanine system. Similar definitions apply to the constants for the tryptophan and histidine systems.



Log  $K$  ( $K$  = stability constants) for ternary and binary metallo-complexes as defined above are listed in Table I. Table II contains log $K$  values for non-metallo

Table I. Stability constants  $\log(K/\text{dm}^3 \text{ mol}^{-1})^a$  for metallo-6<sup>A</sup>-deoxy-6<sup>A</sup>-hydroxyethylamino- $\beta$ -cyclodextrins and related complexes in aqueous solution at 25 °C and I = 0.10 (NaClO<sub>4</sub>).

log K	Co <sup>2+</sup>	Ni <sup>2+</sup>	Cu <sup>2+</sup>	Zn <sup>2+</sup>
<i>K</i> <sub>3</sub>	2.69 ± 0.05	3.72 ± 0.06 <sup>b</sup>	5.84 ± 0.04	3.41 ± 0.09
tryptophan				
<i>K</i> <sub>4</sub>	4.37 ± 0.01	5.78 ± 0.02	7.65 ± 0.03	5.26 ± 0.02
<i>K</i> <sub>5</sub>	3.57 ± 0.04	4.97 ± 0.07	7.67 ± 0.06	4.77 ± 0.06
<i>K</i> <sub>6R</sub>	6.14 ± 0.02	7.02 ± 0.02 <sup>b</sup>	8.43 ± 0.04	7.20 ± 0.07
<i>K</i> <sub>6S</sub>	6.39 ± 0.06	7.75 ± 0.07 <sup>b</sup>	8.68 ± 0.06	7.20 ± 0.03
phenylalanine				
<i>K</i> <sub>4</sub>	4.42 ± 0.03	5.19 ± 0.01	7.80 ± 0.02	4.39 ± 0.02
<i>K</i> <sub>5</sub>	3.44 ± 0.05	4.39 ± 0.06	6.92 ± 0.05	4.02 ± 0.04
<i>K</i> <sub>6R</sub>	5.85 ± 0.03	5.95 ± 0.02 <sup>b</sup>	7.87 ± 0.06	6.10 ± 0.06
<i>K</i> <sub>6S</sub>	5.53 ± 0.05	6.58 ± 0.03 <sup>b</sup>	7.75 ± 0.07	6.10 ± 0.05
histidine				
<i>K</i> <sub>4</sub>	6.96 ± 0.06	8.54 ± 0.07	10.45 ± 0.05	
<i>K</i> <sub>5</sub>	5.42 ± 0.11	6.90 ± 0.12	8.71 ± 0.10	
<i>K</i> <sub>6R</sub>	6.55 ± 0.04	7.49 ± 0.04 <sup>b</sup>	8.91 ± 0.05	
<i>K</i> <sub>6S</sub>	6.72 ± 0.05	8.01 ± 0.04 <sup>b</sup>	8.98 ± 0.03	

<sup>a</sup> Errors quoted for K (means of N runs) represent the standard deviation.

<sup>b</sup> At 45 °C.

binary systems and suggests that the level of enantioselectivity achieved in these systems ranges from very poor in the case of  $\beta$ CD to fair for  $\beta$ CDea. Table III shows the enantioselectivity for the ternary systems as derived from Table I.

## 4. Discussion

### 4.1. ENANTIOSELECTIVITY IN BINARY NON-METALLO SYSTEMS

For the complexation of the amino acids by  $\beta$ CDea (Table IIb) (Equations 1 and 2),  $\log(K_{1R}/\text{dm}^3 \text{ mol}^{-1}) = 4.82 \pm 0.04$ ,  $3.91 \pm 0.04$  and  $3.72 \pm 0.04$  and  $\log(K_{1S}/\text{dm}^3 \text{ mol}^{-1}) = 4.81 \pm 0.05$ ,  $4.17 \pm 0.03$  and  $3.54 \pm 0.03$  were derived in the pH-range 8.5–11.5 for Trp<sup>-</sup>, Phe<sup>-</sup> and His<sup>-</sup> respectively.

The order of complexation with  $\beta$ CDea, i.e., Trp<sup>-</sup> > Phe<sup>-</sup> > His<sup>-</sup> is in accordance with expectations based on the hydrophobic interactions alone. The increased stability of these complexes over those of corresponding native  $\beta$ CD complexes [3] (Table IIa) is surprising. The repulsion between the negative charges could possibly be minimised by having the amino acid approach the CD from the secondary side. Derivatisation of CD extends the hydrophobicity of the cavity and this may con-

Table II. Enantioselectivity in binary non-metallo systems.

	$\beta$ CD			$\beta$ CDea		
	Trp <sup>-</sup>	Phe <sup>-</sup>	His <sup>-</sup>	Trp <sup>-</sup>	Phe <sup>-</sup>	His <sup>-</sup>
log $K_R$	2.33	2.91	–	4.82	3.91	3.72
log $K_S$	2.33	2.83	–	4.81	4.17	3.54
select*	0.00	0.08 (R)	–	0.01 (R)	0.26 (S)	0.18 (R)

\* The isomer for which the  $\beta$ CD or  $\beta$ CDea is enantioselective is given in parentheses.

tribute to the higher stability. Some enantioselectivity is indicated for the  $\beta$ CDea systems, with the exception of Trp<sup>-</sup> (Table IIb). This may suggest that in the latter case the hydrophobic effect is the most important factor in stabilising the complex. Native  $\beta$ CD shows no enantioselectivity.

#### 4.2. FORMATION OF BINARY METALLO-COMPLEXES

There is ample evidence in the literature for the structures of metal ion complexes with ethanolamine [20–26]. In light of this and also on the basis of AA studies (5.56% Cu<sup>2+</sup>, 1:1 ratio  $\beta$ CDea:Cu<sup>2+</sup>) and full elemental analysis (Anal. Calcd: Cu<sup>2+</sup>.4.72, C.39.21, H.6.31, O.48.72, N.1.04; found: Cu<sup>2+</sup>.5.02, C.38.84, H.6.14, N.1.28) carried out on the amorphous blue solid isolated from the binary system Cu<sup>2+</sup>: $\beta$ CDea at pH = 9.5, several structures were proposed for the Cu<sup>2+</sup>- $\beta$ CDea complex. SUPERQUAD results allowed the authors to favour the structure shown in Figure 3, i.e., a binuclear hydroxy-bridged structure with  $\beta$ CDea<sup>-</sup> moieties acting as bidentate ligands to the metal ion centres. The magnetic moment ( $\mu = 1.08$  BM/metal ion) determined at room temperature on the blue powder suggests anti-ferromagnetism and lends support to the presence of a binuclear hydroxy-bridged structure which facilitates magnetic coupling via a superexchange mechanism [27]. Complexes with a similar bridging system have been shown to change colour from blue to green when exposed to air [28]. This colour change is also observed for the Cu(II)- $\beta$ CDea complex providing further support for the proposed structure. Similar models also satisfied the requirements of the SUPERQUAD program for the remainder of the metal ions to the exclusion of other possible models.

The formation of the metallo- $\beta$ CDea complexes (Equation 5) has been characterised by  $\log(K_3/\text{dm}^3 \text{ mol}^{-1}) = 2.69 \pm 0.05$ ,  $3.72 \pm 0.06$ ,  $5.84 \pm 0.04$ , and  $3.41 \pm 0.09$  for Co<sup>2+</sup>, Ni<sup>2+</sup>, Cu<sup>2+</sup> and Zn<sup>2+</sup> respectively (Table I). Stability variation for the binary metallo-cyclodextrins with the nature of M<sup>2+</sup> is as anticipated from the Irving–Williams sequence (Co<sup>2+</sup> < Ni<sup>2+</sup> < Cu<sup>2+</sup> > Zn<sup>2+</sup>) [29] which arises through a combination of the variation of M<sup>2+</sup> size and ligand field effects. In the case of Ni<sup>2+</sup>, the stability constants were determined at 45 °C as interference from metal hydroxide precipitation occurred at 25 °C.

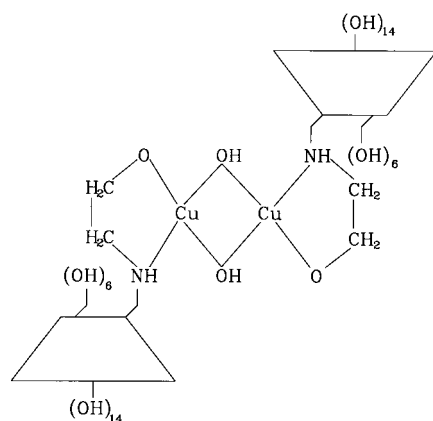


Figure 3. Proposed structure for the complex of  $\beta$ CDea with  $\text{Cu}^{2+}$ .

It is interesting to note the higher stability of the binary metallo- $\beta$ CDea complexes over the corresponding  $\text{M}(\text{ea})$  complexes [20]. The amino function in  $\beta$ CDea ( $\text{pK}_a = 8.08$ ) (Section 3) is certainly less basic towards protonation than that in  $\text{ea}$  ( $\text{pK}_a = 9.50$ ) [30]. This is accounted for in terms of the close proximity of the hydrophobic cavity inhibiting solvation of the protonated species. The increased stability of the  $\text{M}-\beta$ CDea complex may be a function of the proposed binuclear bridged system rather than of the donor ability of the amino function.

The stability constants determined for the metallo-amino acid complexes (Equations 6 and 7) (Table I) are in reasonable agreement with those in the literature [19], and also exhibit variations anticipated from the Irving–Williams series [29]. The stability constants  $K_4$  and  $K_5$  were derived from data obtained in the pH-range 6.5–8.5, 5.5–8.0, 4.0–7.0 and 5.5–7.5 when  $\text{M}^{2+} = \text{Co}^{2+}$ ,  $\text{Ni}^{2+}$ ,  $\text{Cu}^{2+}$  and  $\text{Zn}^{2+}$  respectively. In all these systems,  $K_4 > K_5$  as anticipated for sequential binding of ligands. No enantioselectivity was observed with these binary metallo systems.

#### 4.3. ENANTIOSELECTIVITY IN TERNARY SYSTEMS

The stability constants (Equations 8 and 9) in Table I for the ternary complexes show that the complexes formed with  $\text{Cu}^{2+}$  are the most stable, whereas complexes formed with  $\text{Ni}^{2+}$  are the most enantioselective (Table III). Due to the precipitation of metal hydroxide at 25 °C in the case of  $\text{Ni}^{2+}$ , the experiments were carried out at 45 °C. The stability constants for the ternary complexes are derived from data obtained in the pH-ranges 7.5–8.5, 7.5–9.5, 6.0–10.0 and 6.7–7.5 when  $\text{M}^{2+} = \text{Co}^{2+}$ ,  $\text{Ni}^{2+}$ ,  $\text{Cu}^{2+}$  and  $\text{Zn}^{2+}$  respectively.

The stabilities of the ternary complexes are greater than those of the analogous metal-amino acid and  $\beta$ CDea-amino acid complexes. This is consistent with the proposal that the binding of the carboxylic acid moiety of the amino acid by  $\text{M}^{2+}$  and the hydrophobic interaction between the aromatic moiety and the interior of the



Table III. Enantioselectivity in ternary metallo-systems.

	Co <sup>2+</sup>	Ni <sup>2+</sup>	Cu <sup>2+</sup>	Zn <sup>2+</sup>
Tryptophan	0.25 (S)	0.73 (S)	0.25 (S)	0.00
Phenylalanine	0.32 (R)	0.63 (S)	0.12 (R)	0.00
Histidine	0.28 (S)	0.52 (S)	0.07 (S)	

Enantioselectivity\* =  $|\log K_R - \log K_S|$ .

\* The isomer for which enantioselectivity is observed is shown in parentheses.

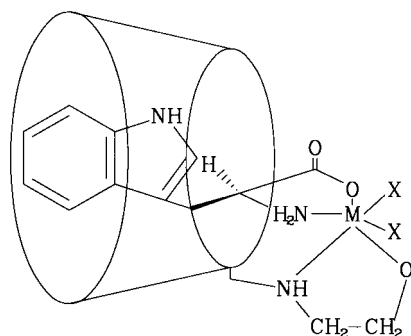


Figure 4. Typical structure proposed for the ternary complex between the metal M,  $\beta$ CD and amino acid ( $X_{1,2} = \text{OH}^-$  or  $\text{H}_2\text{O}$ ) [2–3].

cyclodextrin annulus reinforce each other to stabilise the ternary complex. Previous work by Lincoln *et al.* [2–3], however, did not show reinforcement of these two interactions except in the case of  $\text{Zn}^{2+}$ .

On the basis of NMR [5] and thermodynamic [6] evidence structures were proposed for ternary complexes of histamine monofunctionalised Cu(II) complexes with amino acids having a cis arrangement of the amino groups of the histamine moiety and the amino acid. This results in the aromatic moiety of the acid achieving inclusion in the preferred enantiomer only. This was supported by the reported crystal structure [7] of histamine monofunctionalised Cu(II)-L-Trp complex showing the aromatic moiety of the acid ligand outside the CD cavity. For the preferred enantiomer the structure proposed is that shown in Figure 4 [2–4]. The aromatic moiety of the amino acid resides in the cyclodextrin annulus, with the amino acid chiral centre in the vicinity of the primary hydroxyl groups of the cyclodextrin and the amine and carboxylate groups coordinated to  $\text{M}^{2+}$ . The ethanolamine moiety of  $\beta$ CD is also coordinated to  $\text{M}^{2+}$ . The variation of stability with the nature of  $\text{M}^{2+}$  coincides with the variation of the ionic radii of six-coordinate  $\text{Co}^{2+}$ ,  $\text{Ni}^{2+}$ ,  $\text{Cu}^{2+}$  and  $\text{Zn}^{2+}$  [29].

However, stability and enantioselectivity do not go hand in hand. As mentioned earlier, complexes with  $\text{Ni}^{2+}$  are the most enantioselective (Table III), in all cases showing greater selectivity for the S-isomer over the R-isomer. The selectivity

varies from three-fold for histidine to more than five-fold for tryptophan. The  $\text{Co}^{2+}$  and  $\text{Cu}^{2+}$  analogues show a significant, but lesser degree of selectivity. Enantioselectivity varies with the geometric constraints arising from ligand field effects in  $\text{Co}^{2+}$ ,  $\text{Cu}^{2+}$  and  $\text{Ni}^{2+}$ , and the lack of such constraints in  $d^{10} \text{Zn}^{2+}$ . It is difficult to explain why Ni(II)-complexes are the most selective. It may be simply a function of the ionic size and steric constraints. The colour (blue-green) suggests an octahedral field with solvent molecules occupying the vacant sites. However, colour is not a very reliable criterion of structure. Indeed an equilibrium between octahedral and square planar arrangement may be present. The smaller enantioselectivity observed in the more stable complexes demonstrates that increasing complex stability does not necessarily induce a corresponding increase in enantioselectivity.

Finally, the presence of a metal ion can either reinforce or reverse the enantioselectivity. In the case of the  $\text{Cu}^{2+}$  and  $\text{Co}^{2+}$  complexes, the presence of the metal ion reverses the selectivity order of the corresponding non-metallo complex. With  $\text{Ni}^{2+}$ , enantioselectivity is always towards the (S)-isomer. This suggests that in the case of the  $\text{Co}^{2+}$  and  $\text{Cu}^{2+}$  complexes the nature of the metal ion centre is predominant in determining selectivity, whereas for  $\text{Ni}^{2+}$  complexes the nature of the amino acid is also important.

## 5. Conclusion

While the relative stabilities of the binary metallo- $\beta$ CD<sub>ea</sub> complexes vary with  $\text{M}^{2+}$  in the sequence  $\text{Co}^{2+} < \text{Ni}^{2+} < \text{Cu}^{2+} > \text{Zn}^{2+}$  and are dominated by the nature of the metal ion, the subsequent binding of an amino acid is greatly influenced by its interaction with the cyclodextrin annulus. Thus the combined effects of  $\beta$ CD<sub>ea</sub> and metal ion produce a greater binding of the amino acid in the ternary complex (which also varies in the same metal sequence) than that in either the metallo-amino acid or  $\beta$ CD<sub>ea</sub>-amino acid complexes. The most stable complexes are not necessarily the most enantioselective. Enantioselectivity also varies with the nature of the metal and the geometric constraints due to ligand field effects. It is intended to further investigate the various influences of metal ion coordination, hydrogen bonding, cavity size and amino acid structure on the enantioselectivity demonstrated in these ternary complexes.

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