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Anion recognition by dimetallic cryptates

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Contents

Abstract

Bis-tren cryptands (i.e. octamine cages consisting of two tripodal tetramine subunits covalently linked by given spacers) are able to incorporate first two metal ions, then an ambidentate anion, according to a *cascade* mechanism. In particular, dicopper(II) cryptates behave as effective receptors for anions, which fill the empty cavity of the cage and place their donor atoms in the two axial sites left available by each Cu(II) centre (which adopts a trigonal bipyramidal stereochemistry). Anion encapsulation by dicopper(II) cryptates often induces the development of a rather intense anion-to-metal charge transfer absorption band in the visible region, so that the recognition process is signalled by the appearance of a bright colour. Two examples are considered in detail: (i) that of a *rigid* bis-tren cryptate containing 1,3-xylyl spacers, which does not recognise the shape, but the bite of the polyatomic anion (i.e. the distance between two consecutive donor atoms); and (ii) that of the *flexible* cryptate

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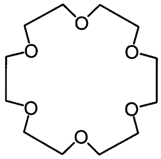
containing 2,5-furanyl spacers, which is able to include also monoatomic anions, in particular halides, displaying peak selectivity in favour of Cl^-.

Keywords: Anion recognition; Dimetallic cryptates; Copper(II) complexes; Cages; Inclusion complexes

1. Introduction

Given a molecular substrate (either neutral or electrically charged), its receptor, i.e. a system capable of establishing selective interactions, can be designed by taking into account three basic parameters: shape, size and energy. In particular, the receptor should provide a concave portion of space (the cavity), whose *shape* is complementary with that of the substrate. Moreover, the *size* of the cavity should be comparable with that of the substrate, so that the receptor framework does not have to undergo any endoergonic rearrangement (either expansion or contraction) in order to conform with the required bond distances. Finally, the *energy* of the receptor substrate interaction has to be high enough to be able to more than compensate the endoergonic terms related to desolvation (both of the receptor and of the substrate). The latter issue is especially significant for the recognition of ionic analytes in an aqueous medium [1].



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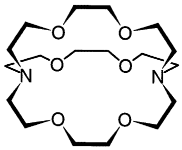

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Alkali metal ions were probably the first substrates systematically investigated for the design of a suitable selective receptor. Such studies could be carried out after the discovery by Pedersen that s block metals can form solution stable complexes with cyclic polyethers (e.g. **1**), named ‘crowns’ in view of their shape [2]. Complexation originates from the interaction of the metal centre with a rich set of ethereal oxygen atoms (mainly electrostatic in nature) and profits from the fact that the ligand, which is almost completely preoriented for coordination, does not have to lose any conformational energy when wrapping around the metal centre (this endothermic contribution is typically provided by non-cyclic multidentate ligands). Conformational energy saving and consequent metal complex solution stability are enhanced when using polycyclic ligands like **2** (cryptands), essentially owing to the increased rigidity of the molecular framework [3]. Donor atoms of **2** are the same as **1** (six ethereal oxygen atoms), whereas the two tertiary nitrogen atoms are not involved in metal binding and play only an architectural role.

The peak diagram in Fig. 1, in which the log *K* of the complexation equilibrium of a current alkali metal ion by cryptand **2** is plotted versus the radius of the cation, illustrates well the concept of selective recognition [4]. The receptor offers a spheroidal cavity suitable for including spherical substrates like alkali metal ions. The very sharp peak selectivity, in favour of the K^+ ion, is determined by size. In particular, the K^+ ion fits well cryptand cavity of **2**, and does not induce any endothermic rearrangement of the ligand framework, as smaller (i.e. Na^+, Li^+) and larger cations (i.e. Rb^+, Cs^+) do. Metal–ligand interaction is energetic enough to allow the complexation to take place in a mixture of polar solvents (MeOH/H_2O 95:5 v/v). However, the use of a more solvating medium (pure water) drastically reduces the solution stability of the complex: in particular, in the case of K^+, log *K* decreases from 9.45 to 5.4.

A rather similar approach has been followed to design receptors for inorganic anions. In this case, the chosen cavity has to be equipped with positively charged groups, in order to establish electrostatic interactions with the substrate. This goal can be achieved by using cryptand-like molecules in which ethereal oxygen atoms are replaced by secondary amine groups, e.g. **3**, L (see Fig. 2). At a controlled pH, the six secondary amine groups are all protonated and the LH_6^{6+} cation is able to include an anion and to establish with it electrostatic interactions. In particular, LH_6^{6+} provides a spheroidal cavity, whose size matches well with the radius of the F^- anion, which is therefore selectively encapsulated in the presence of other competing anions, in a moderately acidic aqueous solution [5]. The octamine **3** is the prototype of a family of all nitrogen cryptands which consist of two tripodal

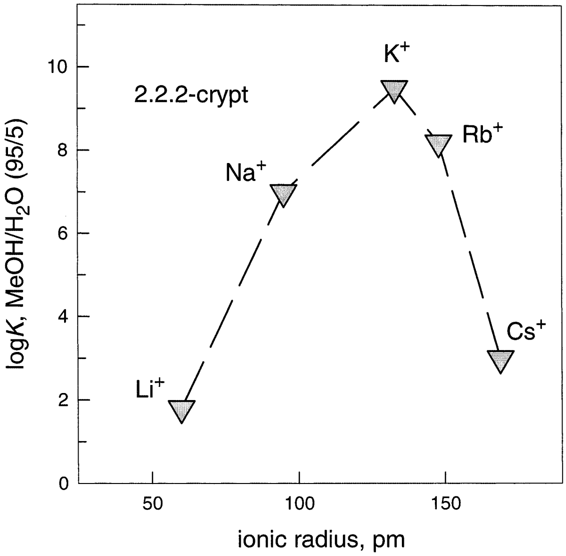
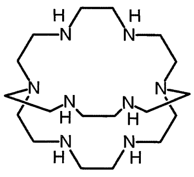


Fig. 1. Selective complexation of alkali metal ions by the 2.2.2-cryptand in a methanol/water solution (95:5). Peak selectivity is observed for the K^+ ion, whose size fits well the spheroidal cavity offered by the ligand (data from Ref. [4]).



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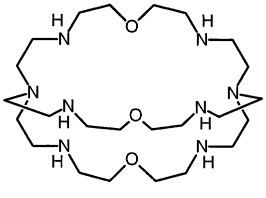

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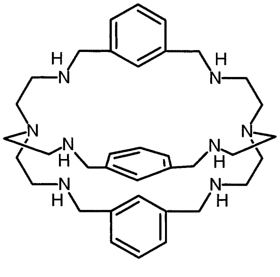

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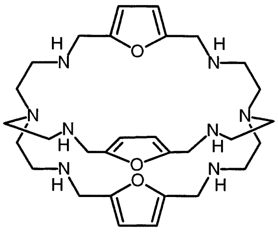

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Fig. 2. Bis-tren cryptands. Each octamine system consists of two tripodal tetramine subunits covalently linked by a given spacer. Bis-tren cryptands (L) can act as receptors for anions in two different ways: (i) in the LH_6^{6+} form (the six secondary amine groups are protonated), providing electrostatic interactions with the included anion; and (ii) in the form of a $[M(II)_2(L)]^{4+}$ homodimetallic complex: each metal centre M(II) occupies a tren cavity and leaves a coordination site available for the donor atom of an ambidentate anion.

tetramine subunits (called tren), linked by given spacers: $-CH_2CH_2-$ fragments in the case of **3**. Size and shape of the cavity of a bis-tren cryptand can be modulated by changing the spacers: in particular, the bis-tren cryptand **4** provides an ellipsoidal cavity, and, in its hexaprotonated form, is able to include the rod-like triatomic anion N_3^- [6].

However, there exists another type of interaction one can profit from for anion recognition purposes: the metal–ligand interaction. In fact, anions may exhibit definite coordinating tendencies towards metal ions, especially those belonging to the d block. In particular, metal complexes possessing one (or more) vacant binding site(s) can act as receptors for anions displaying coordinating properties. An example is illustrated by the copper(II) complex with a derivative of the tren tetramine. Tren tends to impose a trigonal bipyramidal stereochemistry, so that the metal presents a vacant axial position, available for the coordination of either a solvent molecule or an anion. In the complex shown in Fig. 3, the axial position is occupied by the nitrogen atom of the azide anion, N_3^- [7]. The structure illustrates well a unique feature of recognition based on metal–ligand interactions: *directionality*. As a matter of fact, the rod-like anion adopts a 'bent' coordination mode, making a Cu–N–N angle of 127°. The angle reflects the sp^2 nature of the terminal nitrogen atom(s), which points a filled hybrid orbital towards the metal centre.

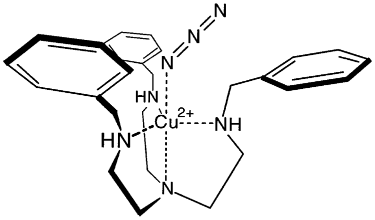


Fig. 3. Directionality of metal–ligand interactions. The Cu(II) centre is bound to a tren platform and leaves a coordination site available for an incoming anion. The azide ion is bent (Cu–N–N angle: 127°), as the terminal nitrogen atom of N_3^- is formally sp^2 hybridised.

Moreover, the energy of the metal–ligand interaction is relatively high, much higher, in most cases, than the energy associated to electrostatic interactions: this provides a further advantage for recognition purposes, as the endoergonic effect associated to the desolvation of both anion and receptor can be abundantly compensated and the interaction with the substrate can take place in polar media, in primis water.

2. Anion encapsulation by dicopper(II) cryptates

Bis-tren cryptands can be conveniently used for making anion receptors operating through the metal–ligand interaction. In fact, each tren subunit can coordinate, according to a trigonal bipyramidal mode, a Cu(II) centre, which leaves one axial position available for anion binding. Thus, there exists the opportunity for the inclusion within the cavity of an anion that possesses two distinct donor atoms (an *ambidentate* anion): these atoms will fill the two vacant binding sites available on the metal centres. The anion can also be monoatomic: in this case, it will bridge the two metal ions by establishing coordinative interactions with two distinct lone pairs.

The *cascade* mechanism by which the bis-tren cryptand sequentially includes first two equivalent metal centres, then an ambidentate anion, is illustrated in Fig. 4.

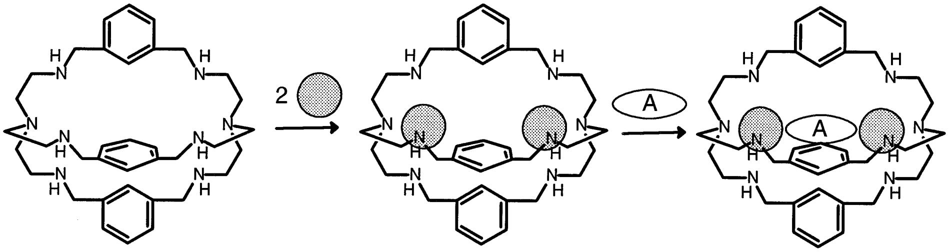


Fig. 4. A cascade mechanism for the inclusion of an anion within a homodimetallic bis-tren complex. Each metal centre wants to be five-coordinated (according to a trigonal bipyramidal stereochemistry) and leaves one of its axial position available for the donor atom of an ambidentate anion.

Again, selectivity is expected to be associated to shape, size and energy. Shape and size of the cavity within the dimetallic cryptate complex can be modulated by varying the nature (length, rigidity) of the spacers which covalently connect the two tren subunits. The energy of the anion–receptor interaction is expected to be especially high, as it results from the sum of two distinct metal–ligand interactions.

A number of dicopper(II) bis-tren cryptates encapsulating a variety of polyatomic inorganic anions have been isolated in the crystalline form and structurally characterised. First reported examples includes the dicopper complexes of **5** (spacer: 1,3-xylyl), which encapsulate: (i) the rod-like triatomic anions N_3^- and NCO^- [8] and (ii) the triangular HCO_3^- anion [9]. The structure of the inclusion complex of the azide ion is sketched in Fig. 5.

In all the dimetallic complexes, each Cu(II) centre exhibits a regular bipyramidal trigonal stereochemistry, in which five-coordination is completed by one of the donor atoms of the encapsulated ambidentate anion, which goes to occupy the vacant axial position. Quite interestingly, in the azide complex, the N_3^- anion is co-linearly bound to the two metal centres. In any case, azide coordinative arrangement is completely different from that observed with the 'half-cage' complex illustrated in Fig. 3, in which the N_3^- ion, in absence of any steric constraint, is bound to the {Cu(II)–tren} platform according to its 'natural mode', i.e. 'bent'. In view of a heavy steric effect, the bis-tren cryptate imposes its merciless rule and forces the N_3^- anion to stay (almost) co-linear. It will be shown in Section 2.1 that this unnatural situation does not disfavour at all the formation of the inclusion complex in solution and that, apparently, the N_3^- ion is particularly happy of being co-linear, in a thermodynamic sense.

2.1. Anion recognition by a 'rigid' bis-tren dicopper(II) cryptate

Anion recognition must be preceded by an investigation of the behaviour of the $[Cu(II)(bis\text{-}tren)]^{4+}$ complex in aqueous solution, over a substantial range of pH. These studies are typically performed by carrying out potentiometric titration experiments on a solution containing the cryptand, 2 equiv. of Cu(II), excess acid,

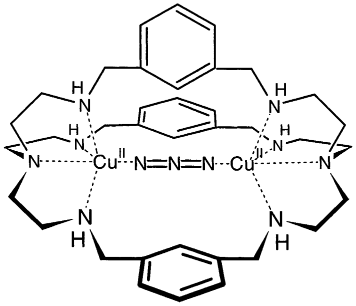


Fig. 5. Inclusion of the rod-like N_3^- anion by the dicopper(II) complex of the bis-tren cryptand **5**, which provides an ellipsoidal cavity (crystal structure in Ref. [8]).

and using a standard NaOH solution as a titrant. Curve fitting of the titration profile (pH versus volume of titrating solution), carried out with a nonlinear least-squares procedure [10], gives the constants of the species present at the equilibrium and allows drawing their distribution diagram over the investigated range of pH. This is an important preliminary step, as it makes it possible to choose the dimetallic complex suitable for anion inclusion: in particular, the pH must be adjusted to the value at which the chosen complex is present as a major species (possibly at 100%).

In the case of the Cu(II)–**5** system, the $[Cu(II)_2(\mathbf{5})OH]^{3+}$ complex is present at 100% at pH ≥ 7. It is believed that in this complex the two available axial positions are occupied by a hydroxide ion on one metal centre and by a water molecule on the other. In any case, both OH^- and H_2O are not firmly bound to the Cu(II) centres and can be easily replaced by an ambidentate anion [11].

For instance a pale blue aqueous solution containing **5**, 2 equiv. of Cu(II) and buffered to pH 8 (in which the $[Cu(II)_2(\mathbf{5})OH]^{3+}$ complex species is present at 100%), when titrated with a standard solution of NaN_3, takes a bright green colour, while a relatively intense absorption band develops at $\lambda = 400$ nm (see the family of spectra recorded during the spectrophotometric titration in Fig. 6). The absorbance at $\lambda = 400$ nm versus equiv. of N_3^- (see inset in Fig. 6) is consistent with the formation of an 1:1 adduct, thus indicating that one N_3^- anion is encapsulated by the dicopper(II) cryptate, to give the $[Cu(II)_2(\mathbf{5})N_3]^{3+}$ inclusion complex, whose structure had been defined through X-ray diffraction studies on the isolated

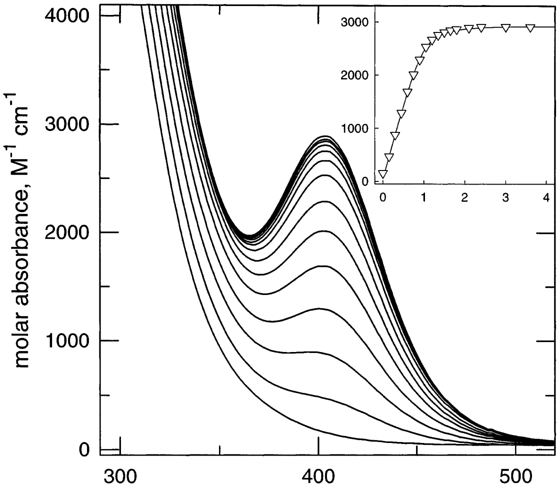


Fig. 6. Titration of an aqueous solution, adjusted to pH 8, of the $[Cu(II)_2(\mathbf{5})]^{4+}$ receptor with a standard solution of N_3^-. The development of the LMCT absorption band at 400 nm and the appearance of a bright-green colour indicate azide inclusion. The titration profile in the inset (molar absorbance versus equiv. of N_3^-) demonstrates the formation of a 1:1 adduct and gives a log *K* value for the inclusion equilibrium of 4.78.

crystalline complex (see the sketch in Fig. 5). Thus, the rather intense absorption band centred at 400 nm (molar extinction coefficient $\varepsilon = 2910\ M^{-1}\ cm^{-1}$) can be assigned to a nitrogen (azide)-to-copper(II) charge transfer (CT) transition. The constant for the inclusion equilibrium: $[Cu(II)_2(\mathbf{5})OH]^{3+} + N_3^- = ([Cu(II)_2(\mathbf{5})N_3] + OH^-$, at pH 8, was calculated through nonlinear least-squares analysis of the titration profile (inset in Fig. 6): $\log K = 4.78 \pm 0.05$.

Analogous titration experiments were carried out with a variety of ambidentate polyatomic anions: in any case, the colour of the solution changed from pale blue to intense blue or green, and a new band or a distinct shoulder developed during the titration. Absorbance versus equiv. of X^- anion profiles indicated in all cases the formation of a 1:1 inclusion complex, $[Cu(II)_2(\mathbf{5})X]^{3+}$, and the corresponding equilibrium constant (at pH 8) are reported in Table 1.

The interpretation of the different stability of the varying anion inclusion complexes is not straightforward: for instance, values reported in Table 1 indicate that the rod-like anions N_3^- and NCO^- display the highest inclusion affinity, an expected behaviour in view of the complementarity of the shape of the anion with the ellipsoidal cavity offered by the dicopper(II) cryptate. However, the NCS^- ion, which has the same shape as N_3^- and NCO^-, shows an inclusion constant remarkably lower. Scarce relevance of anion shape is also demonstrated by the high affinity displayed by HCO_3^-, whose triangular shape is not expected to fit especially well the cryptate cavity (but the other triangular NO_3^- ion shows one of the lowest encapsulation constants). Moreover, in spite of the fact that the inclusion equilibrium involves reactants of opposite electrical charges, the charge of the anion does not seem to have any effect: in particular, the doubly negative SO_4^{2-} ion shows

Table 1
The log K values for the anion inclusion equilibrium: $[Cu(II)_2(\mathbf{5})OH]^{3+} + X^- = [Cu(II)_2(\mathbf{5})X]^{3+} + OH^-$, in an aqueous solution buffered at pH 8.0,[a] at 25°C

Anion, X^-	log K[b]	λ[c] (nm)
N_3^-	4.78(0.05)	400[d] (3895)
NCO^-	4.60(0.05)	340[e] (4904)
NCS^-	2.95(0.05)	352[e] (2696)
SO_4^{2-}	3.26(0.08)	348[e] (2585)
$HCOO^-$	3.32(0.04)	330[e] (4523)
CH_3COO^-	2.97(0.05)	348[e] (3166)
HCO_3^-	4.56(0.04)	360[e] (3733)
NO_3^-	2.70(0.06)	348[e] (3483)

Spectral features of the $[Cu(II)_2(\mathbf{5})X]^{3+}$ anion inclusion complex are also shown.

[a] 0.1 M CF_3SO_3H/morpholine buffer.

[b] Uncertainties are twice the standard deviations obtained through the nonlinear least-squares treatment of spectrophotometric titration data.

[c] Wavelength at which absorbance values were taken for nonlinear least-squares treatment. In parenthesis, the calculated molar extinction coefficient of the $[Cu_2(\mathbf{5})X]^{3+}$ species.

[d] Maximum.

[e] Shoulder.

an inclusion affinity much lower of several mononegative anions, like N_3^-, NCO^- and HCO_3^-.

However, there exists another geometrical parameter, which allows complete rationalisation of the log K values of inclusion equilibria reported in Table 1: it is the 'anion bite length', i.e. the distance between two consecutive donor atoms of the anion. Bite lengths of NO_3^- and of N_3^- are indicated in Fig. 7. Notice that in the case of rod-like anions like N_3^- bite length is coincident with the length of the anion.

Notably, the plot of log K values of the anion inclusion equilibria versus anion bite length (see Fig. 8) discloses a nice peak selectivity profile, quite analogous to that shown in Fig. 1 for encapsulation of alkali metal ions by the hexa-oxa cryptand. The N_3^- ion discloses the highest inclusion affinity (top of the peak), because it has the right bite length to place its donor atoms (the external nitrogen atoms) in the vacant axial positions of the two Cu(II) centres, without inducing any endoergonic rearrangement of the cryptate framework. An anion of either larger

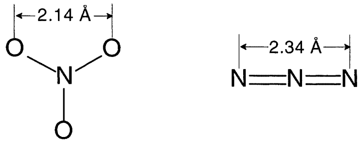


Fig. 7. The coordinative 'bite' of ambidentate anions (i.e. the distance between two consecutive donor atoms). For rod-like anions like N_3^- the bite coincides with ion length.

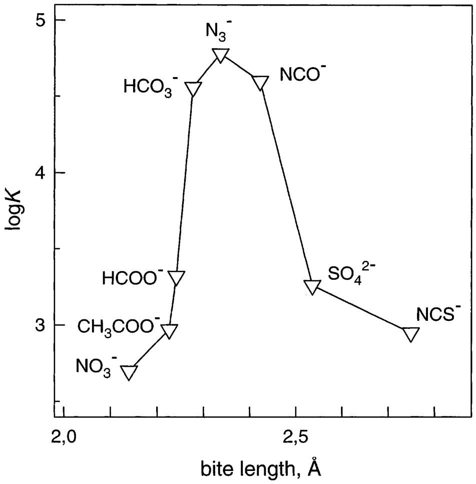


Fig. 8. Peak selectivity in the inclusion of polyatomic anions by the 'rigid' $[Cu(II)_2(\mathbf{5})]^{4+}$ cryptate. The dimetallic receptor does not recognise the shape of the anion, but its *bite*. The highest stability is observed for the inclusion of N_3^-, which is able to place its donor atoms in the vacant positions of the two Cu(II) centres, without inducing any serious endoergonic contraction or expansion of the cryptand framework, as anions of smaller (e.g. NO_3^-) or larger bite (e.g. NCS^-) do.

(i.e. NCS^-) or smaller bite length (e.g. NO_3^-) forces the cryptate to leave its relaxed conformation and to adjust the distance between the two Cu(II) centres at the required value: the more or less significant rearrangement of the cryptand framework (involving either expansion or contraction) is reflected in a concurrent decrease of the log K value. Thus, the $[Cu(II)_2(\mathbf{5})OH]^{3+}$ receptor neither recognises the shape of the anion nor its electrical charge: *it recognises its bite length*.

The sharp and definite selectivity displayed by the $[Cu(II)_2(\mathbf{5})OH]^{3+}$ system as an anion receptor can be related to the scarce deformability of the cage framework, which, in turn, may be associated to the rigidity of the 1,3-xylyl spacers joining the two tren subunits of cryptand **5**. As a consequence of its pronounced indeformability, the $[Cu(II)_2(\mathbf{5})]^{4+}$ cryptate, at any pH, is not able to include monoatomic anions like halides, which can act as ambidentate ligands, but are too small. As a matter of fact, addition of even a large amount of Cl^-, or other halide ions, to a solution of $[Cu(II)_2(\mathbf{5})]^{4+}$, at any pH, neither induces any colour change nor a modification of the absorption spectrum. Definitely, the $[Cu(II)_2(\mathbf{5})]^{4+}$ dimetallic receptor is made for including polyatomic anions, and not their smaller monoatomic counterparts.

2.2. Anion recognition by a 'flexible' bis-tren dicopper(II) cryptate

Among other bis-tren cryptands containing rigid spacers, we observed the singular behaviour of the dicopper(II) complex of **6**, in which the two tren compartments are linked by 2,5-dimethylfurane subunits. In particular, the $[Cu(II)_2(\mathbf{6})(OH)]^{3+}$ complex has been isolated and structurally characterised [12]: in this complex, an OH^- ion bridges the two metal centres, whose Cu(II)–Cu(II) distance is 3.87 Å, a value much smaller than observed with the $[Cu(II)_2(\mathbf{5})(N_3)]^{3+}$ complex (6.10 Å), and which, on the basis of thermodynamic data, can be considered the ideal Cu(II)–Cu(II) distance in the conformationally relaxed cryptate of **5**. This suggested that the cryptate containing furanyl spacers, $[Cu(II)_2(\mathbf{6})]^{4+}$, could be hopefully able to encapsulate monoatonic anions of comparable or higher size than OH^-, e.g. halides.

Fig. 9 shows the percent distribution of the species present at the equilibrium in the system Cu(II)–**6** (2:1 stoichiometric ratio), as investigated through potentiometric studies [13]. Two major dimetallic species are present in the 4–11 pH interval: a $[Cu(II)_2L]^{4+}$ complex in the 4–7 pH range (maximum concentration: 85%, at pH 5; indicated in the graph by 120 triad), and a $[Cu(II)_2L(OH)]^{3+}$ complex in the 6–11 pH range (maximum concentration: 97%, at pH 8, indicated by 12-1 triad). A solution adjusted to pH 8 (~ 100% of the $[Cu(II)_2L(OH)]^{3+}$ complex), emerald green in colour, displays similar spectral features to those observed for an MeCN solution of the crystalline $[Cu(II)_2L(OH)](ClO_4)_3$ complex salt, which had been structurally characterised. Moreover, the absorbance of the band pertinent to the emerald green colour, centred at 362 nm, superimposes well on the percent concentration profile of the $[Cu(II)_2L(OH)]^{3+}$ species (see filled triangles in Fig. 9). This further evidence suggests that also in the aqueous dicopper(II) cryptate the OH^- anion is included within the cavity. On the other hand, in the $[Cu(II)_2L]^{4+}$

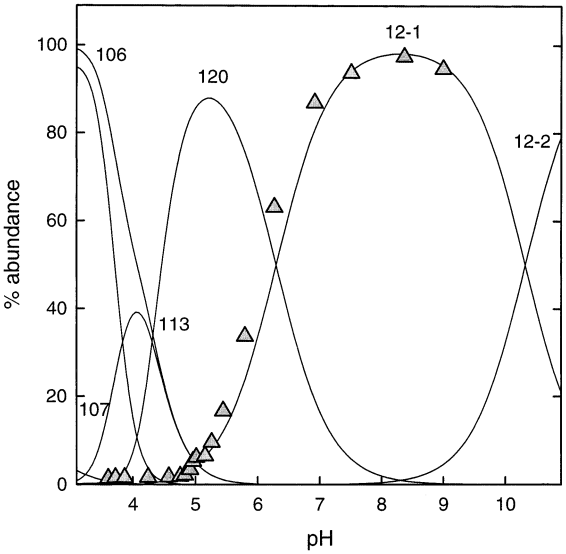


Fig. 9. Concentration (%) of the species present at the equilibrium for the system **6**–Cu(II) (ligand-to-metal ratio 1:2), in an aqueous solution 0.1 M in $NaClO_4$, at 25°: figures in the triads indicate the number of molecules of **6**, Cu^{2+} and H^+ contained in each species; thus, 12-1 symbolises the $[Cu(II)_2(\mathbf{6})(OH)]^{3+}$ complex. Filled triangles indicate the absorbance of the band centred at 362 nm (pertinent to the green $[Cu(II)_2(\mathbf{3})(OH)]^{3+}$ complex, arbitrary values; the limiting value of molar absorbance is 6500 $M^{-1}\,cm^{-1}$).

complex, in absence of coordinating anions, the intermetallic cavity is thought to be ‘empty’ or, more realistically, occupied either by water molecules or the anion of the supporting electrolyte, i.e. ClO_4^-.

Thus, it was considered that the $[Cu(II)_2L]^{4+}$ complex, with its ‘empty’ cavity, could behave as a receptor for anions. In this perspective, a solution buffered to pH 5.2 was titrated with a variety of anions. Unique effects were observed on titration with sodium halides. For instance, on addition of chloride, the pale blue solution of the $[Cu(II)_2L]^{4+}$ complex took a bright yellow colour, while a very intense band developed at 410 nm. Fig. 10 shows the family of spectra which developed in the course of the titration with chloride. The titration profile shown in the inset (absorbance at 410 nm vs. equiv. of Cl^-) indicated the formation of a 1:1 cryptate/chloride adduct, to which a log K value of 3.98 ± 0.02 corresponded. The limiting value of the molar extinction coefficient ($\varepsilon = 12\,600$ $M^{-1}\,cm^{-1}$) is unusually high. Similar behaviour was observed when the pale blue solution of the ‘empty cavity’ complex, $[Cu(II)_2L]^{4+}$, was titrated with standard bromide and iodide solutions: a bright yellow colour formed and an intense band developed above 400 nm (Br^-: $\lambda_{max} = 430$ nm, $\varepsilon = 10\,800$ $M^{-1}\,cm^{-1}$; I^-: $\lambda_{max} = 440$ nm, $\varepsilon = 950$ $M^{-1}\,cm^{-1}$). The log K values for the 1:1 cryptate/halide ion adduct were 3.01 ± 0.01 for bromide and 2.39 ± 0.02 for iodide.

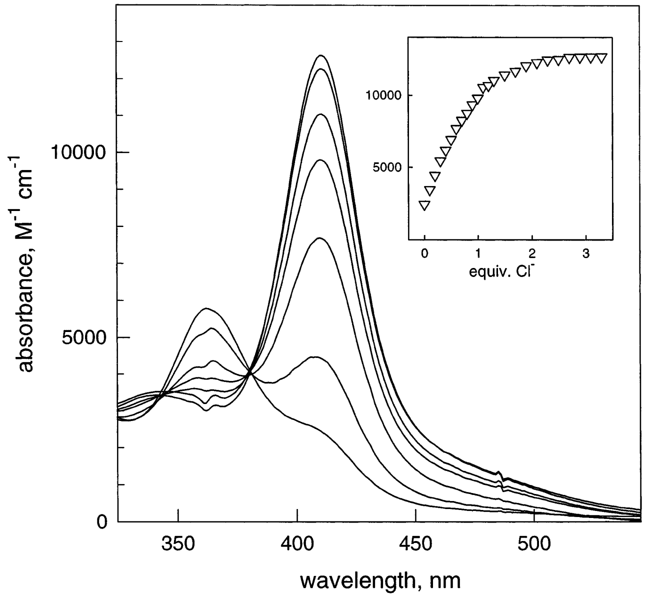


Fig. 10. Family of spectra obtained during the titration with Cl^- of a solution containing the $[Cu(II)_2(\mathbf{6})]^{4+}$ system, adjusted to pH 5.25. The increasing band centred at 410 nm corresponds to the formation of the $[Cu(II)_2(\mathbf{3})(Cl)]^{3+}$ complex, in which the halide ion is encapsulated in the cavity between the two metal centres. The titration profile in inset (molar absorbance versus equiv. of Cl^-) gave a $\log K$ value of 3.98 ± 0.02 for the inclusion equilibrium: $[Cu(II)_2(\mathbf{6})]^{4+} + Cl^- = [Cu(II)_2(\mathbf{6})(Cl)]^{3+}$.

Fortunately, on slow evaporation of the bromide containing solution, adjusted to pH 5.2, yellow crystals of the $[Cu(II)_2(\mathbf{6})(Br)](ClO_4)_3$ complex salt suitable for X-ray diffraction studies were obtained [13]. A schematic view of the crystal structure is illustrated in Fig. 11. The bromide anion is encapsulated within the cage and bridges the two metal centres. Each Cu(II) ion exhibits a trigonal bipyramidal stereochemistry. The metal-to-metal distance is 4.86 Å and the two Cu(II) centres and the halide ion are basically co-linear (Cu(1)–Br–Cu(2) angle: 179.4°). Thus, the

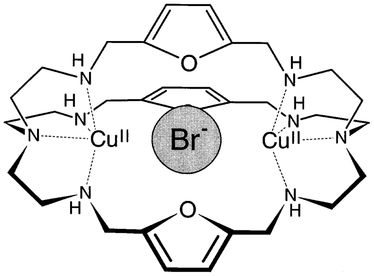


Fig. 11. Inclusion of the spherical bromide anion by the dicopper(II) complex of the bis-tren cryptand **6**, which provides a spheroidal cavity (crystal structure in Ref. [8]).

bright yellow colour and the intense absorption band at around 400 nm have to be ascribed to the inclusion of the halide ion within the dicopper(II) cryptate. The band has a halide-to-metal CT nature and its unusually high intensity (observed, in particular, for chloride and bromide inclusion complexes) can be, at least in part, ascribed to a probability effect, as the LMCT transition can take place in both equivalent directions.

It has to be noted that the yellow halide inclusion complexes do not exist over a large interval of pH: as an example, the absorbance at 410 nm measured for a solution 10^{-3} M in the dicopper(II) cryptate complex and 10^{-2} M in NaCl discloses a bell-shaped profile (open triangles in Fig. 8), which superimposes quite well on the distribution curve of the 'empty cavity' receptor, $[Cu(II)_2L]^{4+}$. Bell-shaped profiles centred at pH 5.2 were also observed in the case of bromide and iodide anions. It derives that, on a moderate pH increase, say from 5 to 8, the bright yellow solution turns emerald green, indicating that the halide ion is replaced by OH^-. Anion replacement is fast and reversible and the solution can be made to turn yellow and green repeatedly, by the consecutive addition of standard acid and base.

The first member of halides, F^-, represents a special case. In fact, titration with NaF of the solution containing the 'empty cavity' receptor, $[Cu(II)_2L]^{4+}$, did not induce any development of the yellow colour. However, it has to be considered that the absorption band responsible for the yellow colour possesses a halide-to-metal CT character, and that its energy must increase with the increasing electronegativity of the halogen atom. It derives that the CT transition for the $[Cu(II)_2(\mathbf{6})(F)]^{3+}$ complex, due to the high electronegativity of fluorine, is markedly shifted to lower wavelengths, in particular in the UV portion of the spectrum, where it is obscured by the intense amine-to-metal CT transitions. However, by monitoring the significant spectral modifications in the UV region, as observed in the titration with NaF of the cryptate solution buffered at pH 5.2, a saturation profile corresponding to a 1:1 inclusion stoichiometry was obtained: the corresponding $\log K$ value for the fluoride encapsulation equilibrium was 3.20 ± 0.02.

Thus, it was possible to draw the classical $\log K$ versus halide ion radius plot, shown in Fig. 12. Indeed, a defined selectivity pattern in favour of chloride is disclosed. However, the anion size effect is rather moderate, ranging within an interval of 1.2 log units (compare, for instance, to analogous $\log K$ versus radius plot determined for hexa-oxa-cryptand **2**/alkali metal ion systems, shown in Fig. 1, where the $\log K$ values range within a much larger interval, ca. 8 log units).

The unique feature of the $[Cu(II)_2(\mathbf{6})]^{4+}$ cryptate is the capability to accommodate anions of varying size and shape. As a matter of fact, not only does it tightly include hydroxide and halide ions, but it is also able to encapsulate linear triatomic anions like N_3^- and NCS^-, as shown by titration studies. In particular, when titrating a solution of the 'empty cavity' receptor, $[Cu(II)_2L]^{4+}$ (solution adjusted to pH 5.2) with a standard solution of NaN_3, the pale blue solution took an intense olive green colour: the plot of the absorbance of the band which developed at 386 nm versus equiv. of N_3^- indicated the formation of a 1:1 adduct with a $\log K = 4.70 \pm 0.06$. The development of a CT band ($\varepsilon = 6100$ M^{-1} cm^{-1}) as well as the 1:1

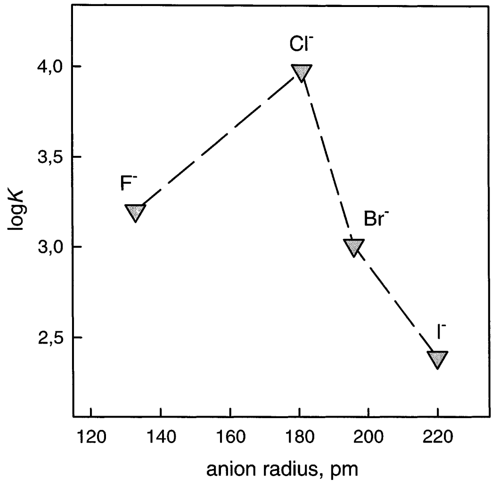


Fig. 12. Peak selectivity behaviour for the halide inclusion within the $[Cu(II)_2(\mathbf{6})]^{4+}$ cryptate. The log *K* values refer to the equilibrium: $[Cu(II)_2(\mathbf{6})]^{4+} + X^- = [Cu(II)_2(\mathbf{3})(X)]^{3+}$ (X^- = halide anion).

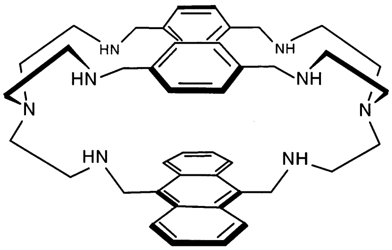
stoichiometry strongly suggest that the N_3^- ion is included within the cage. Similar behaviour was observed with NCS^- ($\log K = 4.28 \pm 0.03$). In conclusion, the $[Cu(II)_2L]^{4+}$ complex displays extreme versatility, being able to contract and to expand its cavity at will, in order to encapsulate anions of variable size and shape, from the small hydroxide to the large thiocyanate.

The plastic behaviour of the $[Cu(II)_2(\mathbf{6})]^{4+}$ complex seems to be associated to the special activity displayed by the 2,5-dimethylfurane spacers. A close inspection of the available crystallographic data indicates that the Cu(II)–Cu(II) distance in both $[Cu(II)_2(\mathbf{6})Br]^{3+}$ and $[Cu(II)_2(\mathbf{6})OH]^{3+}$ complexes can be varied at a low energy cost by adjusting at the proper value the torsion angles along the chain arms adjacent to the 2,5-dimethyl-furane spacers. In particular, each NH–CH_2–C–O group behaves as a spring, which controls the length of the intermetallic cavity and can be operated through the variation of the magnitude of the corresponding dihedral angle. Apparently, an analogous spring mechanism cannot be exhibited by the arms adjacent to the phenyl spacer in the $[Cu(II)_2(\mathbf{5})]^{4+}$ complex, which does not contract its cavity and does not include monoatomic anions.

It has to be noted that the terms ‘rigid’ and ‘flexible’, which have been attributed to the two octamine cages **5** and **6**, respectively, do not derive from a thorough structural analysis (prevented by the limited availability of X-ray diffraction data on crystalline complexes). Rather, the two terms refer to the ability of the corresponding cryptate complex to accommodate anions of a given bite (as derivatives of **5** do) or of varying size and atomicity (a special property exhibited by complexes of **6**).

3. A fluorescent cryptate for anion sensing

Zinc(II), like copper(II), is inclined to five-coordination. Thus, it could replace a copper(II) ion within a bis-tren cryptand, to generate another class of efficient receptors for donor anions. A drawback associated to the Zn(II) ion is that, in view of its $3d^{10}$ electronic configuration, it is irremediably colourless and its coordinatively unsaturated polyamine complexes cannot be utilised as anion receptors in spectrophotometric investigations (in particular, if looking for a colour change associated to either a d–d or an LMCT transition).



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However, the dizinc(II) complex of the bis-tren cryptand **7** has been successfully used as anion receptor in recognition studies carried out by using spectrofluorimetry rather than spectrophotometry as an investigating technique [14]. As a matter of fact, cryptand **7** contains as spacers two 1,4-xylyl fragments and one 9,10-anthracenyl subunit. Anthracene is a classical fluorophore and the anthracenyl has been intentionally inserted in the cryptand framework in order to operate as a fluorescent reporter. Any other pair of 3d metals could not be put within the cage, as a transition metal centre would quench the emission of the proximate fuorophore either through an electron transfer (eT) process or an electronic energy transfer (ET) process. The latter mechanism involves a double electron exchange between the excited fluorophore and some empty or half-filled d level of the metal (the so-called Dexter mechanism). Zn(II) has been deliberately chosen as: (i) being absolutely redox inactive, it cannot be engaged in any eT mechanism; and (ii) possessing a filled d level, it cannot participate to any ET process. In fact, the $[Zn(II)_2(\mathbf{7})]^{4+}$ system (and its hydroxide containing derivatives) displays the full fluorescent emission of anthracene. In particular, $[Zn(II)_2(\mathbf{7})]^{4+}$ is a fluorescent cryptate which can be conveniently used for sensing of polyatomic anion in aqueous solution.

Actually, like the dicopper(II) complex of the structurally similar cryptand **5**, the $[Zn(II)_2(\mathbf{7})]^{4+}$ system selectively includes N_3^- and NCO^- anions. N_3^- encapsulation is signalled by a drastic quenching of the anthracene emission, a phenomenon to be ascribed to the occurrence of an eT process from the electron rich anion to the facing anthracene fragment. The mechanism of signalling process is pictorially sketched in Fig. 13. NCO^- exhibits distinctly lower reducing tendencies than N_3^-,

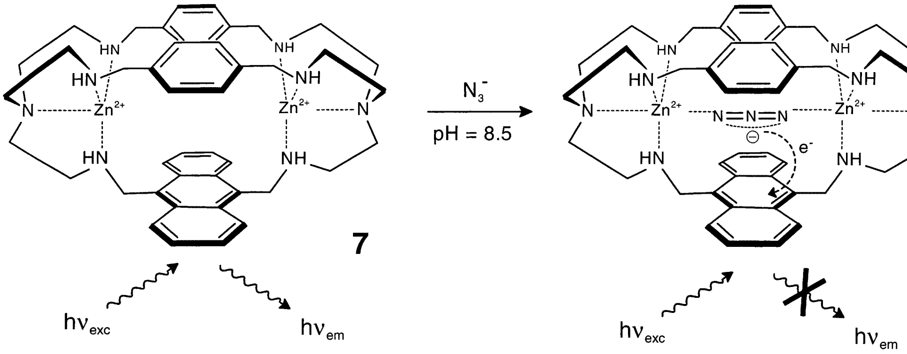

Fig. 13. Fluorescent sensing of the N_3^- anion by a dizinc(II) bis-tren cryptate. Azide encapsulation is signalled by the drastic quenching of the light emission by the anthracene fragment, which act both as a spacer and as a signalling unit. Quenching has to be associated to an electron transfer process from the electron rich N_3^- anion to the proximate excited fluorophore.

and, when included within the cryptate, does not disturb the radiative decay of the proximate fluorophore. Thus, the $[Zn(II)_2(\mathbf{7})]^{4+}$ system displays a selective behaviour both from the point of view of recognition (which is still based on anion bite length) and of signalling (recognition of N_3^- is communicated to the outside, that of NCO^- is not).

4. Conclusions

Dimetallic bis-tren cryptates represent a new and versatile class of receptors for anions both mono- and poly-atomic. In spite of the fact that the synthesis of bis-tren cryptands is simple and convenient (it involves the Schiff base condensation of two molecules of tren and three molecules of the spacer in form of its di-aldehyde, followed by hydrogenation of the C=N bonds with $NaBH_4$), the use of dimetallic cryptates for anion recognition studies in solution is rather limited. In practice, only two complete thermodynamic studies have been reported up to date and they have been described in Section 2.1 (bis-tren cryptand **5**) and 2.2 (bis-tren cryptand **6**). Changing the nature of the spacers (length, rigidity, presence of further heteroatoms) may impart novel selective affinity towards a variety of anions. In particular, varying spacer length, still keeping rigidity, may be of special interest for the recognition of dicarboxylates, e.g. of formula $^-OOC–(CH_2)_n–COO^-$ ($n =$ 0,1,2,3,...).

Copper(II) is certainly the privileged metal centre in view of its highest affinity for most ligands, among 3d metal ions, and for its natural tendency to five-coordination (trigonal bipyramidal in the present case). The latter property does not pertain, for instance, to the nickel(II) ion. As a matter of fact, the dinickel(II) cryptate of **5** includes the N_3^- anion. However, crystallographic investigation revealed that one of the Ni(II) centres exhibited the regular trigonal bipyramidal stereochemistry, but the other was octahedral, the sixth coordinative position being occupied by a water molecule [15]. The binding properties of a series of bis-tren cryptands, including **5** and **6**, towards transition metal ions from Co(II) to Zn(II) in aqueous solution have been recently investigated [16]. In any case, the formation of the most stable complex has been observed for the Cu(II) cation.

Acknowledgements

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