

## Transition metals as assembling and templating species: From catenanes and knots to organized multi-porphyrins arrays

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**Abstract.** New dicopper(I) knots have been synthesized as well as their face-to-face isomers. The knots range from 80 to 90-membered rings and their preparation yields depend crucially on structural parameters such as number of methylene fragments linking the two chelating units and length of the polyethyleneoxy unit used in the cyclization reaction. The best yield was obtained for an 84-membered knotted ring with a  $-(CH_2)_6-$  connector: this relatively long fragment allows pronounced winding of the double helix precursor and is thus favorable to the knotting reaction. The X-ray structures of two dicopper trefoil knots are also presented and discussed.

The transition metal-directed threading of a molecular fragment containing a central chelate and an end-attached gold(III) porphyrin into a presynthesized coordinating ring affords a general precursor to a rotaxane-type structures. After threading, construction of the second porphyrin acting as an efficient stopper affords a copper(I) complexed [2]-rotaxane as well as a novel compartmental [3]-rotaxane.

### Introduction

The *topology* of DNA is fascinating since it can form beautiful and complex catenanes (systems consisting of interlocking rings) and knots (single, closed but knotted curves) like the famous trefoil knot.

Using modern synthetic methodologies, consisting of gathering and orienting organic fragments around transition metals prior to incorporating them into cyclic molecules (the so-called "template effect"), many important topologies can be constructed with molecules. An example, which is not only related to DNA but also linked with mathematics and graphic art, is the *trefoil knot*, recently prepared at the molecular level. The making of topologically and geometrically non-trivial chemical objects, obviously represents a synthetic challenge, which is part of the motivation for their actual preparation. Porphyrin-stoppered rotaxanes represent a second family of highly functional compounds whose synthesis was made possible thanks to the same general principle of 3D-template synthesis.

### Synthesis of dicopper(I) trefoil knots and related unknotted molecular systems.

Although molecular knots were discussed in chemical literature more than three decades ago (1) it is only recently that the first chemical knot was synthesized (2,3). The use of transition metals as assembling and templating species turned out to be crucial in the development of preparative methods allowing to synthesize macroscopic amounts of catenanes and knots (4,5). A recent report describes the experimental procedure for making the original di-copper knotted 86-membered ring as well as its face-to-face isomer complex, consisting of two 43-membered rings arranged around two copper(I) centers (6). In an attempt to improve the very poor yield (the dicopper trefoil knot was obtained in 3% yield only), some of us investigated the effect of structural parameters on the course of the reaction. The results obtained have recently been reported as a preliminary communication (7). The strategy used (2) is indicated in Fig. 1. Figure 2 describes in a schematic way the alternative cyclization reaction leading to the unknotted face-to-face complexes and the equilibrium which interconverts the helical and the non helical precursors.

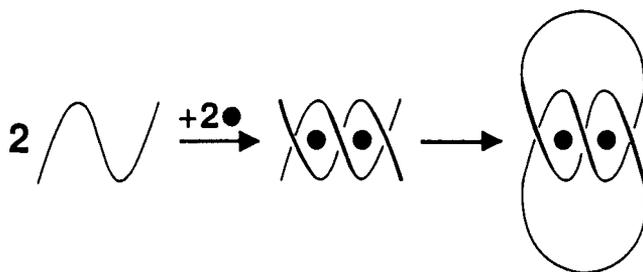


Fig. 1. Principle of the strategy leading to a dimetallic trefoil knot. First step : interlacing of two molecular strings around two transition-metal coordinating centres, with formation of a helicoidal precursor. Second step : connection, with the appropriate linkers, between the four ends of the double helix to afford the knot.

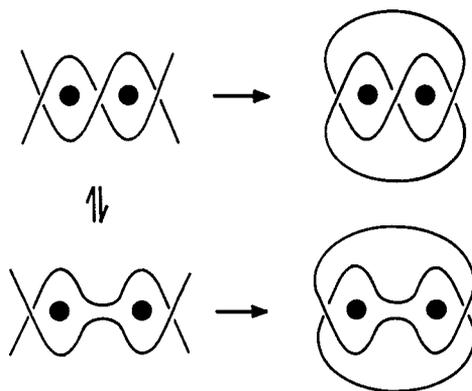


Fig. 2. The equilibrium between the helicoidal interlaced system and its face-to-face analogous complex. Interconversion between the two isomeric cyclic products is of course not possible.

What will be determining is (i) the proportion of double helix precursor formed versus face-to-face open chain complex (Fig. 2) and (ii) the spatial arrangement of the four reacting ends of the helicoidal dinuclear complex. This latter factor will reflect the degree of winding of the two molecular strings interlaced around the copper(I) atoms. The chemical structures of the starting compounds and the complexes synthesized and studied in the present paper are depicted in Figs. 3a, 3b and 3c.

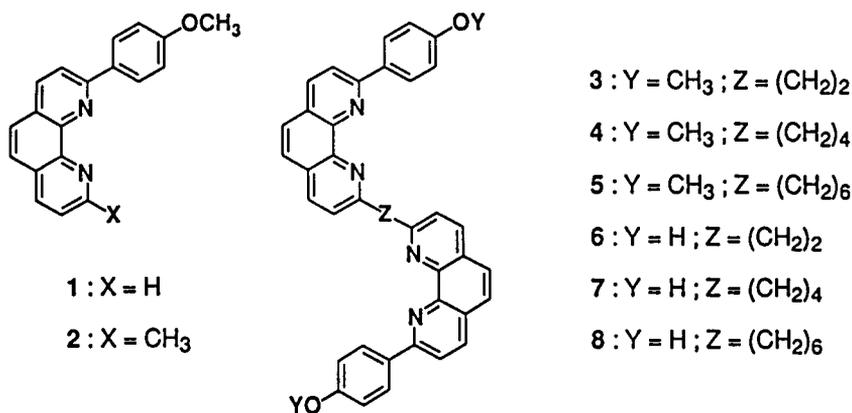


Fig. 3a. The organic precursors.

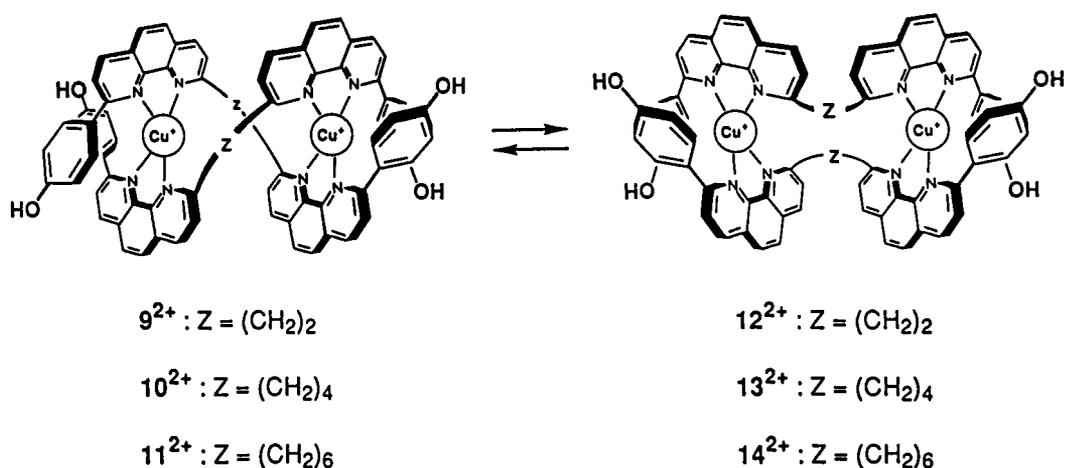


Fig. 3b. The acyclic precursors.

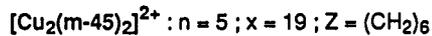
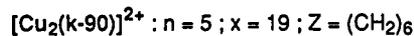
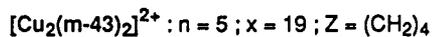
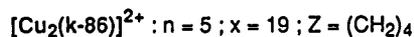
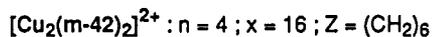
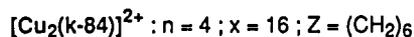
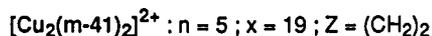
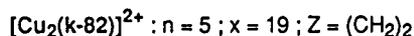
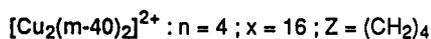
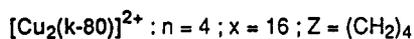
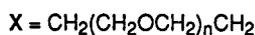
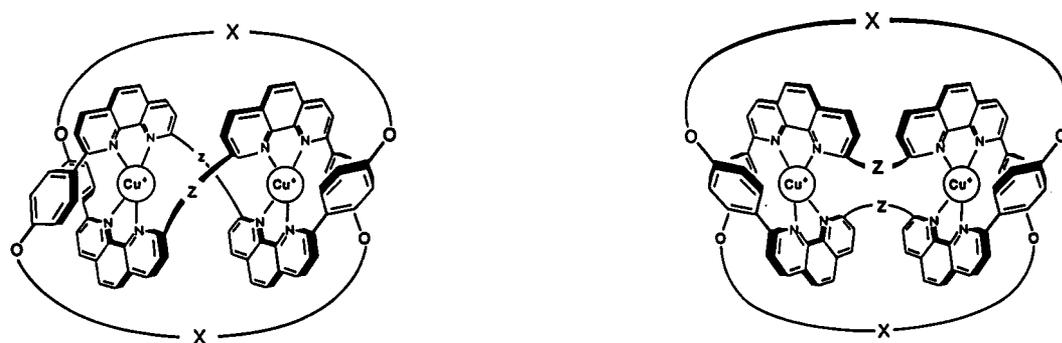


Fig. 3c. For the cyclic compounds, the total number of atoms  $x$  connecting two phenolic oxygen atoms is 16 if  $n=4$  (pentakis(ethyleneoxy) fragment) or 19 if  $n=5$  (hexakis(ethyleneoxy) linker). Each knot is represented by the letter  $k$  accompanied by the overall number of atoms included in the cycle. The face-to-face complexes contain two monocycles (letter  $m$ ), the number of atoms in each ring also being indicated. It can be noted that each knot has a face-to-face counterpart. For instance,  $[\text{Cu}_2(\text{k-90})]^{2+}$  and  $[\text{Cu}_2(\text{m-45})_2]^{2+}$  are constitutional isomers. They are by no means topological stereoisomers (8).

1,10-Phenanthroline was treated with *p*-lithioanisole (9) in ether at 0°C to afford 1 in 69% yield after hydrolysis and oxidation by MnO<sub>2</sub>. 2 was prepared by reacting 1 and methylolithium followed again by hydrolysis and oxidation; it was obtained as a white solid in 92% yield from 1. The *bis*-phenanthroline compound 3 was made by the oxidative coupling (iodine) of the deprotonation product generated from 2 with lithium diisopropylamide (LDA). It was obtained in good yield (77%) from 2. 4 was prepared as previously described (6). The bis-chelating ligand 5 was synthesized by reacting 1 with 1,6-dilithiohexane (10) in ether at 0°C, followed by hydrolysis and MnO<sub>2</sub> treatment. 5 was obtained as a pale yellow solid in 60% yield. The three diphenols 6, 7 and 8 were prepared following a demethylation procedure described earlier (4,5,11). The anisyl derivative (3, 4 or 5) was heated at ~200°C in pyridinium chloride, followed by work-up and careful drying. The yields were excellent in spite of the brutal conditions used.

The dicopper(I) complexes 9<sup>2+</sup> to 14<sup>2+</sup> were made by mixing Cu(CH<sub>3</sub>CN)<sub>4</sub><sup>+</sup> with the corresponding diphenol (6, 7 or 8). It must be stressed that mixtures of complexes were obtained, corresponding to the equilibrium of Fig. 2. All the cyclization reactions leading to the dicopper trefoil knots [Cu<sub>2</sub>(k-80)]<sup>2+</sup> to [Cu<sub>2</sub>(k-90)]<sup>2+</sup> and the face-to-face dinuclear complexes [Cu<sub>2</sub>(m-40)]<sup>2+</sup> to [Cu<sub>2</sub>(m-45)]<sup>2+</sup> were carried out under similar conditions, on the crude mixture of precursors (double helix and face-to-face complex). The phenolic complexes (9<sup>2+</sup> + 12<sup>2+</sup>), (10<sup>2+</sup> + 13<sup>2+</sup>) or (11<sup>2+</sup> + 14<sup>2+</sup>) were reacted with the desired diiodo derivative (penta- or hexa-ethyleneglycol) in DMF, in presence of Cs<sub>2</sub>CO<sub>3</sub>, with vigorous stirring. The knotted and the face-to-face complexes were obtained in various proportions, depending on which open chain compounds were used: bis-phenanthroline 6, 7 or 8, and diiodo derivative. The respective yields are given in Table 1.

TABLE 1. Preparation of [Cu<sub>2</sub>(m-40)]<sup>2+</sup> to [Cu<sub>2</sub>(m-45)]<sup>2+</sup> and [Cu<sub>2</sub>(k-80)]<sup>2+</sup> to [Cu<sub>2</sub>(k-90)]<sup>2+</sup>.

Acyclic precursor	Diiodo fragment	Isolated complexes	Yield
9 <sup>2+</sup> + 12 <sup>2+</sup>	hexa	[Cu <sub>2</sub> (m-41)] <sup>2+</sup>	0.5%
		[Cu <sub>2</sub> (k-82)] <sup>2+</sup>	0.5%
10 <sup>2+</sup> + 13 <sup>2+</sup>	penta	[Cu <sub>2</sub> (m-40)] <sup>2+</sup>	4.6%
		[Cu <sub>2</sub> (k-80)] <sup>2+</sup>	0.7%
10 <sup>2+</sup> + 13 <sup>2+</sup> (see ref. 7)	hexa	[Cu <sub>2</sub> (m-43)] <sup>2+</sup>	24%
		[Cu <sub>2</sub> (k-86)] <sup>2+</sup>	3%
11 <sup>2+</sup> + 14 <sup>2+</sup>	penta	[Cu <sub>2</sub> (m-42)] <sup>2+</sup> [Cu <sub>2</sub> (k-84)] <sup>2+</sup>	unstable complex 8%
11 <sup>2+</sup> + 14 <sup>2+</sup>	hexa	[Cu <sub>2</sub> (m-45)] <sup>2+</sup>	21%
		[Cu <sub>2</sub> (k-90)] <sup>2+</sup>	2.5%

It can be noted that all the preparation yields are rather low, except for some face-to-face complexes which can be obtained in more than 20% yield. As far as dicopper(I) knots are concerned, the best results was obtained with [Cu<sub>2</sub>(k-84)]<sup>2+</sup> (8% yield). A possible explanation is that the -(CH<sub>2</sub>)<sub>6</sub>- fragment linking the two phenanthroline units is particularly favorable either to double helix formation versus face-to-face precursor or to cyclization to the knot. The latter explanation seems reasonable on the basis of a recent X-ray crystallographic study on [Cu<sub>2</sub>(k-84)]<sup>2+</sup> (12). The structure shows the helicoidal core to be very well adapted to the formation of a knot, particularly with a highly twisted helix, owing to the relatively long -(CH<sub>2</sub>)<sub>6</sub>- fragment.

The X-ray structures of  $[\text{Cu}_2(\text{k-86})]^{2+}$  (3) and  $[\text{Cu}_2(\text{k-84})]^{2+}$  (12) are represented in Fig. 4. Both molecules are very symmetrical and their overall shapes are similar. However, the central double helix of  $[\text{Cu}_2(\text{k-84})]^{2+}$  is *more wound* than that of  $[\text{Cu}_2(\text{k-86})]^{2+}$ . The Cu--Cu distances are also significantly different: 7.03 Å in  $[\text{Cu}_2(\text{k-84})]^{2+}$  and 6.3 Å in  $[\text{Cu}_2(\text{k-86})]^{2+}$ , in accordance with the longer methylenic fragments connecting both sub-complexes in the former system.

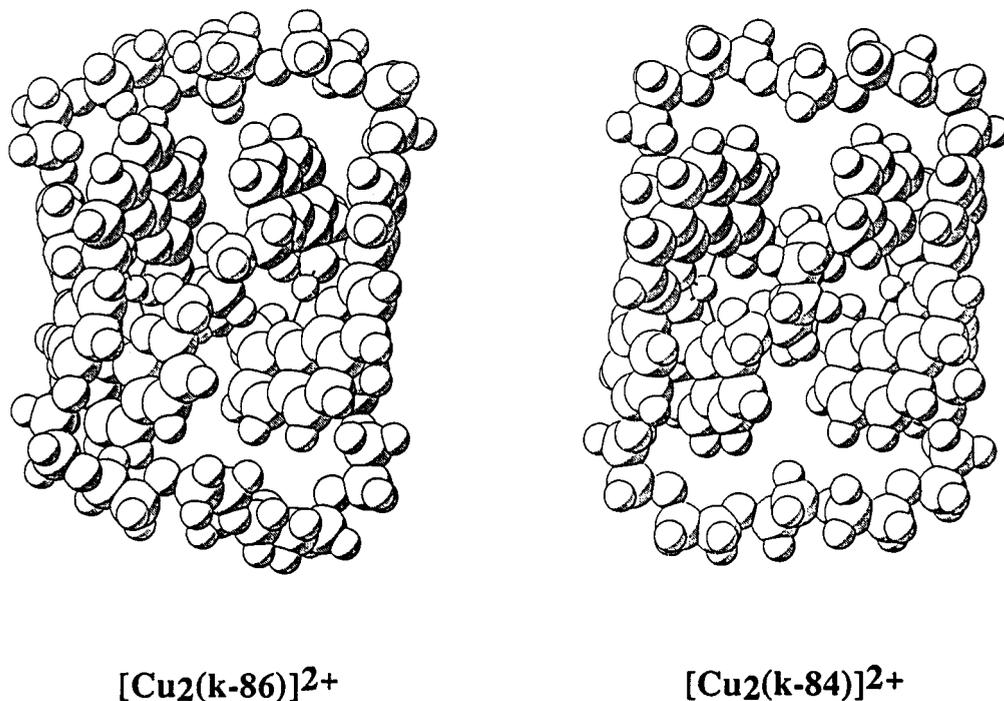


Fig.4. X-ray structures of  $[\text{Cu}_2(\text{k-86})]^{2+}$  (3) and  $[\text{Cu}_2(\text{k-84})]^{2+}$  (12).

#### Transition metal templated formation of [2]- and [3]-rotaxanes with porphyrins as stoppers

In order to make rotaxanes (13) usable as parts of molecular devices and with the purpose of studying long-range electron transfer processes within large molecular systems of well controlled geometries, the introduction of photo- and electroactive components seemed to be a valuable extension. In particular, the stoppers having to be bulky groups, it was envisioned that porphyrins would constitute interesting components able : (i) to act as blocking groups, (ii) to respond to photonic excitation by electron transfer or abstraction , and (iii) behave as electron donor or acceptor groups in their ground state. In Fig. 5 are indicated the two possible strategies leading either to a [2]-rotaxane or to a [3]-rotaxane.

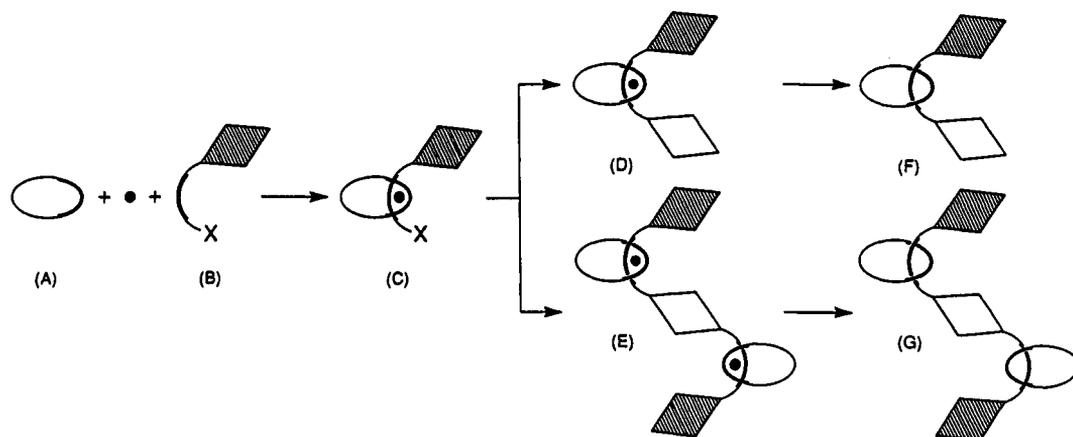


Fig. 5. The macrocycle (A) incorporating a coordinating fragment (thick line) interacts with a metal centre (black circle) and a non-symmetrical open chain chelate (B) bearing one porphyrin and a precursor function X which is small enough to pass through the ring. After the threaded intermediate C is formed, the additional porphyrin ring is constructed, affording the transition metal-complexed rotaxanes D and E. Demetalation leads to the free-ligand rotaxanes F and G from D and E, respectively.

Compounds **15** and **16<sup>+</sup>** were made according to literature procedures (14, 15). The sequence of reactions leading to the transition metal-complexed [2]- and [3]-rotaxanes **20<sup>2+</sup>** and **22<sup>4+</sup>**, respectively (Fig. 6b), is shown in Fig. 6a. Pre-rotaxane **17<sup>2+</sup>** was first formed. Macrocycle **15** was complexed with Cu(I) by reaction with  $\text{Cu}(\text{CH}_3\text{CN})_4 \text{BF}_4$  in  $\text{CH}_3\text{CN}/\text{CH}_2\text{Cl}_2$  solution. Then the gold porphyrin **16<sup>+</sup>**( $\text{BF}_4^-$ ) was added. **17<sup>2+</sup>** was obtained quantitatively. It was used in the next step, without further purification :  $\text{17}^{2+}(\text{BF}_4^-)_2$ , di-*tert*-butyl-3,5-benzaldehyde and diethyl-3,3'-dimethyl-4,4'-dipyrrylmethane in molar ratio 1:4:10 were mixed and stirred in dichloromethane, in the presence of trifluoroacetic acid (3:1) for 17 h. Subsequently, a large excess of chloranil (30:1) was added in order to oxidize the intermediate porphyrinogen and the reaction mixture was heated to reflux for 1.5 h.

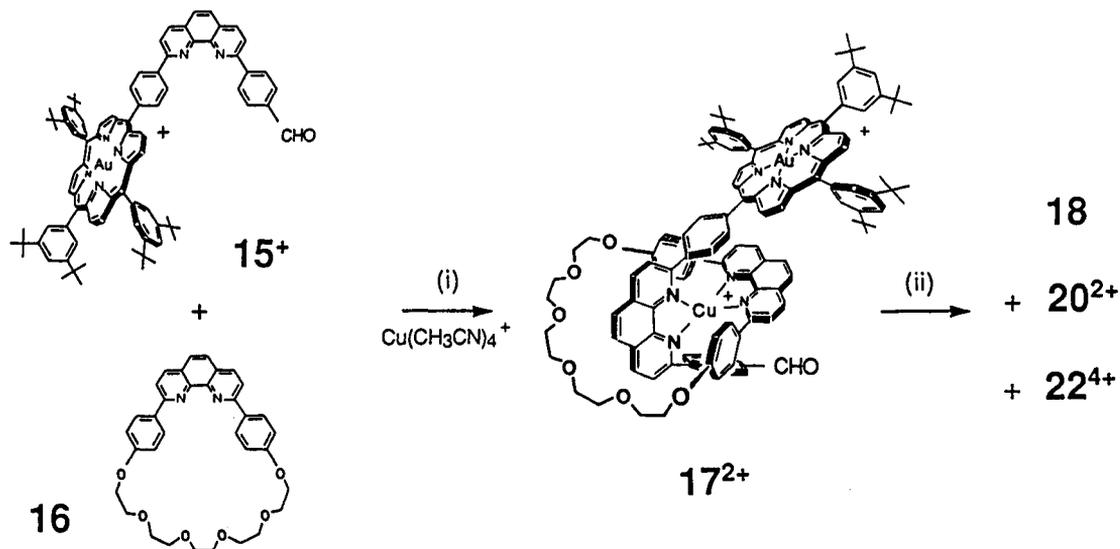


Fig. 6a. Synthesis of the various [2]- and [3]-rotaxanes : (i)  $\text{CH}_2\text{Cl}_2 / \text{CH}_3\text{CN}$ , room temperature ; (ii) di-*tert*-butyl-3,5-benzaldehyde, diethyl-3,3'-dimethyl-4,4'-dipyrrylmethane,  $\text{CF}_3\text{CO}_2\text{H}$ ,  $\text{CH}_2\text{Cl}_2$ , room temperature, then chloranil,  $\text{CH}_2\text{Cl}_2$ , reflux.

After work-up and chromatographic separations, three porphyrins were isolated : etioporphyrin **18**, the desired copper(I) [2]-rotaxane **20**<sup>2+</sup> and the compartmental bis-copper(I) [3]-rotaxane **22**<sup>4+</sup>. The rotaxanes were isolated as their PF<sub>6</sub><sup>-</sup> salts in 25% and 32% yields respectively. All three compounds contained a free-base etioporphyrin and could be readily metalated with Zn(OAc)<sub>2</sub>·2H<sub>2</sub>O to afford **19**, **21**<sup>2+</sup> and **23**<sup>4+</sup>, respectively.

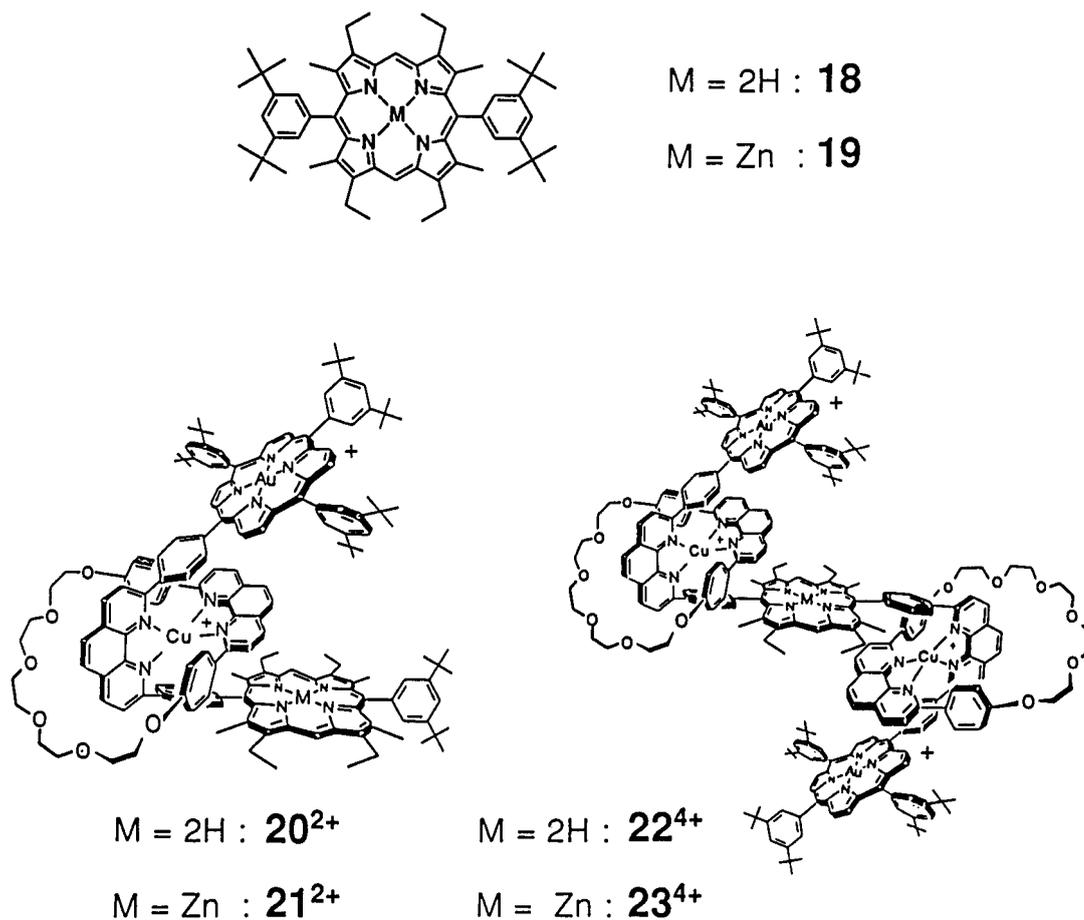


Fig. 6b. The various products of rotaxane synthesis.

In conclusion, transition metals can govern a large variety of assembling and templating processes, leading to complex multinuclear species. By using multisite molecular strings, double helices or face-to-face edifices can be obtained. The former compounds are precursors to trefoil knots, the topology of which being particularly attractive. On the other hand, by combining cyclic organic fragments and coordinating molecular strings with metals, the string bearing a metallo-porphyrin, interesting threaded assemblies are formed which lead to various porphyrin-stoppered rotaxanes. The "locking" reaction is a cyclization step in the case of catenate synthesis, but, for the preparation of metallo-rotaxanes, it is the formation of the second porphyrin. The use of Lindsey's (16) procedure turned out to be determining. Furthermore and unexpectedly, this reaction afforded a good yield of compartmental [3]-rotaxane beside the desired [2]-rotaxane. Compartmental [3]-rotaxanes are promising species as far as multistep long-range electron transfer is concerned and as components of photochemical molecular devices (17).

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