Supramolecular Chemistry

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Copper(I)-Directed Formation of a Cyclic Pseudorotaxane Tetramer and Its Trimeric Homologue**

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In the past decade, catenanes and rotaxanes[1] have been extensively exploited as functional units of molecular assemblies related to controlled dynamic systems ("molecular machines"[2]) or polymers. Several multicomponent assemblies have been reported in which the ring is covalently attached to a filament-like fragment threaded through the same ring[3] or through the cyclic unit belonging to another ring–filament conjugate. Particularly significant examples are the purely organic systems prepared by Huang and Gibson,[4] which lead to the formation of supramolecular polymers, or those reported by Stoddart and co-workers[5] and termed "daisy chains". Interesting cyclodextrin-based assemblies have also been reported by Harada and co-workers[6] as well as by other research groups.[7]

Transition-metal-based systems have only rarely been used to generate cyclic rotaxane or pseudorotaxane oligomers, with the only example being that of a dicopper(I) rotaxane dimer,[8] the precursor of a molecular "muscle" which is able to stretch or contract under the action of an external signal.[9] We now report that multinuclear cyclic pseudorotaxanes can be generated by copper(I)-mediated assembly of a ligand in which a chelate-containing macrocycle is rigidly attached to a filament bearing another bidentate ligation site (Figure 1).

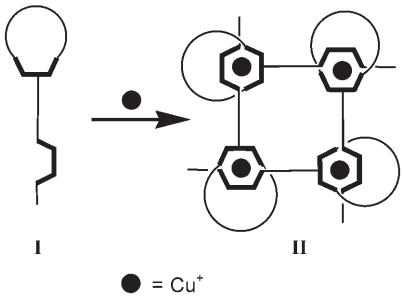

Figure 1. Formation of multinuclear cyclic rotaxane tetramer (**II**) from the two-chelate ligands (**I**) and a templating metal center.

The reaction relies on the gathering and threading process described long ago to make catenanes[10] and rotaxanes.[11] The success of this step is mostly due to the fact that one of the chelates is incorporated in a ring and cannot, therefore, form a metal bischelate complex without the threading of another chelate (not belonging to a cycle) through the ring in which it is incorporated. The two bidentate chelates of **I** are disposed in such a way that their coordination axes are orthogonal to each other. This arrangement implies that a tetrameric species **II** should be formed provided the metal center forms a tetrahedral complex.

We used the copper(I)/1,10-phenanthroline system to build the cyclic rotaxane tetramer analogous to **II**. It is preferable to use 1,10-phenanthroline (phen) ligands bearing substituents at their 2- and 9-positions to stabilize the 4-coordinate tetrahedral copper(I) complex. We have thus incorporated a 2,9-diphenyl-1,10-phenanthroline (dpp) fragment into the ring and a 2,9-dimethyl-1,10-phenanthroline (dmp) chelate into the filament. The ligand **1** (Scheme 1) containing two bidentate chelates was prepared[12] in 13 steps from 1,10-phenanthroline and other commercially available compounds. Its chemical structure should provide strict control over the geometry of the whole system: the molecule is highly rigid and, as a consequence of the oxazole unit used

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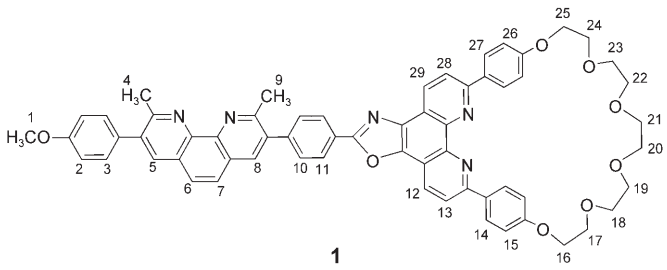

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Scheme 1. Structure of ligand **1** with the numbering of the protons.

as a spacer, the coordination axes of the phen chelates are, in an ideal case, orthogonal to one another. Furthermore, the two methyl groups attached *ortho* to the nitrogen atoms of the phen units should favor a tetrahedral geometry of the corresponding complexes.

Addition of an equimolar amount of $[Cu(CH_3CN)_4]PF_6$ in acetonitrile to a suspension of **1** in the same solvent resulted in rapid formation of a brown-red solution. Samples of concentration 10^{-2} M and 10^{-5} M were prepared from this solution and analyzed by high-resolution ESI-MS.

The ESI mass spectrum (see Supporting Information) of a solution of the complex at 10^{-5} M in acetonitrile revealed only one significant peak at *m*/*z* 1059.29 with an isotope spacing corresponding to the triply charged species $[(\mathbf{1}+Cu)_3]^{3+}$. At the highest concentration measured (10^{-2} M) two significant peaks were present above *m*/*z* 1000: a major peak at *m*/*z* 1059.32, with an isotope spacing corresponding to the species $[(\mathbf{1}+Cu)_4]^{4+}$, and a peak at *m*/*z* 1461.15 corresponding to $[(\mathbf{1}+Cu)_4PF_6]^{3+}$. These results strongly suggest that the complex is a mixture of the cyclic trimeric and tetrameric species **3** and **4** (Scheme 2), respectively, in which the former prevails at low concentration whereas the latter homologue is more abundant at high concentration.

$$\underset{\mathbf{2}}{\mathbf{1} + [Cu(CH_3CN)_4]^+} \longrightarrow \underset{\mathbf{3}}{[(\mathbf{1}\cdot Cu)_3]^{3+}} + \underset{\mathbf{4}}{[(\mathbf{1}\cdot Cu)_4]^{4+}}$$

Scheme 2. Reaction of ligand **1** with $[Cu(CH_3CN)_4]^+$ (**2**) in CH_3CN leads to a mixture of trimeric and tetrameric complex, with their relative proportion depending strongly on the solution concentration.

The ^{1}H NMR spectra of the complex in CD_3CN in the measurable range of concentrations (5×10^{-3} to 5×10^{-5} M) were recorded to gain a deeper insight into the structure of the complexes as well as into their mutual composition. Complete assignment of all the protons was achieved by 2D COSY and ROESY methods.

Spectra acquired at the upper concentration limit (5×10^{-3} M) revealed one major set of signals together with a set of less-intense signals that were attributed to tetrameric and trimeric species, respectively, which is in accordance with the ESI-MS results. Comparison of the ^{1}H NMR spectra with that of the free ligand **1** revealed typical shifts in the protons of the Cu^I-complexed dpp units; for example, H-15 and H-26 of the phenyl moiety are shifted upfield by $\Delta\delta = 1.2$ ppm in tetramer **4**. The initially minor signals of the trimer **3** intensify as the concentration is decreased, and dominate over signals of the tetramer **4** at 5×10^{-5} M. The singlets of the terminal methoxy groups (H-1 which resonates at $\delta = 3.92$ and 3.90 ppm for the trimer and tetramer, respectively) are suitable labels for the determination of the ratios of the two species in solution. Thus, by integration of the two signals (Figure 2), the ratio

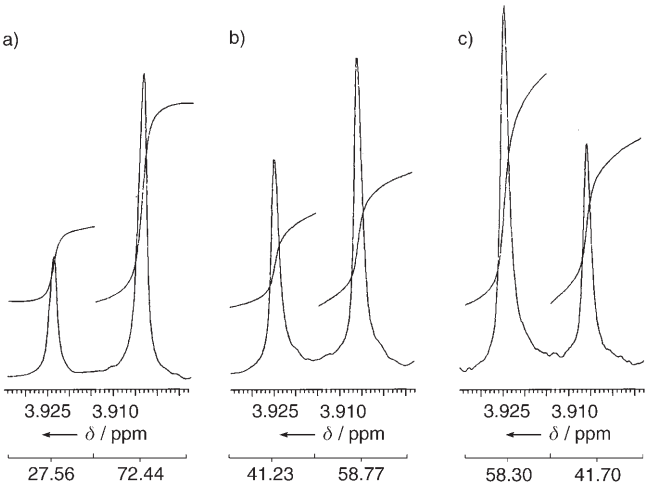
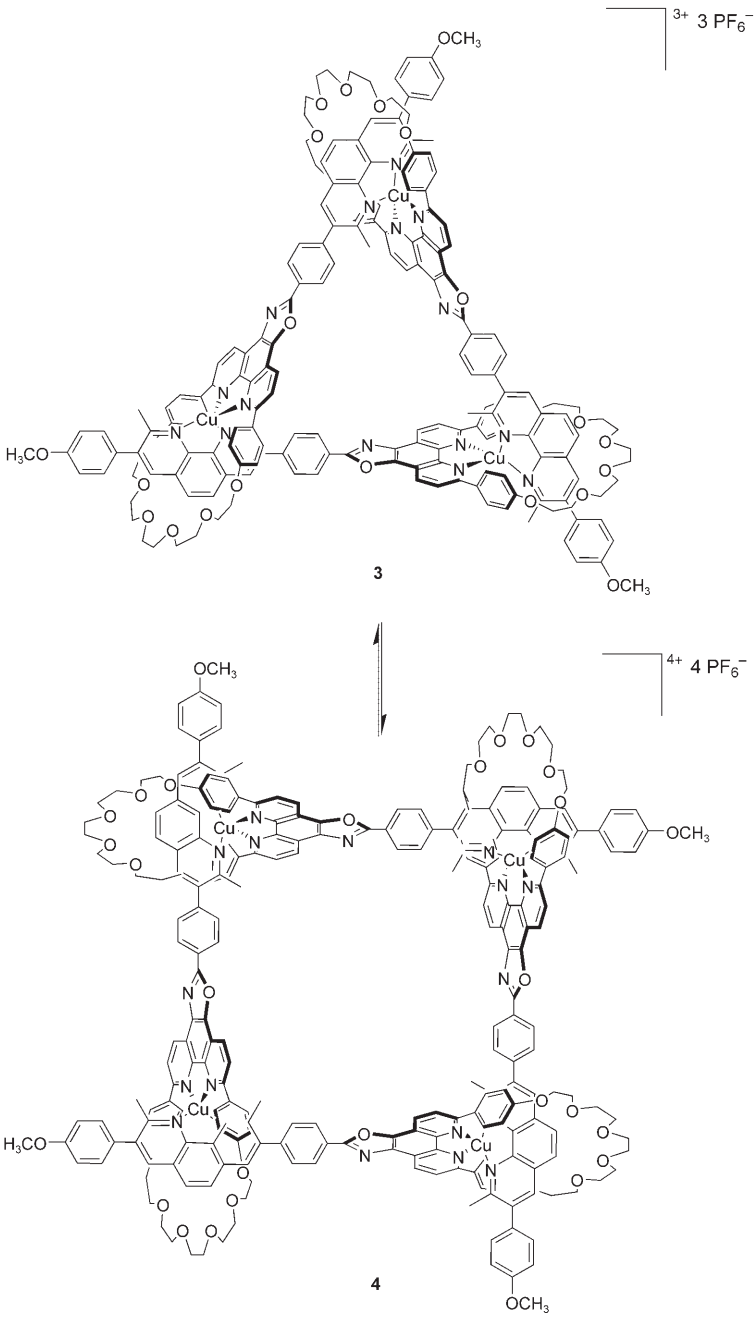


Figure 2. ^{1}H NMR spectrum of the -OCH_3 groups (H-1) as a function of concentration; the signals corresponding to the trimer (left) and the tetramer (right) are sufficiently shifted from one another to allow determination of the relative proportion of each compound with good accuracy: a) 5×10^{-3} M, b) 10^{-3} M, c) 5×10^{-5} M.

tetramer/trimer was found to be 72:28 and 42:58 at 5×10^{-3} and 5×10^{-5} M, respectively. Significant NOE interactions between the CH_3 protons of the dmp unit (H-4, H-9) and protons of the phenyl rings of the macrocycle (H-14, H-27) were observed, thus proving convincingly that the dmp unit threads through the dpp-containing ring upon complexation.

The presence of the oxazol moiety results in each copper(I) center becoming stereogenic in the triangular and squarelike complexes. Accordingly, the presence of diastereomers could be expected in the solution of the complex. We found that protons H-12 and H-29 of the dpp units are particularly sensitive to diastereoisomerism and their resonances appear as doublets at different chemical shifts in the ^{1}H NMR spectra. Whereas these differences are very small (at 500 MHz) for the tetrameric complex and do not allow for the resolution of the individual diastereoisomers, the two possible diastereomers of the trimer could be readily observed by NMR spectroscopy.

It is particularly noteworthy that the tetrameric complex, which was expected to be the sole product because of the structure of ligand **1**, was formed in 72% yield only in concentrated solutions and was the minor compound in more dilute solutions. This phenomenon once again demonstrates the importance of entropic factors in such complexation reactions. For entropic reasons the smallest assembly (the trimer, in the present case) is expected to be formed preferentially. On the other hand, the strainless tetrahedral geometry of the squarelike copper(I) complex should be favored in terms of enthalpy. Thus, the delicate balance of the two factors determines the ratio of the two species in the reaction mixture (Scheme 3) and can be tuned by changing



Scheme 3. Representation of the equilibrium between the trimer and the tetramer (only one diastereomer is depicted for each trimer and tetramer); in dilute solution (5×10^{-5} M) the trimer is the major component, whereas in concentrated solution (5×10^{-3} M) the tetramer proportion is 72%.

the concentration of the solution. Related observations were made a few years ago by Fujita et al. on nonthreaded species containing palladium(II) ions and 4,4′-bipyridine (square/triangle).[13]

The equilibration in the present system is remarkably slow: dilution of the 5×10^{-3} M sample to 5×10^{-5} M resulted in the tetramer/trimer ratio changing from an initial 72:28 to only 64:36 after 20 h (at the end of the first 20-hour period of ^{1}H signal accumulation). The ratio was only 51:49 after 72 h, and it took 10 days to reach the final ratio of 42:58. This slow ligand exchange, which involves decoordination of the Cu^I center and threading/dethreading processes, has already been observed in the formation of a related dimer.[8,9] It has also been exploited in the isolation of non-stoppered copper(I)-complexed threaded species containing different rings threaded on a two-site linear fragment.[14]

The two cyclic pseudorotaxanes presented herein can be regarded as higher homologues of the rotaxane dimer[8] that was used in the preparation of a musclelike compound.[9] The incorporation of additional chelates of the 2,2′,6′,2″-terpyridine (terpy) type into the filament should lead to novel cyclic dynamic species, "expanding squares", thus extending the concept of linear motion of the previous "muscle" into two dimensions.

Experimental Section

Preparation of the copper(I) complexes: A solution of $[Cu(CH_3CN)_4]PF_6$ (3.73 mg, 0.01 mmol) in CH_3CN (0.5 mL) was added in an argon atmosphere to a stirred suspension of ligand **1** (9.96 mg, 0.01 mmol) in degassed CH_3CN (0.5 mL). The solids disolved within 5 min and a brown-red solution was formed. For ESI-MS studies, the solution was diluted with CH_3CN to final concentrations of 10^{-2} M and 10^{-5} M. Samples for NMR spectroscopic analysis were prepared by evaporation of the concentrated solution under a stream of argon and subsequent dilution with CD_3CN. The chemical shifts marked with an asterisk below correspond to the averaged values for given protons that appear at slightly different positions because of their symmetry non-equivalence in the diastereoisomers.

Trimer **3**: ^{1}H NMR (500 MHz; CD_3CN): $\delta\approx2.0$ overlapped with solvent (s, 9H; H-9), 2.46 (s, 9H; H-4), 3.38 (m, 2H; H-16, H-25), 3.45 (m, 2H; H-17, H-24), 3.59 (m, 2H; H-18, H-23), 3.66 (m, 2H; H-19, H-22), 3.74 (s, 2H; H-20, H-21), 3.92 (s, 9H; H-1), 6.11* (m, 12H; H-15, H-26), 7.16 (m, $J_{2,3}=8.8$ Hz, 6H; H-2), 7.54* (m, 12H; H-14, H-27), 7.54 (m, $J_{3,2}=8.8$ Hz, 6H; H-3), 7.68* (m, 6H; H-10), 8.11 (d, $J_{7,6}=8.8$ Hz, 3H; H-7), 8.31 (d, $J_{6,7}=8.8$ Hz, 3H; H-6), 8.35* (5 × d, $J_{13,12}=J_{28,29}=8.4$ Hz, 6H; H-13, H-28), 8.49 (s, 3H; H-5), 8.57* (m, 6H; H-11), 8.63 (s, 3H; H-8), 9.13* (4 × d, $J_{12,13}=8.4$ Hz, 3H; H-12), 9.22* ppm (3 × d, $J_{29,28}=8.8$ Hz, 3H; H-29).

Tetramer **4**: ^{1}H NMR (500 MHz; CD_3CN): $\delta=2.21$ (s, 12H; H-9), 2.25 (s, 12H; H-4), 3.38 (m, 16H; H-16, H-25), 3.45 (m, 16H; H-17, H-24), 3.59 (m, 16H; H-18, H-23), 3.66 (m, 16H; H-19, H-22), 3.74 (s, 16H; H-20, H-21), 3.90 (s, 12H; H-1), 6.08* (m, 16H, H-15, H-26), 7.14 (m, $J_{2,3}=8.8$ Hz, 8H; H-2), 7.47 (m, $J_{3,2}=8.8$ Hz, 8H; H-3), 7.60* (m, 16H; H-14, H-27), 7.81 (m, $J_{10,11}=8.4$ Hz, 8H; H-10), 8.24 (d, $J_{7,6}=8.8$ Hz, 4H; H-7), 8.26 (d, $J_{6,7}=8.8$ Hz, 4H; H-6), 8.39* (3 × d, $J_{13,12}=J_{28,29}=8.8$ Hz, 8H; H-13, H-28), 8.47 (s, 4H; H-5), 8.56 (s, 4H; H-8), 8.64 (m, $J_{11,10}=8.4$ Hz, 8H; H-11), 9.17* (4 × d, $J_{12,13}=8.5$ Hz, 4H; H-12), 9.26* ppm (3 × d, $J_{29,28}=8.8$ Hz, 4H; H-29).

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[12] The synthesis of ligand **1** will be described elsewhere. Structural characterization: ^{1}H NMR (500 MHz; $CDCl_3$): $\delta = 2.93$ (s, 3H; H-4), 2.98 (s, 3H; H-9), 3.72 (m, 4H; H-19, H-21), 3.77 (m, 4H; H-18, H-23), 3.78 (s, 4H; H-20, H-21), 3.88 (m, 4H; H-17, H-24), 3.91 (s, 3H; H-1), 4.37 (m, 4H; H-16, H-25), 7.06 (m, $J_{2,3} =$ 8.8 Hz, 2H; H-2), 7.21 (m, $J_{15,14} = 8.9$ Hz, 2H; H-15), 7.22 (m, $J_{26,27} = 8.9$ Hz, 2H; H-26), 7.42 (m, $J_{3,2} = 8.8$ Hz, 2H; H-3), 7.71 (m, $J_{10,11} = 8.4$ Hz, 2H; H-10), 7.792 (d, $J_{7,6} = 8.8$ Hz, 1H; H-7), 7.794 (d, $J_{6,7} = 8.8$ Hz, 1H; H-6), 8.07 (s, 1H; H-5), 8.17 (s, 1H; H-8), 8.21 (d, $J_{13,12} = 8.5$ Hz, 1H; H-13), 8.23 (d, $J_{28,29} = 8.4$ Hz, 1H; H-28), 8.461 (m, $J_{27,26} = 8.9$ Hz, 2H; H-27), 8.465 (m, $J_{14,15} =$ 8.9 Hz, 2H; H-14), 8.52 (m, $J_{11,10} = 8.4$ Hz, 2H; H-11), 8.72 (d, $J_{12,13} = 8.5$ Hz, 1H; H-12), 8.98 ppm (d, $J_{29,28} = 8.4$ Hz, 1H; H-29), see also the Supporting Information; ESI-MS: m/z 996.5 $[M+H]^+$.

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