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Helicate, Macrocycle, or Catenate: Dynamic Topological Control over Subcomponent Self-Assembly

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Abstract: The aqueous reaction between equimolar amounts of 2-(2-(2-aminoethoxy)ethoxy)ethanamine, 1,10-phenanthroline-2,9-dialdehyde and copper(I) produced a dimeric helical macrocycle in quantitative yield. This ring could also be generated by the addition of two equivalents of the diamine to an acyclic helicate containing four mono-imine residues: A transimination occurred, the chelate effect being implicated as a driving force. In the case of a helicate containing mono-imines derived from anilines, the substitution of diamine for monoamine was reversible upon lowering the pH. The aliphatic diamine was protonated at a higher pH than the arylamine, which left the arylamine free for incorporation instead of the alkyl diamine. This reaction thus opened the possibility of switching between closed macrocyclic and open helicate topologies by changing the pH. An additional closed topology became accessible through the use of a diamine that incorporates two rigid phenylene spacer groups between a flexible chain and the imine-forming nitrogen atoms. The resulting catenate consists of a pair of topologically interlinked macrocycles. The presence of the phenylene groups appeared to dictate the topology of the final product, making the formation of a single macrocycle energetically disfavoured.

Keywords: catenates · chemical topology · copper · dynamic covalent chemistry · self-assembly

Introduction

To create useful molecular machines,[1] control over the molecular topology[2,3] must be exercised. The subcomponents of molecular-scale devices must be threaded together with the same precision as the yarns of a textile or the shafts and gears of a macroscopic machine; the complex topologies of biochemical machinery[4] bear witness to the necessity of the correct form for a particular function.

The use of metal-ion templates to control the topology of mechanically interlinked structures by Sauvage and co-workers[5] represents a key advance in the synthetic control of the molecular topology, and allows knots and catenanes to be prepared in multigram quantities. Important milestones in supramolecular control over topology were likewise the use of π interactions between electron-rich and electron-poor arenes to program the self-assembly of oligocatenanes by Stoddart's group,[6] the dynamic reassembly of two cages to form a single triply-linked catenane by Fujita and co-workers[7] and the control of product topology as a function of the order in which reaction steps were carried out by Leigh and co-workers.[8] Recently, several groups[9,10] have demonstrated the application of dynamic covalent chemistry[11] in the form of olefin metathesis[12] to the syntheses of catenanes, dramatically improving yields through error checking, whereby "incorrectly templated" structures reassemble into a thermodynamically favoured "correct" product.

At the intersection of dynamic covalent[11] and supramolecular[13] chemistries lies the domain of subcomponent self-assembly, during which covalent (carbon–heteroatom) and dative (heteroatom–metal) bonds form as part of the same process. The resulting strict (thermodynamic) self-assem-

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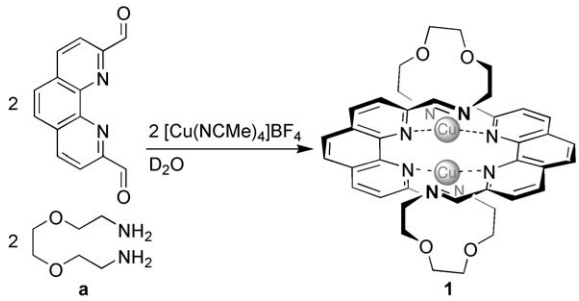
Supporting information for this article (^{1}H, ROESY, and NOE difference spectra of **4**, space-filling images of the three topological isomers of **4**, and MS/MS spectra of sodiated **5**) is available on the WWW under http://www.chemeurj.org/ or from the author.

bly[14] allows complex structures to be generated from simple building blocks;[15–17] these structures may then dynamically rearrange on both covalent and supramolecular levels.[16–19] The generation of topological complexity by this method has recently been demonstrated through the syntheses of catenates,[10] rotaxanes[20] and a Borromean link.[21] We report herein the development of a subcomponent self-assembly reaction that allowed either of two distinct product topologies, a helical macrocycle or catenate, to be uniquely selected based upon the geometry of the ligand components employed. Dynamic control over the topology of the macrocyclic product was also demonstrated as a function of the pH: in the presence of sulfanilic acid, the macrocycle was transformed into a topologically open helicate at low pH, whereas the closed macrocycle was regenerated when the pH was raised.

Results and Discussion

The reaction of 2-(2-(2-aminoethoxy)ethoxy)ethanamine (diamine **a**) with 1,10-phenanthroline-2,9-dialdehyde and copper(I) tetrakis(acetonitrile) tetrafluoroborate in aqueous solution gave a single product whose NMR spectra were consistent with macrocyclic structure **1** (Scheme 1).

X-ray crystallography confirmed the presence of this structure in the solid state. An ORTEP diagram of dication **1** is shown in Figure 1. The dicopper bis(phenanthrolinediimine) double helicate moiety originally reported by Ziessel and co-workers[22] thus served as the structure-determining motif for this macrocycle, defining the points of attachment for the diamines that closed the loop. To make a single, stable macrocycle, diamine **a** must thus be long enough to close the structure without strain (as can be seen in Figure 1), yet not be so long as to be able to create multiple, nearly isoenergetic structures that have different connectivities, conformations or topologies.



Scheme 1. The preparation of helical macrocycle **1** from ligand subcomponents and copper(I).

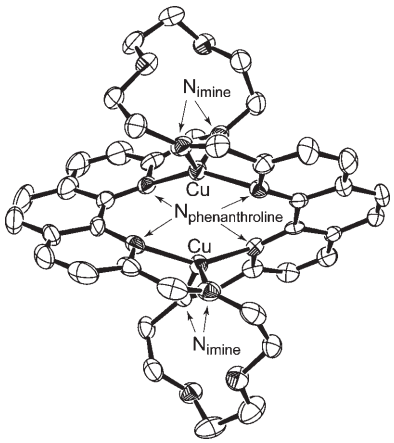
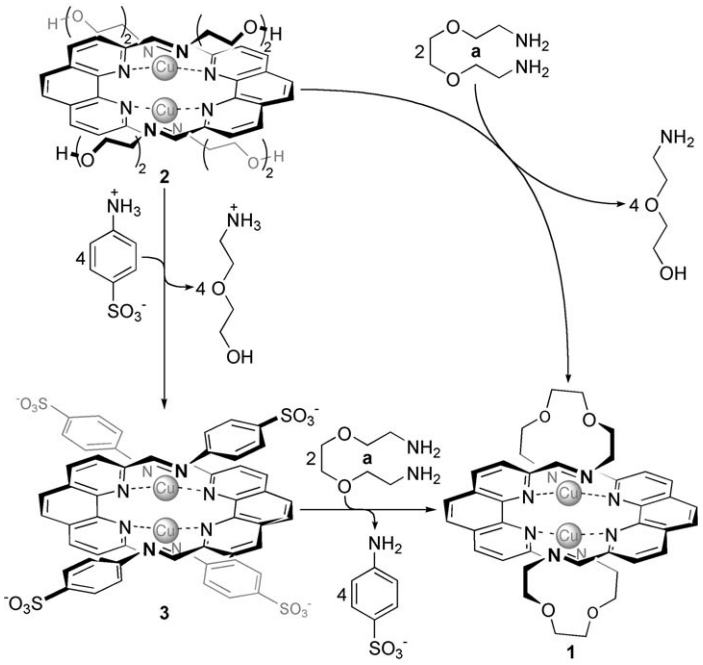


Figure 1. Structure of macrocycle **1** (ORTEP diagram; ellipsoids are represented with 50% probability); anions are not shown. Cu···Cu 2.735(1) Å; mean values: $Cu–N_{phenanthroline}$ 2.093(16), $Cu–N_{imine}$ 2.005(16) Å; $N_{phenanthroline}$-Cu-$N_{phenanthroline}$ 149.5(10), N_{imine}-Cu-N_{imine} 128.1(1)°; dihedral angle between the mean planes of the phenanthrolines is 64.0(1)°.

Abstract in French: *La réaction équimolaire en milieu aqueux de (2-(2-aminoethoxy)ethoxy)ethanamine, de 1,10-phenanthroline-2,9-dialdehyde et de cuivre(I) mène à la formation quantitative d'un macrocycle hélicoïdal dimérique. Cet anneau peut également être généré par l'addition de deux équivalents de diamine sur un équivalent d'hélicate acyclique incorporant quatre fonctions mono-imine. Il s'agit d'une transimination dirigée par l'entropie. Si l'hélicate utilisé est formé à partir d'anilines, cette réaction de substitution est réversible en diminuant le pH. Les diamines aliphatiques sont en effet protonées à pH plus élevé que les arylamines, laissant les arylamines s'incorporer à la place des diamines aliphatiques. Cette réaction permet ainsi de passer de la topologie "macrocycle-fermé" à la topologie "hélicate ouvert" en variant le pH. Une autre structure fermée et topologiquement différente est accessible en utilisant une diamine incorporant deux groupements phénylènes rigides de part et d'autre d'une chaîne aliphatique flexible: un catenate, c'est-à-dire deux anneaux entrelés. La topologie du produit final dépend da la présence de ces groupements phénylènes, rendant la formation d'un unique macrocycle énergétiquement défavorable.*

Although the copper(I)-bound imine bonds of these helical structures are thermodynamically stable in aqueous solution,[19] they are nonetheless capable of dynamic interchange with free amines. This property gives rise to rich and varied substitution chemistry. Both enthalpic (differences in basicity) and entropic (chelate effect)[23] effects are implicated as driving forces for the interconversions of these structures.

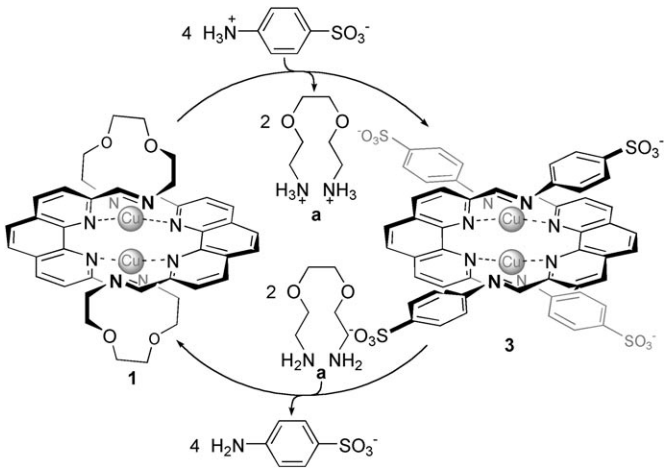
As shown in Scheme 2, when diamine **a** (2 equiv) was added to an aqueous solution of a helicate (1 equiv) containing either alkyl amine (**2**) or aryl amine (**3**) residues, macrocycle **1** was the unique product observed. We suspect that entropy gain provides the principal driving force for this transformation; microcalorimetric measurements to test this hypothesis are planned. In the same manner as the chelate effect,[23] the entropy gained through the liberation of two monodentate ligand subcomponents thus appeared to drive the incorporation of one bidentate ligand subcomponent, even though the formation of an 11-membered ring would be expected to substantially reduce any entropic gain.



Scheme 2. The subcomponent substitution of diamine **a** for both aryl (**3**→**1**) and alkyl (**2**→**1**) monoamines, complementing the substitution of arylamines for alkylamines (**2**→**3**).

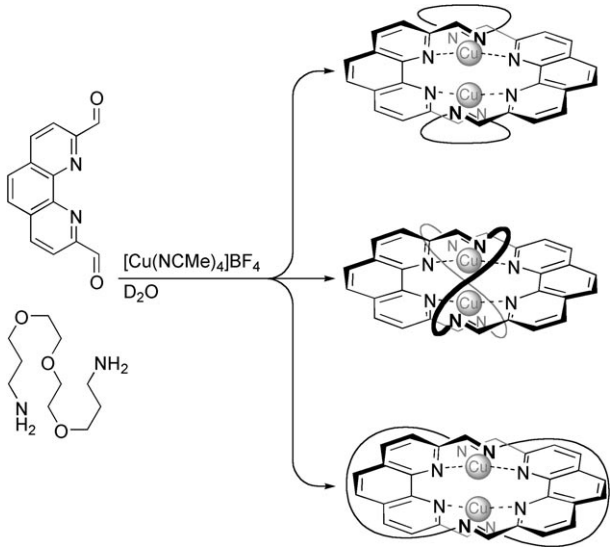
In an identical fashion to what has been reported previously,[17,19,24] helicate **2** was transformed into **3** upon the addition of sulfanilic acid (4 equiv) (Scheme 2). We postulated that proton transfer from a stronger acid (sulfanilic acid) to a weaker one (aminoethoxyethanol) provides an enthalpic driving force for this reaction. The use of the chelate effect as a driving force in the **2**→**1** and **3**→**1** conversions thus provides an additional hierarchical layer of control over ligand subcomponent substitution.

As shown in Scheme 3, the addition of sulfanilic acid (4 equiv) to an aqueous solution of macrocycle **1** resulted in its conversion to helicate **3**, reversing the **3**→**1** transformation seen under neutral conditions. Basification of this solution by the addition of $NaHCO_3$ (4 equiv) resulted in the regeneration of **1**, closing the cycle. By changing the pH, it was thus possible to switch dynamically between the open topology of helicate **3** and the closed topology of macrocycle **1**.



Scheme 3. Cycling between **1** and **3** as a function of the protonation state of diamine **a**.

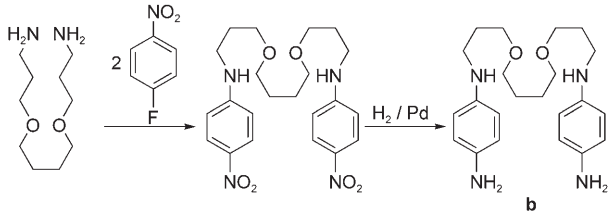
When the longer 4,7,10-trioxa-1,13-tridecanediamine was allowed to react with 1,10-phenanthroline-2,9-dialdehyde and Cu^{I}, NMR spectra indicated that a mixture of at least two products was obtained. The NMR spectra did not change over the course of three days at room temperature, which suggested that the products, capable of dynamic interchange, were of comparable thermodynamic stability. Models suggested that this amine is long enough to bridge between nitrogen atoms in three distinct ways, potentially forming two different macrocyclic topologies and a catenate (Scheme 4). Diamine **a**, in contrast, is only long enough to bridge in one way, which limited the product to the single topological isomer **1**.



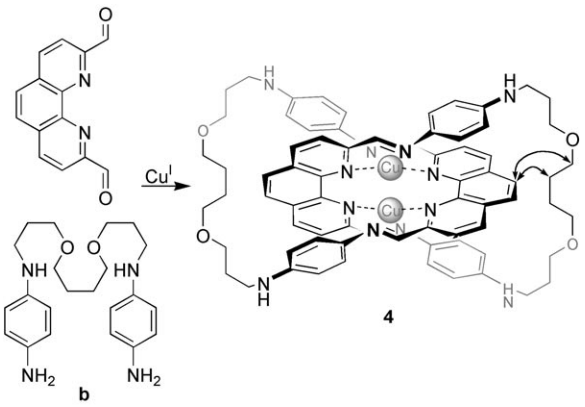
Scheme 4. Three possible topological isomers that could result from the reaction of 4,7,10-trioxa-1,13-tridecanediamine, 1,10-phenanthroline-2,9-dialdehyde and Cu^{I}.

We reasoned that positioning a pair of rigid phenylene spacer groups between the imine nitrogens and the ends of a flexible chain might cause this chain to stretch in a macrocyclic structure similar to **1**, thus raising its energy with respect to an isomeric catenate. The synthesis of dianiline **b** was thus undertaken in two steps from 1-fluoro-4-nitrobenzene and 4,9-dioxa-1,12-dodecanediamine (Scheme 5) by means of a nucleophilic aromatic substitution strategy.[25]

When dianiline **b** was employed instead of diamine **a** as a ligand component, a single product, **4**, was observed by NMR spectroscopy (Scheme 6). In the absence of a crystal structure, we offer three distinct sets of observations supporting the assignment of **4** as a catenate.



Scheme 5. The synthesis of dianiline **b**.



Scheme 6. The preparation of catenate **4** from ligand subcomponents and copper(I). Double-headed arrows correspond to observed ^{1}H NOE signals.

Firstly, molecular mechanics calculations were undertaken to compare the energy of the catenated structure of **4** with its macrocyclic isomers. The structure of the bis(phenanthrolinedi(phenyleneimine)) core was extracted from the crystal structure of helicate **3**[17] by removing the sulfonate groups. The positions of these core atoms were not allowed to vary during energy minimisations. Two 4,9-dioxo-1,12-dodecanediamino chains were added to link the structure into either a macrocycle with the topological configuration of **1** (Scheme 4, top), a "crossed" macrocyclic topology, (Scheme 4, centre), or catenate **4** (Scheme 4, bottom). The resulting isomeric structures were minimised (steepest descent minimisation, convergence to 4.18 J mol^{-1}), by means of the MM2 force field.[26] Since the energy of the "frozen" core was the same in all three structures, the differences in minimised energy should reflect the differences in stability between the topologies adopted by the linking chains.

The minimised energy of the catenated isomer was thus calculated to be 335 kJ mol^{-1} lower than that of the macrocycle with the topology of **1**, and 569 kJ mol^{-1} lower than that of the "crossed" macrocycle. Although exhaustive conformer searching was not undertaken, the structures were examined to ensure that chains were not "stuck" in chemically unreasonable positions, which would lead to local minima of high energies. Space-filling models of the three topological isomers are presented in the Supporting Information. Although we could draw no conclusions on the sole basis of the results of these low-level calculations, they reinforced the idea that it was reasonable to imagine that the catenate would be the exclusive product based upon the magnitude of the difference in energy between catenated and macrocyclic isomers.

Secondly, a nuclear Overhauser effect was observed between NMR resonances corresponding to the alkyl and phenanthroline protons, as noted by the double-headed arrows in Scheme 6. Macrocycle **1** displayed no nOe between any of the phenanthroline and alkyl protons, and examinations of models of the three topological isomers of **4** (see the Supporting Information) suggest that these protons would be close to each other only in a catenate.

Thirdly, the results of a mass spectrometric study performed upon **4** and its derivatives were consistent with a catenated structure but not with the presence of either a single, large macrocycle or a pair of smaller macrocycles that were associated but not topologically interlinked. Although mass spectrometric evidence for a certain structure is always indirect, this method allows the observation of certain key differences between topologically distinct structures, as discussed below.

The ESI-FTICR mass spectrum of **4** was clean and could be optimised for maximum intensity of the dication generated by stripping off both counterions (Figure 2). For the

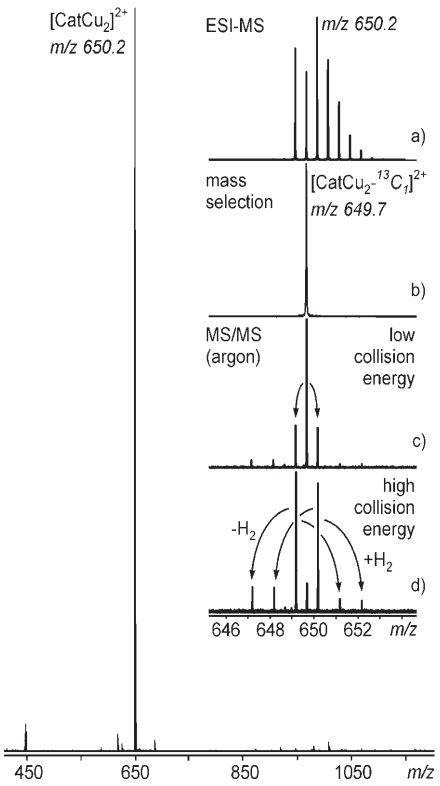


Figure 2. ESI-FTICR mass spectrum obtained from a ≈100-μM solution of **4** in acetone. Insets from top to bottom: a) Experimental isotope pattern, which was in excellent agreement with the one calculated based on natural abundances. The peak spacing of 0.5 amu indicated a dication. b) Mass selection of the second signal in the pattern ensured that the ions contained exclusively ^{63}Cu, and exactly one ^{13}C atom. c) Collisions with argon generated two singly charged fragments with equal intensities and elemental compositions, one of which bears the ^{13}C. d) At higher energy, fragments appearing at +2 and −2 amu relative to the position of the two major fragments indicated hydrogen transfer between the two macrocycles of the catenate.

tandem MS experiments, a single isotopomer of **4**, containing two ^{63}Cu nuclei and only one ^{13}C, was initially mass-selected. Upon collisions with argon during MS/MS experiments, this dication was observed to fragment cleanly into a pair of daughter ions possessing half of the initial mass and charge, distinguishable from each other by the fact that only one daughter ion possessed the ^{13}C nucleus.

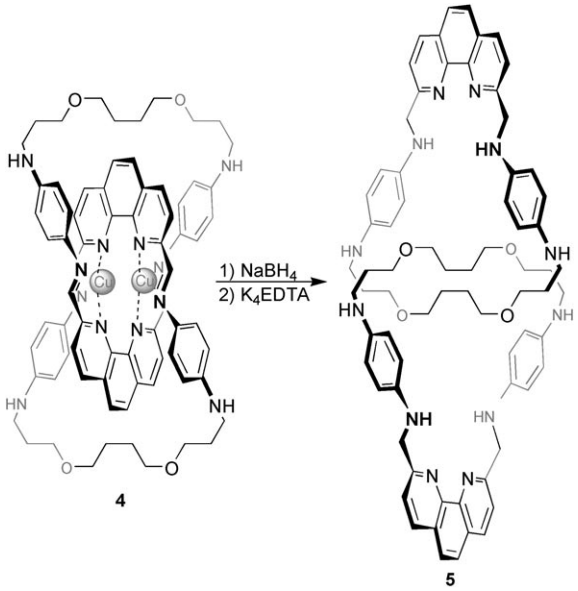
This symmetrical fragmentation behaviour has been observed in other catenated systems[27] and is characteristic of a topologically interlinked structure. Once a covalent bond of **4** has been broken, the only interactions holding the structure together would be coordinative bonds to copper(I). These weaker linkages could readily come apart under fragmentation conditions capable of breaking covalent bonds, resulting in facile dethreading of the ruptured macrocycle. Since charge repulsion supported the binding of one copper ion to each of the fragments, two daughter ions of half the initial mass and charge were observed.

At higher collision energies, a second process became more easily visible: "satellite" peaks appeared at positions 2 amu higher and lower than the major fragments. While the signals below them may have come from a loss of molecular hydrogen from the primary fragment, those appearing above the mass of the parent ion clearly indicated the transfer of two hydrogen atoms from one macrocycle to the other within the parent ion *prior* to fragmentation. No such process was observed for the demetallated species (see below); the participation of the Cu^{I} ions is thus implicated in this rearrangement. Even without detailed mechanistic knowledge, it is thus clear that rearrangement could compete energetically with the cleavage of the complex into two halves. This would not be expected for a simple Cu-bridged dimer of non-intertwined macrocycles.

To compare their fragmentation behaviour with that of catenate **4**, we conducted a series of MS/MS experiments on topologically "open" helicate **2** (Scheme 2) and "closed" macrocycle **1**. It was immediately clear that helicate **2** fragmented more readily than catenate **4**: to generate the intact dication of the helicate, much softer ionisation conditions were necessary than for the generation of the catenate dication. As with **4**, the ions of **2** corresponding to the second signal in the isotope pattern were mass-selected and subjected to collisions with argon. They also fragmented into two identical halves that were recognisable owing to the fact that only one of them contained a ^{13}C atom. No H_2 transfers between the two halves were observed, although **2** bore similar structural elements to catenate **4**. This suggested that the barrier for H_2 transfer must thus be higher than that for dissociation in the open-chain helicate. In the catenate, however, the mechanical inter-linkage prevented dissociation driven by charge-repulsion, which allowed H_2 shifts to compete with covalent bond rupture.

Macrocycle **1** did not fragment cleanly, but generated a series of different fragments consistent with its monocyclic structure. The rupture of any one covalent bond would give an open chain having the same mass as the initial macrocycle. A second covalent bond would need to be broken in order for fragmentation to occur, and there is no reason to expect this process to proceed cleanly or symmetrically.

As an additional cross-check, we reduced the imine bonds of **4** with borohydride and removed the copper by treatment with EDTA under basic, aerobic conditions (Scheme 7),[28]



Scheme 7. The reduction and demetallation of catenate **4** to give catenane **5**.

to give catenane **5**. Protonated, as well as sodiated, copper-free **5** displayed the same symmetrical MS/MS fragmentation behaviour as did **4**: as the fragmentation voltage was increased, **5** likewise fragmented symmetrically into two daughter ions of identical mass, implicating the presence of a catenated structure and precluding the presence of two non-interlinked macrocycles linked together by copper coordination in some unforeseen way.

Conclusion

In summary, we have demonstrated topological control over a subcomponent self-assembly reaction, allowing macrocyclic or catenated products to be uniquely selected based upon the rigidity and length of the subcomponents employed. It has also proven possible to switch reversibly between a macrocyclic topology and an open, double-helical topology as a function of the pH. We are investigating the use of this control over topology for the construction of more complex assemblies incorporating catenated subunits, in addition to the construction of other topologically interesting structures, such as knots.[3,29] Unlike the original Sauvage catenanes,[5] catenate **4** is helically chiral in addition to possessing the possibility of becoming topologically chiral through the incorporation of an asymmetrical dianiline. The investigation of both kinds of chirality in catenates similar to **4** is being investigated, particularly in the context of sub-

component substitution chemistry starting from enantiopure helicates.

Experimental Section

General: All manipulations were carried out in degassed solvents with reagents of the highest commercially available purity. $[Cu(NCMe)_4]BF_4$[30] and 1,10-phenanthroline-2,9-dialdehyde[31] were prepared following literature procedures. The ^1H NMR spectra of **1** and **4** were assigned with the help of COSY, ROESY, HSQC and HMBC measurements.[32] All chemical shifts were referenced to the residual proton or carbon signal of the deuterated solvent, or in aqueous solution to 2-methyl-2-propanol at 1.24 ppm (^1H) or 30.29 ppm (^{13}C) as the internal standard.

Dianiline precursor 1,12-bis[(4-nitrophenyl)amino]-4,9-dioxadodecane: 1-Fluoro-4-nitrobenzene (2.89 g, 20.5 mmol), 4,9-dioxa-1,12-dodecanediamine (1.64 g, 8.2 mmol) and triethylamine (3.5 mL, 24.9 mmol) were stirred overnight in dimethyl sulfoxide (40 mL) at 353 K. The product mixture was added to dichloromethane (250 mL), and washed with water (200 mL). The aqueous layer was washed with dichloromethane (250 mL) and the organics were washed with water (100 mL), then dried over $MgSO_4$ and filtered. Volatiles were then removed to yield 2.57 g (5.6 mmol, 70.1 %) of yellow microcrystalline product, which was pure by ^1H NMR spectroscopy. ^1H NMR (400 MHz, 298 K, [D$_6$]DMSO): δ = 7.97 (d, J = 9.0 Hz, 4H; phenyl), 7.27 (t, J = 5.5 Hz, 2H; -NH-), 6.61 (d, J = 9.5 Hz, 4H; phenyl), 3.42 (t, J = 6.0 Hz, 4H; -NH-$CH_2CH_2CH_2OCH_2CH_2$), 3.36 (m, 4H; -NH-$CH_2CH_2CH_2OCH_2CH_2$), 3.19 (m, 4H; -NH-$CH_2CH_2CH_2OCH_2CH_2$), 1.77 (*pseudo*-quint., J = 9.0 Hz, 4H; -NH-$CH_2CH_2CH_2OCH_2CH_2$), 1.54 ppm (m, 4H; -NH-$CH_2CH_2CH_2OCH_2CH_2$).

Dianiline b, **1,12-bis[(4-aminophenyl)amino]-4,9-dioxadodecane**: 1,12-Bis[(4-nitrophenyl)amino]-4,9-dioxadodecane (1.82 g, 4.1 mmol), Pd/C (0.275 g, 15 wt %) and ethanol (50 mL) were stirred overnight under an atmosphere of H_2. The solution was filtered through diatomaceous earth, and the volatiles were evaporated to give a purple solid (1.45 g, 3.8 mmol; 92.6 % yield), which was pure by NMR spectroscopy. ^1H NMR (400 MHz, 298 K, [D$_6$]DMSO): δ = 6.41 (d, J = 8.5 Hz, 4H; phenyl), 6.35 (d, J = 8.5 Hz, 4H; phenyl), 4.59 (br s, 2H; -NH-), 4.21 (br s, 4H; NH_2-phenyl), 3.44 (t, J = 6.0 Hz, 4H; -NH-$CH_2CH_2CH_2OCH_2CH_2$), 3.37 (br m, 4H; -NH-$CH_2CH_2CH_2OCH_2CH_2$), 2.94 (t, J = 6.5 Hz, 4H; -NH-$CH_2CH_2CH_2OCH_2CH_2$), 1.72 (*pseudo*-quint., J = 6.5 Hz, 4H; -NH-$CH_2CH_2CH_2OCH_2CH_2$), 1.54 ppm (br m, 4H; -NH-$CH_2CH_2CH_2OCH_2CH_2$); ^{13}C NMR (100.62 MHz, 298 K, [D$_6$]DMSO): δ = 140.31, 138.90, 115.50, 113.58, 69.86, 68.20, 41.43, 29.32, 26.14 ppm; FAB-MS: m/z (%): 386 (100).

Macrocycle 1: Into a 50-mL Schlenk flask was added diamine **a** (32.5 mg, 0.219 mmol), 1,10-phenanthroline-2,9-dialdehyde (51.8 mg, 0.219 mmol), $[Cu(NCMe)_4]BF_4$ (68.9 mg, 0.219 mmol) and water (5 mL) to give a brown-orange solution. The flask was sealed, and the atmosphere was purged of dioxygen by five evacuation/argon fill cycles. The reaction mixture was stirred overnight at room temperature. The solution was cannula-filtered, and volatiles were removed under a dynamic vacuum to give a black-brown microcrystalline product (97 mg, 0.097 mmol; 88.8 % yield), which was pure by NMR spectroscopy. When this reaction was conducted in an NMR tube, **1** was the only observed product. ^1H NMR (500 MHz, 298 K, D_2O): δ = 8.81 (d, J = 8.0 Hz, 4H; 4,7-phenanthroline), 8.59 (s, 4H; imine), 8.21 (s, 4H; 5,6-phenanthroline), 8.19 (d, J = 8.0 Hz, 4H; 3,8-phenanthroline), 3.37 (br d, J = 10.5 Hz, 4H; C=$NCH_2CH_2OCH_2$), 3.28 (br t, J = 11.0 Hz, 4H; C=$NCH_2CH_2OCH_2$), 3.10 (br d, J = 9.5 Hz, 4H; C=$NCH_2CH_2OCH_2$), 2.86 (br d, J = 10.5 Hz, 4H; C=$NCH_2CH_2OCH_2$), 2.39 (br t, J = 9.0 Hz, 4H; C=$NCH_2CH_2OCH_2$), 2.19 ppm (br d, J = 11.5 Hz, 4H; C=$NCH_2CH_2OCH_2$); ^{13}C NMR (125.77 MHz, 298 K, D_2O): δ = 162.99, 149.77, 141.81, 138.82, 133.16, 129.09, 126.69, 71.25, 70.51, 58.66 ppm; ESI-MS: m/z (%): 412.5 (100)([**1**]$^{2+}$), 909.5 (12)([**1**+BF_4]$^+$).

Interconversion between 1 and 3: Into an NMR tube with a Teflon screw-cap was added **1** (1.3 mg, 1.3×10^{-6} mol), sulfanilic acid (0.9 mg, 5.2×10^{-6} mol) and deuterium oxide (0.6 mL) to give a brown solution. The atmosphere was purged of dioxygen by five evacuation/argon fill cycles. After one night at room temperature, the solution had turned green and the only observed product in the ^1H NMR spectra was **3**. $NaHCO_3$ (0.5 mg, 5.9×10^{-6} mol) was added, and the atmosphere was again purged of dioxygen by five evacuation/argon fill cycles. The solution was observed to become brown again, and the peaks corresponding to **1** were observed to reappear after three days at room temperature.

X-ray crystal structure of 1: Fragile crystals of the perchlorate salt of **1** were obtained by counter-diffusion of aqueous solutions of **1** and Ba$(ClO_4)_2$. $[(C_{40}H_{40}N_8O_4)Cu_2](ClO_4)_2$; M_r = 1022.9; triclinic, $P\bar{1}$, a = 12.2197(10), b = 12.8477(9), c = 16.5290(15) Å, α = 86.173(10), β = 68.684(10), γ = 63.868(8)°, V = 2156.8(4) Å^3, Z = 2, μ = 0.182 mm^{-1}, ρ_{calcd} = 1.575 g cm^{-3}, 200 K, Stoe IPDS diffractometer, $Mo_{K\alpha}$ radiation. (λ = 0.71073 Å). The structure was solved by direct methods (SIR 97),[33] all other calculations were performed with the XTAL system[34] and ORTEP-3[35] programs; 22872 measured reflections, 7785 unique reflections of which 3585 were observables ($|F_o|>3\sigma(F_o)$); R = 0.043, ωR = 0.039. The oxygen atoms of perchlorate *a* are disordered and refined on two distinct sites with population parameters of 0.70 and 0.30, respectively. CCDC-266712 (**1**) contains the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.

Catenate 4: Into a 50-mL Schlenk flask was added 1,10-phenanthroline-2,9-dialdehyde (24.7 mg, 0.105 mmol), $[Cu(NCMe)_4]BF_4$ (33.0 mg, 0.105 mmol) and freshly distilled nitromethane (3 mL) to give a dark red solution. The flask was sealed, and the atmosphere was purged of dioxygen by three evacuation/argon fill cycles. When the mixture was homogeneous, a solution of dianiline **b** (40.4 mg, 0.105 mmol) in freshly distilled nitromethane (3 mL) was added, and the atmosphere was purged again by three evacuation/fill cycles. This mixture was heated at 323 K overnight with stirring. Volatiles were then evaporated under dynamic vacuum to give a dark red product (77 mg, 0.052 mmol; 99.4 % yield), which was pure by NMR spectroscopy. ^1H NMR (500 MHz, 298 K, CD_3NO_2): δ = 8.75 (s, 4H; imine), 8.36 (d, J = 8.0 Hz, 4H; 4,7-phenanthroline), 8.06 (d, J = 8.0 Hz, 4H; 3,8-phenanthroline), 7.76 (s, 4H; 5,6-phenanthroline), 6.06 (d, J = 8.5 Hz, 8H; phenylene next to imine), 5.80 (d, J = 8.5 Hz, 8H; phenylene next to amine), 3.63 (m, 16H; $NHCH_2CH_2CH_2OCH_2CH_2$), 3.05 (m, 8H; $NHCH_2CH_2CH_2OCH_2CH_2$), 1.85 ppm (m, 16H; $NHCH_2CH_2CH_2OCH_2CH_2$); ^{13}C NMR (125.77 MHz, 298 K, CD_3NO_2): δ = 151.67, 150.66, 150.05, 142.98, 137.58, 136.43, 133.05, 129.03, 126.46, 124.43, 112.97, 72.21, 69.91, 41.57, 30.16, 28.15 ppm; ESI-MS: m/z (%): 650.2(100)([**4**]$^{2+}$).

MS experiments: High-resolution ESI mass spectra and MS/MS spectra were recorded on a Bruker APEX IV Fourier-transform ion-cyclotron-resonance (FT-ICR) mass spectrometer with an Apollo electrospray ion source equipped with an off-axis 70° spray needle. Typically, the spray solvent was acetone, and ≈50 μM solutions of the analytes were used. Analyte solutions were introduced into the ion source with a syringe pump (Cole-Palmers Instruments, Series 74900) at flow rates of ≈3–4 μL min^{-1}. Ion transfer into the first of three differential pumping stages in the ion source occurred through a glass capillary with 0.5-mm inner diameter and nickel coatings at both ends. Ionisation parameters were adjusted as follows: capillary voltage: −4.5 kV; endplate voltage: −4.1 kV; capexit voltage: +150 to +190 V; skimmer voltages: +8 to +12 V; temperature of drying gas: 423 K. The flows of the drying and nebuliser gases were kept quite low. The ions were accumulated in the instrument's hexapole for 0.5–1 s and then introduced into the FT-ICR cell, which was operated at pressures below 10^{-10} mbar, and detected by a standard excitation and detection sequence. For each measurement, 16 to 128 scans were averaged to improve the signal-to-noise ratio.

For MS/MS experiments, the whole isotope patterns of the ion of interest were isolated by applying correlated sweeps. Since the macrocycle **1** as well as the catenate complex **4** are dications, the peak spacing of the isotope pattern was $\Delta m/z$ = 0.5. It was important to mass-select the second isotope peak, since the formation of two identical singly charged fragments in a symmetrical cleavage would otherwise lead to ions appearing

at exactly the same mass-to-charge ratio as the parent ion. The choice of the second isotope peak guaranteed that the ions contained only ^{63}Cu and exactly one ^{13}C. The two symmetrical fragments observed upon increasing the fragmentation voltage thus must differ by 1 Da from each other and by 0.5 Da from the parent ion on account of their different ^{13}C content. After isolation of the required isotope peak by shots that selectively removed the unwanted isotope peaks, the ions of interest were subjected to the CID experiment. Argon was introduced into the ICR cell as the collision gas through a pulsed valve at a pressure of $\approx 10^{-8}$ mbar. The ions were accelerated by a standard excitation protocol and detected after a 2 s pumping delay. A sequence of several different spectra was recorded at different excitation pulse attenuations to obtain at least a rough and qualitative idea of the effects of different collision energies on the fragmentation patterns.

Demetallation and reduction of 4 to afford 5: Complex **4** (3.5 mg, 2.3×10^{-6} mol) was dissolved in DMSO (0.3 mL) under argon. To this mixture was added a methanolic solution (0.3 mL) of $NaBH_4$ (7.0 mg, 1.8×10^{-4} mol). This solution was deoxygenated by three evacuation/argon fill cycles and kept at room temperature overnight. The colour of the solution changed from red to yellow. The solution was filtered through a cotton plug in a Pasteur pipette, and the product was precipitated by the addition of doubly distilled water. The supernatant was decanted, and the solid was washed with a saturated aqueous solution of tetrapotassium EDTA (4 mL). The isolated product **5** was dried under vacuum and used directly for mass spectrometric measurements. Because the reaction was not scaled up, the yield was difficult to determine. Based on a comparison between the product resonances and the residual proton resonance of the solvent, we estimated the yield to be $>50\,\%$. ^{1}H NMR (400 MHz, 298 K, [D$_6$]DMSO): $\delta = 8.32$ (d, $J = 8.0$ Hz, 2H; 4,7-phenanthroline), 7.85 (s, 2H; 5,6-phenanthroline), 7.62 (d, $J = 8.0$ Hz, 2H; 3,8-phenanthroline), 5.63 (d, $J = 8.5$ Hz, 4H; phenylene), 5.56 (d, $J = 8.5$ Hz, 4H; phenylene), 4.15 (s, 4H; phenanthroline-CH_2-NH-phenylene), 3.40 (m, 8H; -NH-CH$_2$CH$_2$CH_2OCH$_2$CH$_2$, -NH-CH$_2$CH$_2$CH$_2$OCH_2CH$_2$), 2.94 (m, 4H; -NH-CH_2CH$_2$CH$_2$OCH$_2$CH$_2$), 1.73 (br m, 4H; -NH-CH$_2$CH$_2$CH$_2$OCH$_2$CH_2), 1.59 ppm (*pseudo*-quint., $J = 7.0$ Hz, 4H; -NH-CH$_2$CH_2CH$_2$OCH$_2$CH$_2$); ESI-MS: *m*/*z*: 1203.6 ([**5**+Na]$^+$), 1181.7 ([**5**+H]$^+$), 613.3 ([$^1/_2$**5**+Na]$^+$), 602.3 ([**5**+2Na]$^{2+}$), 591.3 ([$^1/_2$**5**+H]$^+$). MS/MS experiments were conducted following the procedure described above. When the ion corresponding to [**5**+Na]$^+$ was mass-selected, this species was observed to fragment cleanly, yielding a daughter ion peak that corresponds to [$^1/_2$**5**+Na]$^+$, with the intensity of this peak increasing as the collision energy was increased. The spectra are given in the Supporting Information.

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