

Templated Synthesis of Catenanes and Rotaxanes

Andrew C. Moreland

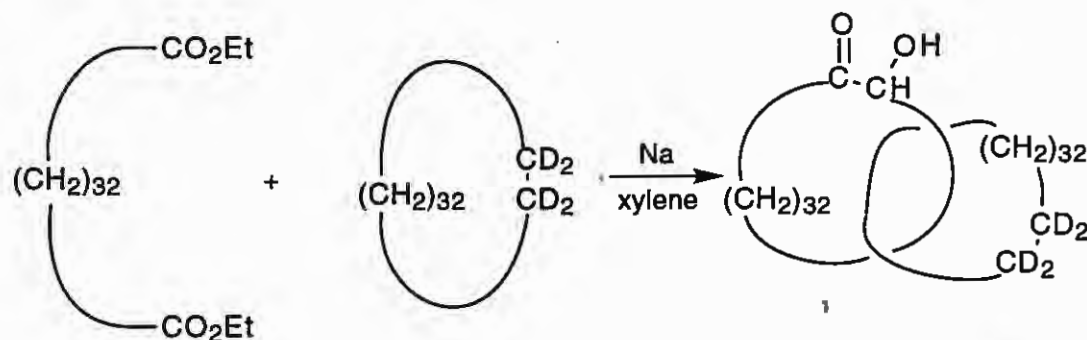
Literature Seminar

October 3, 1996

Catenanes are compounds composed of interlocking rings resembling the links of a chain, while rotaxanes are characterized by a ring encircling a linear fragment stoppered with bulky groups on either end.¹ These types of compounds are of interest not only from a synthetic standpoint but as precursors to molecular level devices² and topologically asymmetric species.³

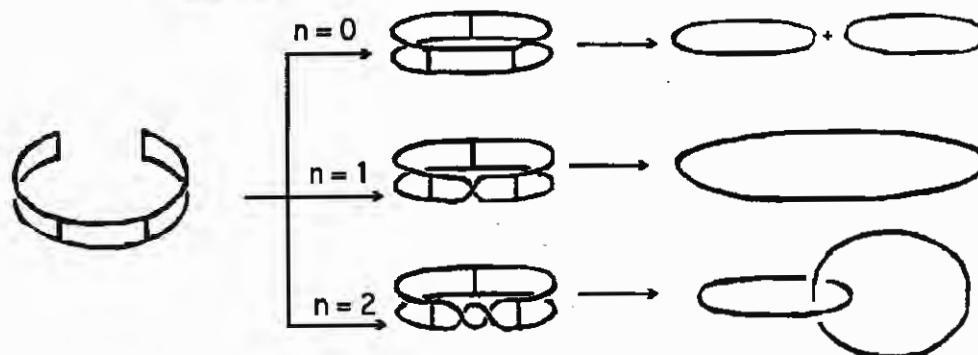
Much of the interest in catenanes stems from the discovery of catenated structures in the DNA of some bacteria and viruses.⁴ These catenane species, known as duplex circular DNA consist of interlocked rings and have been isolated in forms such as [2]-catenanes and higher homologs.⁵

There are several different strategies in the synthesis of catenanes. The first catenane synthesis, in 1960, was achieved following a statistical threading approach. Wasserman⁶ used the acyloin condensation⁷ of a 34 carbon diester in the presence of a labeled 34 carbon ring.



A small percentage of the purified acyloin product contained C-D bonds by IR spectroscopy, thus proving that a catenane could be formed by this methodology.

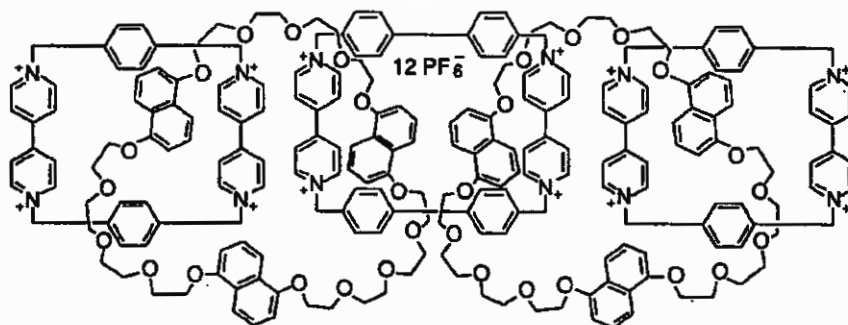
A second strategy to catenane synthesis is the mobius strip approach, based on a molecular ladder, shown schematically below.⁸



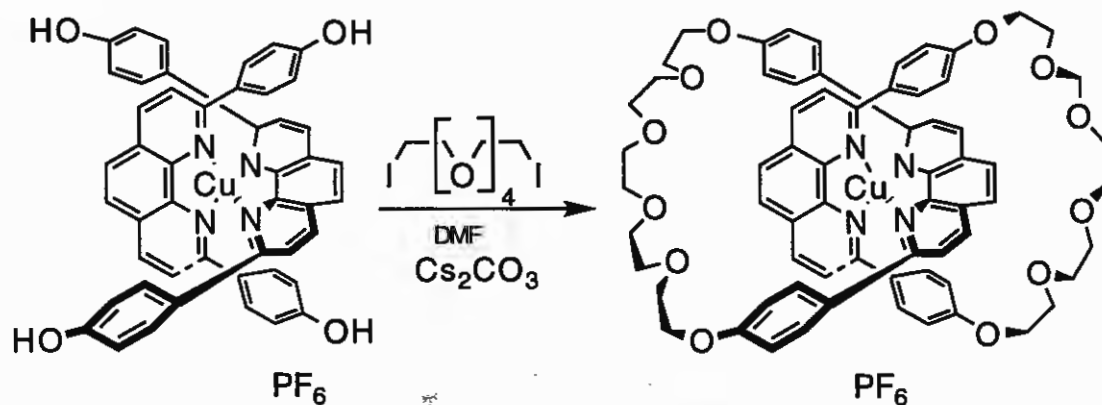
Depending on the number of twists the molecular ladder takes before it is closed, the final product is two small rings, one large ring, or a [2]-catenane. This methodology was tested by Walba in 1982.⁹ A molecular ladder based on THYME (tetrahydroxymethylethylene) was cyclized using NaH in DMF at high dilution. Equimolar amounts of the cylinder ($n=0$) and singly twisted mobius strip ($n=1$) were isolated. This synthesis, while interesting for conjecture, has yet to produce a catenane, presumably due to steric destabilization of the doubly twisted mobius strip.

Virtually all work on catenanes today is based on the templated approach.¹⁰ If a ring and a thread have a driving force to associate, such as a template, prior to ring closure of the thread, catenated structures can be formed with much more predictability and in much higher yields. There are currently two types of templates, those based on π - π interactions, and templates based on metal ions.

The work of J. F. Stoddart pioneered the area of organic templated catenanes and rotaxanes.¹¹ The template interaction is based on the fact that π -electron rich aromatic rings tend stack in a parallel fashion with π -electron deficient rings. Therefore, if the substituents can be placed on the rings with the proper steric and electron-donation requirements, catenanes follow easily in high yield.¹² The Stoddart group has been able to make some quite impressive supramolecular assemblies based on this strategy, such as the molecule, Olympiadane, based on the design of the Olympic rings.¹³



The other type of templated interaction is based on metal ions, which can arrange incoming ligands into predictable geometries.¹⁴ Utilizing assorted coordination geometries of transition metals, such as square planar¹⁵ or tetrahedral,^{4,16-19} catenane syntheses can be designed using ligands with catenation geometry. The best known example of the metal template approach is the work of J. P. Sauvage.^{4,16-19} The Sauvage group relies on the tetrahedral coordination of Cu(I) with the ligand 2,9-dianisyl-1,10-phenanthroline as a catenane precursor.



Once in the proper catenation geometry, the ligands can then be cyclized at high dilution using the diiodide derivative of pentaethyleneglycol to give the corresponding catenane.¹⁷

The catenand, or catenane ligand, stabilizes the Cu(I) to electrochemical reduction and slows the rate demetallation with CN⁻.¹⁸ This "catenand effect" can be taken advantage of to stabilize metal ions which prefer a tetrahedral geometry.¹⁹ Since aromatic nitrogen ligands

are known to stabilize low oxidation states,²⁰ a catenand containing a derivative of 1,10-phenanthroline should be expected to stabilize low oxidation state metal ions which prefer a tetrahedral geometry. One example of this stabilization is the isolation of a Ni(I) catenane.¹⁹ The Cu catenane is demetallated with CN⁻ giving free ligand, which is added to a solution of Ni(H₂O)₆(NO₃)₂. The resulting Ni(II) complex is reduced electrochemically to give a Ni(I) species. The Ni(I) catenane takes several days to be reoxidized by oxygen saturated CH₂Cl₂, whereas a Ni(I) phenanthroline is oxidized by air in minutes, further evidence of the catenand effect.

Overall, the templated synthesis of catenanes is far superior to other synthetic strategies due to the preassociation of the two rings to be linked.^{11,17} This association helps to dramatically increase yields and predictability of the synthetic method.

References

1. Vögtle, F. "Catenanes, Catenands and Catenates," in *Supramolecular Chemistry: An Introduction*, Wiley: New York; 1991, 116-128.
2. Bissell, R. A.; Cordova, E.; Kaifer, A. E.; Stoddart, J. F. "A Chemically and Electrochemically Switchable Molecular Shuttle," *Nature* **1995**, *369*, 133-137.
Lindsey, J. S. "Self-Assembly in Synthetic Routes to Molecular Devices. Biological Principles and Chemical Perspectives: A Review," *New J. Chem.* **1991**, *15*, 153-180.
Collin, J. P.; Gavina, P.; Sauvage, J. P. "Electrochemically Induced Molecular Motions in a Copper(I) Complex Pseudorotaxane," *Chem. Comm.* **1996**, 2006-2007.
3. Mitchell, D. K.; Sauvage, J. P. "A Topologically Chiral [2]Catenand," *Angew. Chem. Int. Ed. Engl.* **1988**, *27*, 930-931.
4. Dietrich-Buchecker, C. O.; Sauvage, J. P. "Interlocking of Molecular Threads: From the Statistical Approach to the Templated Synthesis of Catenands," *Chem. Rev.* **1987**, *87*, 795-810.
5. Hudson, B.; Vinograd, J. "Catenated Circular DNA Molecules in HeLa Cell Mitochondria," *Nature* **1967**, *216*, 647-651.
6. Wasserman, E. "The Preparation of Interlocking Rings: A Catenane," *J. Am. Chem. Soc.* **1960**, *82*, 4433-4435.
7. March, J. "Acylol Ester Condensation," in *Advanced Organic Chemistry*, 4th ed., Wiley: New York, 1992, 1228-1232.
8. Frisch, H. L.; Wasserman, E. "Chemical Topology," *J. Am. Chem. Soc.* **1961**, *83*, 3789-3795.
9. Walba, D. M.; Richards, R. M.; Haltiwanger, R. C. "Total Synthesis of the First Molecular Mobius Strip," *J. Am. Chem. Soc.* **1982**, *104*, 3219-3221.
10. Amabilino, D.; Stoddart, J. F. "Interlocked and Intertwined Structures and Superstructures," *Chem. Rev.* **1995**, *95*, 8, 2725-2828.
11. Philp, D.; Stoddart, J. F. "Self-Assembly in Organic Synthesis," *Synlett.* **1991**, 445-458.

12. Ashton, P. R.; Goodnow, T. T.; Kaifer, A. E.; Reddington, M. V.; Slawin, A. M. Z.; Spencer, N.; Stoddart, J. F.; Vicent, C.; Williams, D. J. "A [2]-Catenane Made to Order," *Angew. Chem. Int. Ed. Engl.* **1989**, *28*, 1396-1399. Gunter, M. J.; Hockless, D. C. R.; Johnston, M. R.; Skelton, B. W.; White, A. H. "Self-Assembling Porphyrin [2]-Catenanes," *J. Am. Chem. Soc.* **1994**, *116*, 4810-4823. Ottens-Hildebrandt, S.; Harren, J.; Vögtle, F. "Sulfonamide-based Catenanes - Regioselective Template Synthesis," *Liebigs Ann.* **1995**, 1855-1860.
13. Amabilino, D.; Ashton, P. R.; Reder, A. S.; Spencer, N.; Stoddart, J. F. "Olympiadane," *Angew. Chem. Int. Ed. Engl.* **1994**, *33*, 1286-1290.
14. Chambron, J. C.; Dietrich-Buchecker, C. O.; Nierengarten, J. F.; Sauvage, J. P. "Transition Metals as Templating Species: From Catenanes and Knots to Strings Threaded through Molecular Rings," *Pure & Appl. Chem.* **1994**, *66*, 7, 1543-1550.
15. Fujita, M.; Ibukuro, F.; Hagihara, H.; Ogura, K. "Quantitative Self-Assembly of a [2]-Catenane from Two Preformed Molecular Rings," *Nature* **1994**, *367*, 720-723. Fujita, M.; Ibukuro, F.; Yamaguchi, K.; Ogura, K. "A Molecular Lock," *J. Am. Chem. Soc.* **1995**, *117*, 4175-4176. Fujita, M.; Ibukuro, F.; Seki, H.; Kamo, O.; Imanari, M.; Ogura, K. "Catenane Formation from Two Molecular Rings through Very Rapid Slippage. A Mobius Strip Mechanism," *J. Am. Chem. Soc.* **1996**, *118*, 899-900.
16. Amabilino, D. B.; Dietrich-Buchecker, C. O.; Sauvage, J. P. "Rings-and-String Approach to the Construction of Porphyrin Arrays by Transition-Metal-Directed Threading," *J. Am. Chem. Soc.* **1996**, *118*, 3285-3286.
17. Dietrich-Buchecker, C. O.; Sauvage, J. P.; Kern, J. M. "Templated Synthesis of Interlocked Macrocyclic Ligands: The Catenands," *J. Am. Chem. Soc.* **1984**, *106*, 3043-3045.
18. Albrecht-Gary, A. M.; Saad, Z.; Dietrich-Buchecker, C. O.; Sauvage, J. P. "Interlocked Macrocyclic Ligands: A Kinetic Catenand Effect in Copper(I) Complexes," *J. Am. Chem. Soc.* **1985**, *107*, 3205-3209. Chambron, J. C.; Dietrich-Buchecker, C.; Nierengarten, J. F.; Sauvage, J. P.; Solladie, N.; Albrecht-Gary, A. M.; Meyer, M. "Transition-Metal-Directed Threading of Molecular Strings into Coordinating Rings: Synthetic Aspects and Kinetic Study of the Dethreading Process," *New J. Chem.* **1995**, *19*, 409-426.
19. Dietrich-Buchecker, C. O.; Guilhem, J.; Kern, J. M.; Pascard, C.; Sauvage, J. P. "Molecular Structures of a Monovalent and Divalent Nickel Catenate: Competition Between Metal Orbital Requirements and Geometrical Constraints Imposed by the Ligand," *Inorg. Chem.* **1994**, *33*, 3498-3502.
20. Cotton, F. A.; Wilkinson, G. *Advanced Inorganic Chemistry*, 4th ed.; Wiley: New York, 1980, 119-120.