# Cu(I)/Cu(II) templated functional pseudorotaxanes and rotaxanes

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**Abstract.** Threaded complexes like pseudorotaxanes, rotaxanes based on Cu(I)/Cu(II) ions have shown to be promising for the construction of mechanically interlocked molecular-level architectures. In this short review, we focus on the synthetic strategies developed to construct pseudorotaxanes and rotaxanes using Cu(I)/Cu(II) ions as template. Further, brief discussions on chemical and mechanical properties associated with some of the selected to Cu(I)/Cu(II) based pseudorotaxanes and rotaxanes are presented.

**Keywords.** Interlocked molecules; metal template; shuttling; substitution; self-sorting.

## 1. Introduction

Sauvage *et al*. showed the first template directed synthesis of a threaded complex using Cu(I) in 1983.[1] Even after 30 years of its discovery this template strategy is very popular to the supramolecular chemists to achieve the goal to synthesize all kinds of threaded molecules.[2] The development in the field of template directed synthesis of interlocked molecules gives the scope to synthesize more and more complicated threaded structures of complex properties to mimic different mechanical properties in the molecular level.[3] These molecules, in which some of the components are connected mechanically rather than by covalent bonds, could potentially find application in the modification of physical and chemical properties, as smart materials with switchable surface properties and in molecular electronics and other types of molecular machinery.[4] Interlocked molecules such as pseudorotaxanes, rotaxanes, catenanes and knots have attracted a great deal of attention in recent years.[2,4,5] This is because of their challenging
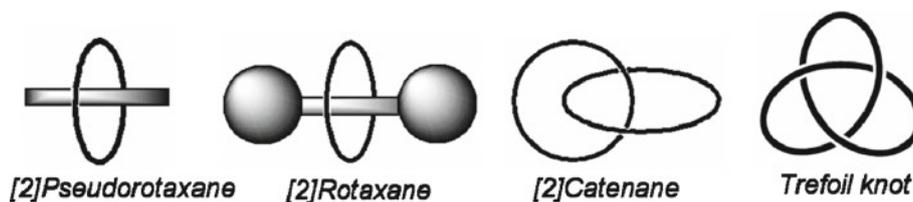


construction and potential applications in areas such as molecular devices, molecular switches, molecular wires, and information storage.[6,7] This century demands the execution of interlocked molecules for the machinery work played at the molecular level using these threaded complexes. Among these threaded systems pseudorotaxanes are shown important building blocks for syntheses of higher generation mechanically interlocked structures such as rotaxanes and catenanes, etc.[8] Pseudorotaxanes have got huge attention in recent decades due to their unique nature to undergo many flexible reactions and perform versatile tasks, on account of their assembly/disassembly behaviours.[9] Different types of synthetic strategies have been developed for the construction of pseudorotaxanes and rotaxanes molecules.[2,10,11] Rotaxanes could easily be achieved by introducing bulky stopper units at the both ends of a pseudorotaxane molecule.[8] Alternatively, clipping approach is also used to construct rotaxane molecules.[11] Among variety of strategies developed, metal template has shown promising synthetic tool for the construction of pseudorotaxanes and rotaxanes.[2] Further, copper ions have shown promising template for such interlocked molecular construction.[5b, 10,12] Present

situations in this subject demands to explore the interesting chemical and mechanical properties associated to the threaded molecules along with their synthetic developments. In the present discussion, we focus on copper ion-assisted synthesis of pseudorotaxanes, rotaxanes and their chemical or mechanical properties like shuttling, switching, threading/dethreading, self-sorting, and signalling and axle substitution phenomenon.

## 2. Classical templates

Two different approaches like threading and clipping methods are developed for the template synthesis of pseudorotaxanes and rotaxanes. Different types of non-covalent interactions are encountered between wheel and axle for the effective template synthesis of inter-locked molecules. The major non-covalent interactions that are extensively used for the construction of threaded assemblies are (i) metal/ligand coordination, (ii) donor/acceptor forces, (iii) hydrogen bonding, (iv) $\pi-\pi$ stacking, (v) electrostatic forces.[13] Metal ions as templates has shown accessible pathways to synthesize various topologically complex interlocked molecules that would be sometime unobtainable by classical chemistry methods. Thus, in the last few years, chemists in this area are showing much more interest to the metal templated synthesis of interlocked molecules. In the absence of a metal template, negligible threading of one component through another can be observed for such reactions. Generally, without templation above reaction favours the formation of oligomers and/or macrocycles of various sizes.

## 3. Cu(I)/Cu(II) template

A large number of transition metal ions are reported as template for the synthesis of various interlocked molecules.[2] However, copper ions has taken the leading role to achieve such interesting supramolecular assem-
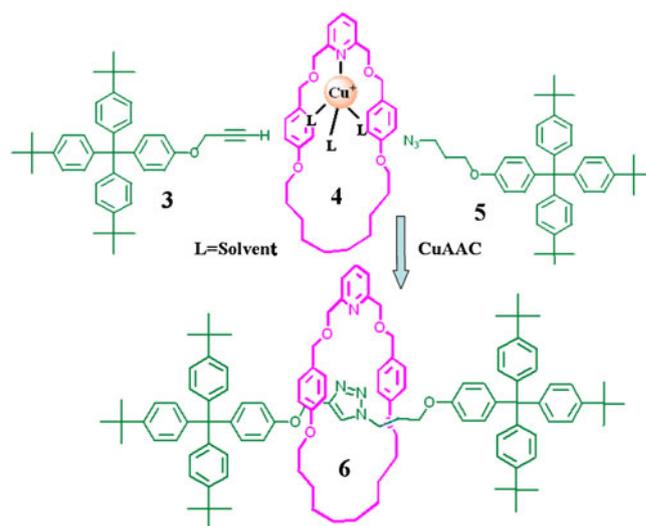


**Figure 2.** Active metal template synthesis of interlocked molecules.

blies.[12] Sauvage group mostly used Cu(I) as template for the synthesis of 1,10 phenanthroline based threaded architectures.[12] The coordinating building units are phenanthroline that gives suitable tetrahedral geometry around Cu(I) centre (figure 1). Cu(I) is also used in active metal template strategy, where the Cu(I) acts as a template as well as plays an active role in promoting the crucial covalent bond formation to generate an interlocked structure.[10a] The tetrahedral arrangement of ligands around Cu(I) should direct the copper(I)-catalysed azide–alkyne cycloaddition (the CuAAC 'click' reaction) reaction of appropriately 'stoppered' alkyne and azide units through the cavity of macrocycles to afford the corresponding [2]rotaxanes (figure 2). But template synthesis by Cu(II) is relatively less explored area of research.[14] Recent reports show the promising nature of Cu(II) as template for the synthesis of mononuclear and multinuclear pseudorotaxanes.[15]

A series of [2]pseudorotaxanes are reported using different bidentate ligands, **9–12** as axles (figure 3).[15a]
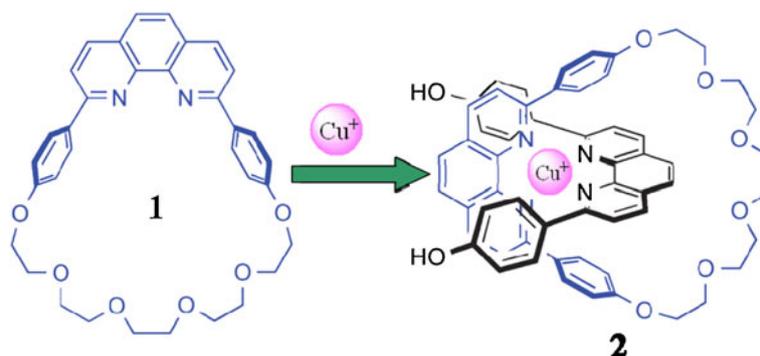


**Figure 1.** Sauvage's Cu(I) templation.
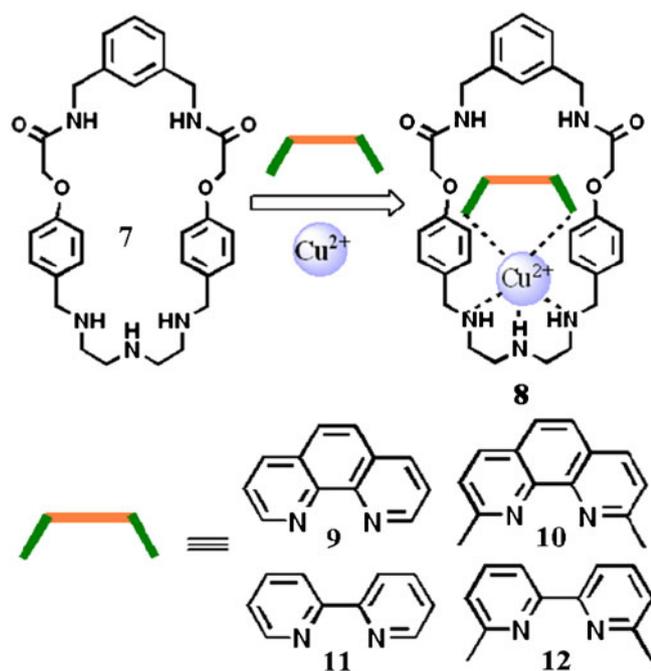
**Figure 3.** Cu(II) template synthesis of [2]pseudorotaxanes.

The solid state structure of the Cu(II) templated 1,10 phenanthroline (**9**) threaded [2]pseudorotaxane shows that Cu(II) centre is in pentacoordination with trigonal bipyramidal geometry.[15a] Three of the coordination sites are attached to –NH of the macrocyclic wheel, **7** and the other two are coordinated with nitrogen centres of **9**. A multinuclear Cu (II) templated [3]pseudorotaxane is also synthesized using a bisbidentate fluorophoric axle, **13** and **7** (figure 4).[15b] The solid state structural analysis shows a square pyramidal geometry around the Cu (II) centres.

## 4. Activity of Cu(I)/Cu(II) based pseudorotaxanes and rotaxanes

Despite some early synthetic difficulties, the field of mechanically interlocked molecules has matured into a rich and rewarding field of research and this category of molecules are continually being produced. Presently, these compounds are attractive for their characteristic and interesting static and dynamic properties that also include their topological behaviour as well as switching properties. In this section, we will discuss the interesting properties reported so far with the Cu(I)/Cu(II) based pseudorotaxanes and rotaxanes.

### 4.1 *Molecular shuttle*

Molecular shuttles are a potential class of molecular machines. A ring (macrocyle) can glide along an axis (linear molecule) on which it has been threaded in a controlled fashion. This translocation of ring can even be realized over large distances by designing axle with the various lengths incorporated in the thread and the number of stations (ring arresting site) with which a given part of the ring is able to interact. The approach is based on transition metals and, in particular, on Cu(I) and Cu(II). A Cu(I) templated rotaxane, **15** having axle with two metal binding station (figure 5).[16] The principle of a two-stations molecular shuttle whose motions are driven by changing the metal centre oxidation state is indicated in figure 5. The stable 4-coordinate monovalent complex is first oxidized to an intermediate tetrahedral divalent species. This compound undergoes a complete reorganization process by translating the ring along the thread to afford the stable 5-coordinate Cu (II) complex. Upon reduction, an unstable Cu(I) 5-coordinated complex is formed, and finally undergoes the inverse conformational change that regenerates the starting complex.

### 4.2 *Redox-driven pirouetting motion*

An interesting copper(I)-templated [2]rotaxane is described that shows fast-moving pirouetting motion, triggered by an electrochemical signal.[17] It consists of a
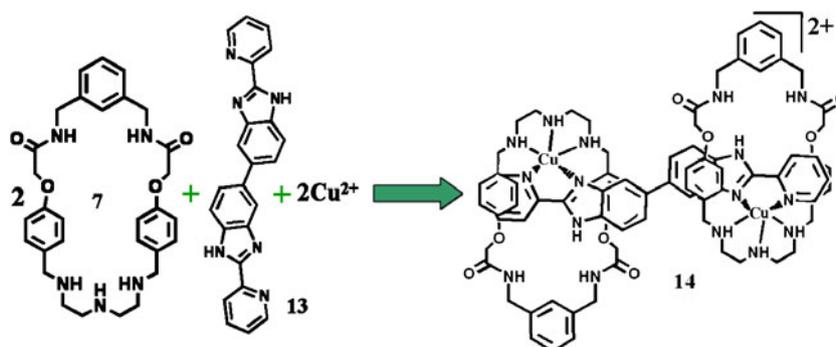


**Figure 4.** Cu(II) template synthesis of [3]pseudorotaxane.
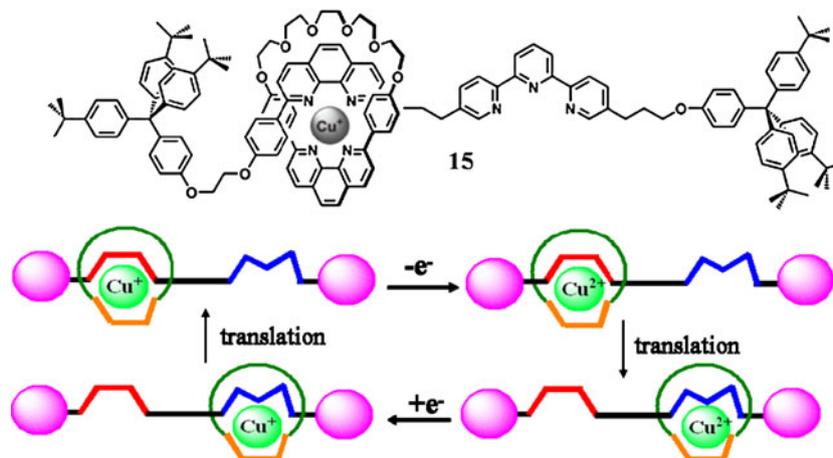
**Figure 5.** Cu(I) templated rotaxane with two metal binding station and schematic representation of the [2]rotaxane acting as an electrochemically-driven molecular shuttle.

two-coordination site ring threaded by a sterically non-hindering 2,2′-bipyridine derivative (figure 6). An electrochemical signal [oxidation or reduction of the copper centre, Cu(I) or Cu(II)] induces rearrangement of the system. By using long and flexible linkers between the stoppers and the central complex, ligand exchange is fast, which leads to short response times (on the millisecond time scale and even below).

4.3 *Translational motion between two triazole station*

A rotaxane **17** with *bis* triazole ring in the axle is synthesized using CuAAC reaction with good yield.[18] The

triazole ring is a good metal coordinating ligand and can act as binding sites for a metal coordinated macrocycle. The movement of the wheel between the two triazole stations of a rotaxane is investigated in the presence of Cu(I) by ¹H NMR studies at room temperature (CD₂Cl₂–CD₃CN 1: 9, 298 K) (figure 7). A comparative study of ¹H NMR spectrum of the free axle with that of the rotaxane indicates that the wheel is randomly explores the full length of the axle. When Cu(I) is added to the rotaxane to form the copper(I)-complex of rotaxane that shows fast shuttling of the wheel between the two triazole stations at room temperature. This type of fast shuttling between well-defined macrocycle binding
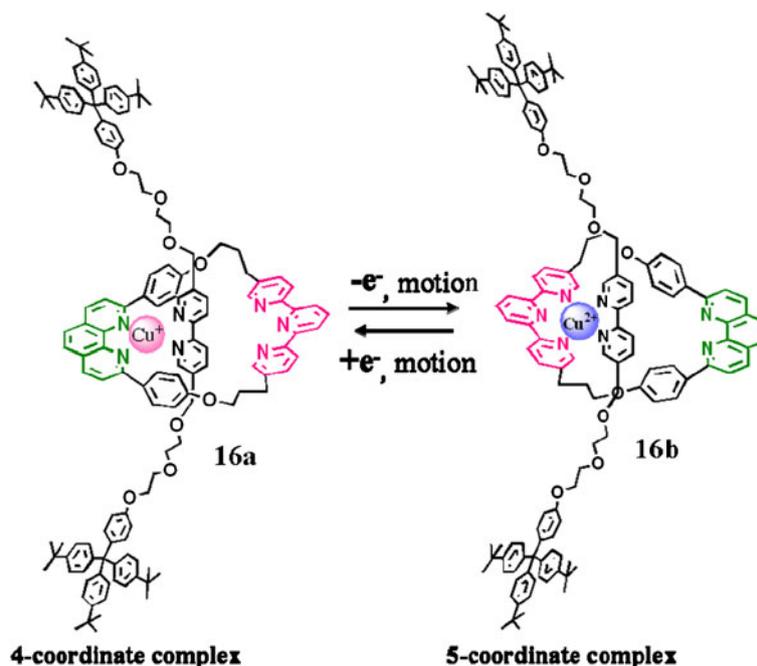


**Figure 6.** Translational motion of a Cu(I) template rotaxane.
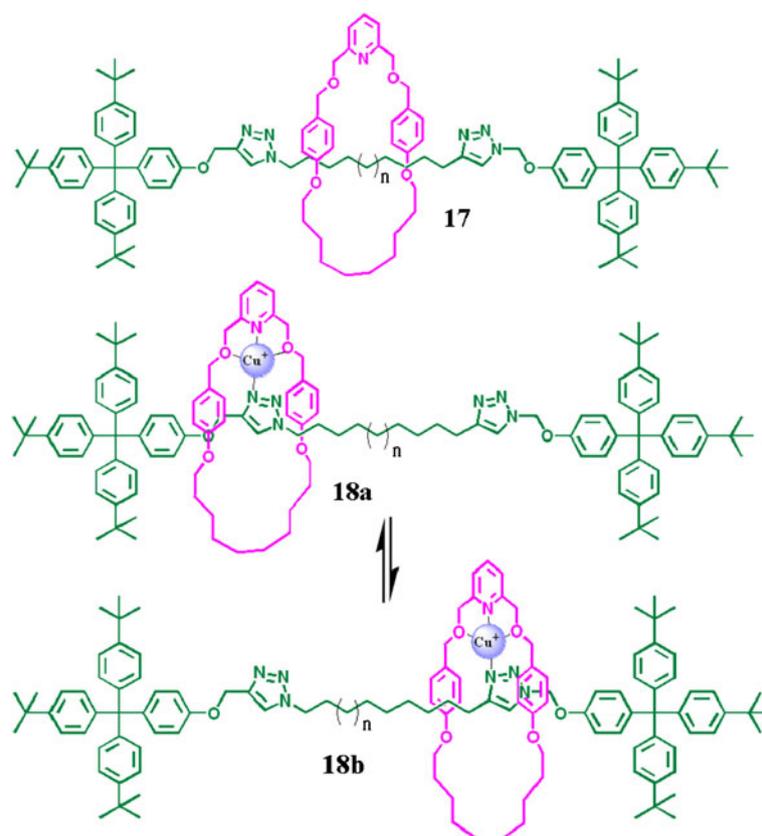
**Figure 7.** *Bis* triazole-based rotaxane and the dynamics of the macrocycle movement between the triazole units in the presence of Cu(I) ion.

sites is very unusual for metal-coordinated molecular shuttles.

### 4.4 *Ligand based switching*

Ligand-based switching is an attractive area in supramolecular chemistry compared to the switch originating from changes in a metal's oxidation state. To elaborate this fact, a redox active ligand, 3,6-*bis*(5-methyl-2-pyridine)-1,2,4,5-tetrazine, **21** is used as axle to form Cu(I) templated pseudorotaxane, **19**

(figure 8).[19] A reduction-induced switching of [2]pseudorotaxane **19** to the reduced [3]pseudorotaxane, **20** is observed upon reduction of the redox active axle of **19** by a bimolecular mechanism. This behaviour is confirmed using variable scan-rate cyclic voltammetry (CV). UV-vis-NIR spectroelectrochemistry is used to confirm the 1:1 product stoichiometry for **20:21**. The driving force ($\Delta G_D^* = -5.1$ kcal mol$^{-1}$) for the reaction is based on the enhanced stability of the reduced **20** over reduction of **19** by 365 mV (8.4 kcal mol$^{-1}$). The stoichiometry of the products and net chemical
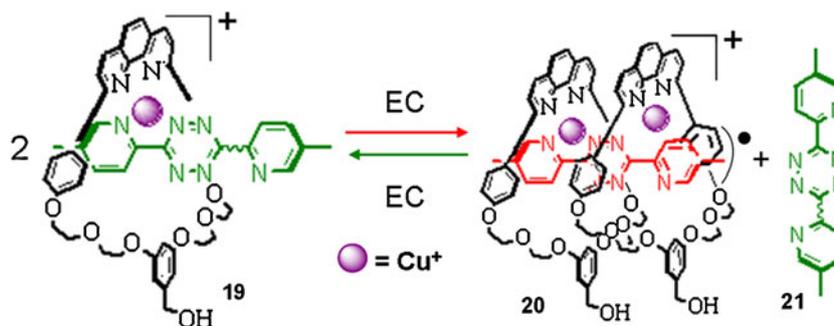


**Figure 8.** Redox active ligand based switching.
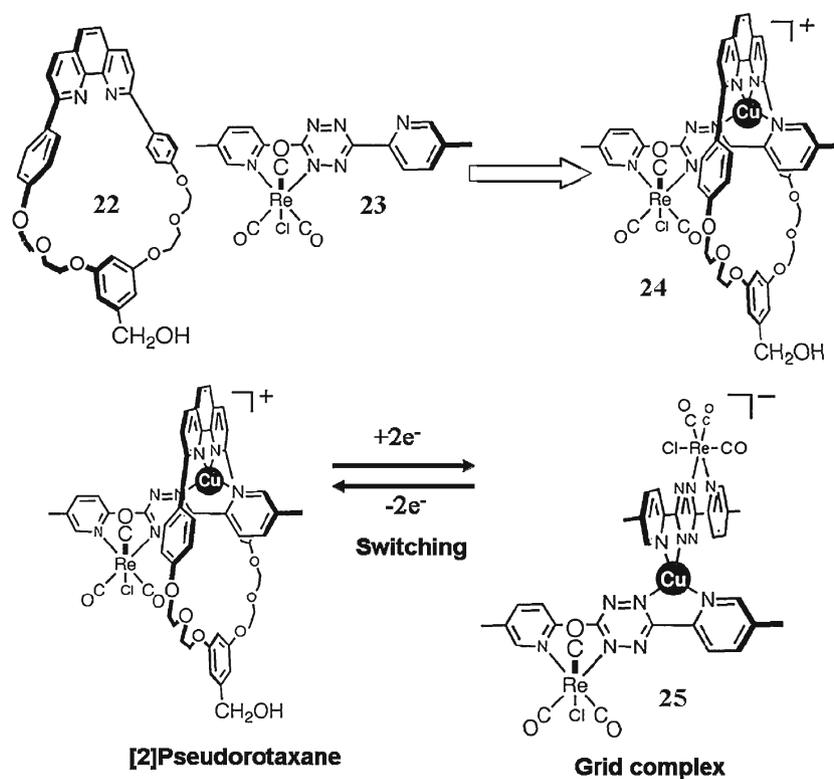
**Figure 9.** Redox-driven switching between two distinct architectures: pseudorotaxane, to grid-corner complex.

reversibility are supported using UV-vis-NIR spectro-electrochemistry.

### 4.5 *Inter-conversion between two different architectures*

This belongs to the study on self-assembled different architectures around a dynamic Cu(I) template of a suitable ligand. Reduction of the ligand backbone plays role to switch between two different self-assembled architectures. Two types of ligands are designed to explore this phenomenon. The redox active bischelating axle, **21** is mononucleated with the rhenium(I) tricarbonylchloro, {Re(CO)₃Cl}, moiety to afford one chelating site, rather than two, thus simplifying the complexity of the self-sorting mixture and can be reduced easily.[20] The second ligand is a strong sigma-donating, sterically bulky and redox-innocent phenanthroline-based macrocycle, **22** which prevents the formation of a *bis*-macrocycle complex. These two molecules form self-assembled structure of [2]pseudorotaxane, **24** in the presence of Cu(I) ion (figure 9). Upon ligand-based reduction of an appropriate mixture of these components lead to the formation of the grid complex, **25** (figure 9). The redox-driven inter conversion between two distinct architectures: pseudorotaxane, **24** and grid-corner complex, **25** is investigated using digital CV simulations. The reorganization from

both the singly and doubly reduced mixtures into the grid corner occurs through bimolecular pathways as verified by variable-concentration CVs.
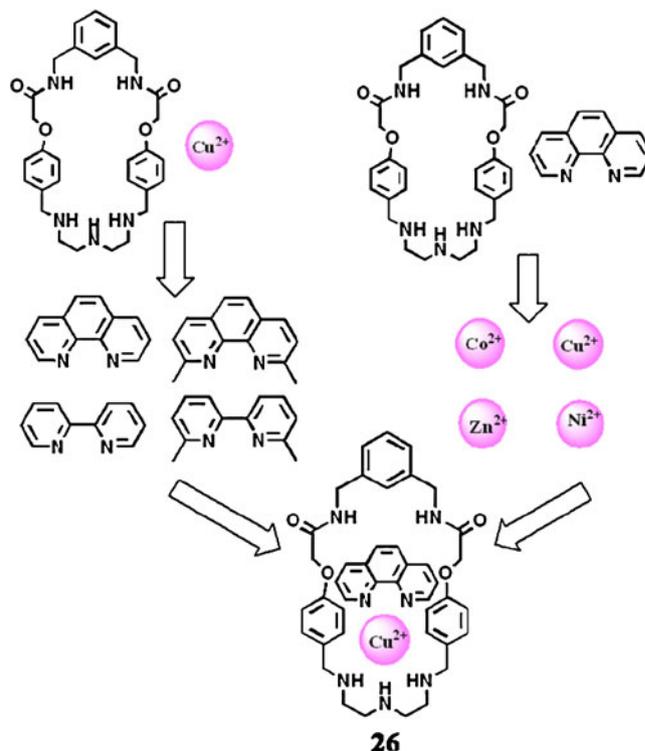


**Figure 10.** Selective formation of a [2]pseudorotaxane, **26**.

**Figure 11.** Sixteen possibility of formation of [2]pseudorotaxanes.

### 4.6 *Self-sorting in pseudorotaxane*

Self-assembly of many different building blocks to generate complex, functional architectures via self-sorting phenomena is of current research interest. It is challenging to develop an artificial set of molecules which can generate a self-assembled structure from a complex mixture of multiple components. A kind of demonstration is well accounted using a triamino macrocycle ligand, **7**.[15a] The selectivity of **7** towards the formation of the 1,10-phenanthroline (**9**) threaded [2]pseudorotaxane, **26** is observed among a series of bidentate chelating ligands **9–12** and transition metal ions with common stable oxidation numbers ($Co^{2+}$, $Ni^{2+}$, $Cu^{2+}$, $Zn^{2+}$) (figure 10). Treatment of macrocycle, **7** with chelating ligands **9–12** in the presence of $Cu^{2+}$, shows only formation of **9** threaded [2]pseudorotaxane, **26**. Similarly, when macrocycle, **7** and bidentate chelating ligand, **9** are added to the mixture of metal ions, a clean formation of **26** is observed. Interestingly, when all the bidentate ligands **9–12** and metal ions ($Co^{2+}$, $Ni^{2+}$, $Cu^{2+}$, $Zn^{2+}$) are mixed together in the presence of **7**, selective formation of [2]pseudorotaxane, **26** is observed.

However in that mixture as many as 16 possible [2]pseudorotaxanes are possible upon threadeing of **7** (figure 11).

### 4.7 *Axle substitution in a metallo-pseudorotaxane*

In cases of pseudorotaxanes the axle part could be dethreaded or replaced by other competing axle molecules. In case of metal templated pseudorotaxanes depending upon the coordination preference to the metal centre, relatively weak coordinating ligand could easily be replaced by stronger coordinating axles. This phenomenon is well-documented in this section. This kind of axle substitution reaction is performed in fluorophoric axle based Cu(II) templated multinuclear [3]pseudorotaxane.[15b] When [3]pseudorotaxane molecule is treated with stronger bidentate chelating ligand 1, 10 phenanthroline, **9** the fluorophoric axle is replaced by this ligand (figure 12). UV/Vis and fluorescence studies are used to establish the mechanism of the axle substitution reaction. These studies show two units of **9** are required to replace one unit of *bis*-bidentate axle, **13** of [3]pseudorotaxane. Though the
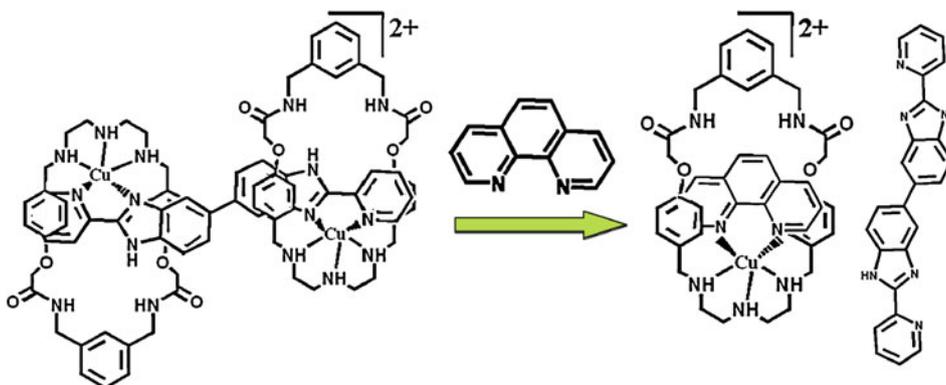


**Figure 12.** Axle substitution reaction.

axle is fluorophoric in nature, [3]pseudorotaxane itself is non-fluorescent compound, gives fluorescence 'OFF' signal due to the coordination to the Cu(II) centre. But in that solution on addition of two equivalent of phen the fluorophoric axle is released and the resulting solution shows fluorescence 'ON' signal. This can be regarded as a unidirectional molecular switch by an axle substitution reaction in a pseudorotaxane system via fluorescence ON–OFF signal.

## 5. Conclusion

Construction of mechanically interlocked molecules is a rapidly developing field because of its interesting physical and mechanical properties that are useful for the development of nanotechnology. In the present discussion, we encouraged the Cu(I)/Cu(II) templated threaded molecules (pseudorotaxanes, rotaxanes) and their interesting shuttling and switching properties. The role of Cu(I) as active metal template becomes popular because of its easy coupling between alkyne and azide to construct interlocked molecules with good yield, without affecting other functionality. Cu(I) triggerred fast shuttling of wheel between two triazole station is achieved at room temp. A redox active axle based pseudorotaxane shows axle based switching. Interconversion between two architectures is observed in a redox active ligand based pseudorotaxane. Finally, an unidirectional switching from [3]pseudorotaxane to [2]pseudorotaxane is explained in a multinuclear Cu(II) template [3]psudorotaxane, based on the coordination preference of the axle to the metal centre. Development of Cu(I)/Cu(II) template synthesis of pseudorotaxane, rotaxane and their coherent properties could be a powerful tool for the construction of molecular level machine in this century.

## Acknowledgements

## References

1. Dietrich-Buchecker C O, Sauvage J P and Kintzinger J P 1983 *Tetrahedron Lett.* **24** 5095

2. Beves J E, Blight B A, Campbell C J, Leigh D A and McBurney R T 2011 *Angew. Chem. Int. Ed.* **50** 9260

3. (a) Stoddart J F 2009 *Chem. Soc. Rev.* **38** 1802; (b) Balzani V, Credi A and Venturi M 2009 *Chem. Soc. Rev.* **38** 1542

4. Coskun A, Banaszak M, Astumian R D, Stoddar J F and Grzybowski B A 2012 *Chem. Soc. Rev.* **41** 19

5. (a) Saha S and Stoddart J F 2007 *Chem. Soc. Rev.* **36** 77; (b) Champin B, Mobian P and Sauvage J P 2007 *Chem. Soc. Rev.* **36** 358; (c) Kinbara K, Aida T 2005 *Chem. Rev.* **105** 1377; (d) Balzani V, Venturi M and Credi A 2003 *Molecular devices and machines: A journey into the nanoworld*, (Weinheim: Wiley-VCH); (e) Schalley C A, Beizai K and Vögtle F 2001 *Acc. Chem. Res.* **34** 465

6. (a) Qu D H and Feringa B L 2010 *Angew. Chem. Int. Ed.* **49** 1107; (b) Balzani V, Credi A and Venturi M 2009 *Chem. Soc. Rev.* **38** 1542; (c) Tian H and Wang Q C 2006 *Chem. Soc. Rev.* **35** 361; (d) Harada A 2001 *Acc. Chem. Res.* **34** 456; (e) Sauvage J P (ed.) 2001 *Molecular machines and motors*; *Structure and bonding*; Berlin, Germany: Springer

7. (a) Kay E R, Leigh D A and Zerbetto F 2007 *Angew. Chem. Int. Ed.* **46** 72; (b) Cavallini M, Biscarni F, Lewn S, Zerbetto F, Bottari G and Leigh D A 2003 *Science* **299** 531; (c) Stanier C A, Alderman S J, Claridge T D W and Anderson H L 2002 *Angew. Chem. Int. Ed.* **41** 1769

8. (a) Sharma S, Davidson G J E and Loeb S J 2008 *Chem. Commun.* 582; (b) Chiu C W, Lai C C and Chiu S H 2007 *J. Am. Chem. Soc.* **129** 3500; (c) Huang F and Gibson H W 2005 *Prog. Polym. Sci.* **30** 982

9. (a) Gong H Y, Rambo B M, Karnas E, Lynch V M, Keller K M and Sessler J L 2011 *J. Am. Chem. Soc.* **133** 1526; (b) Zhang H Y, Wang Q C, Liu M H, Ma X and Tian H 2009 *Org. Lett.* **11** 3234; (c) Collin J P, Durola F, Frey J, Heitz V, Sauvage J P, Tock C and Trolez Y 2009 *Chem. Commun.* 1706; (d) Lankshear M D and Beer P D 2007 *Acc. Chem. Res.* **40** 657

10. Crowley J D, Goldup S M, Lee A L, Leigh D A and McBurney R T 2009 *Chem. Soc. Rev.* **38** 1530

11. (a) Yin J, Dasgupta S and Wu J 2010 *Org. Lett.* **8** 1712; (b) Meyer C D, Joiner C S and Stoddart J F 2007 *Chem. Soc. Rev.* **36** 1705

12. Selected references: (a) Collin J P, Durola F, Frey J, Heitz V, Reviriego F, Sauvage J-P, Trolez Y and Rissanen K 2010 *J. Am. Chem. Soc.* **132** 6840; (b) Frey J, Tock C, Collin J P, Heitz V, Sauvage J P and Rissanen K 2008 *J. Am. Chem. Soc.* **130** 11013; (c) Collin J P, Dietrich-Buchecker C, Gaviña P, Jimenez-Molero M C and Sauvage J P 2001 *Acc. Chem. Res.* **34** 477 and references cited therein.

13. (a) Lehn J M, Atwood J L, Davies J E D, MacNicol D D and Vögtle F 1996 (eds.). *Comprehensive supramolecular chemistry*, Oxford: Pergamon; (b) Steed J W and Atwood J L 2000 *Supramolecular chemistry*, (Weinheim: Wiley-VCH)

14. (a) Hogg L, Leigh D A, Lusby P J, Morelli A, Parsons S and Wong J K Y 2004 *Angew. Chem. Int. Ed.* **43** 1218; (b) Leigh D A, Lusby P J, Teat S J, Wilson A J and Wong J K Y 2001 *Angew. Chem. Int. Ed.* **40** 1538;

(c) Pentecost C D, Chichak K S, Peters A J, Cave G W V, Cantrill S J and Stoddart J F 2007 *Angew. Chem. Int. Ed.* **46** 218

15. (a) Saha S, Ravikumar I and Ghosh P 2011 *Chem. Commun.* **47** 6272; (b) Saha S, Ravikumar I and Ghosh P 2011 *Chem. Eur. J.* **17** 13712
16. Durola F, Lux J and Sauvage J P 2009 *Chem. Eur. J.* **15** 4124
17. Létinois-Halbes U, Hanss D, Beierle J, Collin J P and Sauvage J P 2005 *Org. Lett.* **7** 5753
18. Aucagne V, Berna J, Crowley J D, Goldup S M, Hanni K D, Leigh D A, Lusby P J, Ronaldson V E, Slawin A M Z, Viterisi A and Walker D B 2007 *J. Am. Chem. Soc.* **129** 11950
19. McNitt K A, Parimal K, Share A I, Fahrenbach A, Witlicki E H, Pink M, Bediako D K, Plaisier C L, Le N, Heeringa L P, Griend D A V and Flood A H 2009 *J. Am. Chem. Soc.* **131** 1305
20. Parimal K, Witlicki E H and Flood A H 2010 *Angew. Chem. Int. Ed.* **49** 4628