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Mechanically Interlocked Molecules and Their Applications

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Abstract: Mechanically interlocked molecules such as rotaxanes, pseudorotaxanes and catenanes are used widely nowadays in many useful applications due to their distinctive architectures. The literature is full of research studies including the use of these mechanically interlocked species as molecular machines, polymers, prototypes of molecular machines, building blocks for interlocked supramolecular assemblies, preparation of molecular sensors, synthetic biology, etc. In this review, the structures, preparation methods and applications of some interlocked compounds including rotaxanes, pesudorotaxanes and catenanes will be studied.

Keywords: Rotaxanes, Cyclodextrins, Catenanes, Inclusion complexes, Artificial molecular machines.

1 Introduction

Rotaxanes [1-5], pseudorotaxanes [6-9] and catenanes [10,11] are examples of mechanically interlocked molecules that have relatively similar properties. These compounds may be synthesized from a commonly known intermediate compounds [12]. Rotaxanes are mechanically architecture consist of macrocyclic rings inserted into a linear component called the thread or the axis, the end of this thread is attached with two bulky groups called stoppers or caps. The nomenclature of these compounds is represented by the general formula [**x**]-rotaxane, where **x** indicates the number of components in the molecule, for example, [2]-rotaxane would consist of one thread and one macrocyclic ring. The essentially linkage in these supramolecular molecules depend on noncovalent bonding interactions. Pseudorotaxanes are interlocked molecules that can be dissociate under many conditions such as, temperature, competitive guests and change in solvent. Therefore, it should be fixed by stoppering or by macrocyclization. Wasserman was the first one who studied the chemistry of the mechanically interlocked molecules fifty years ago when he synthesized the first catenane *via* a statistical synthetic method [13]. Rotaxane that contain cyclodextrins was produced for first time by Ogino [14]. At present time rotaxanes and pseudorotaxanes [15] that include cyclodextrins which have long hydrophobic fragments were prepared and characterized [16]. Nowadays, many researches are concerned with pseudorotaxanes and rotaxanes derived from hydrophilic-hydrophobic forces [17,18]. These compounds should be formed in polar solvent such as dimethyl formamide and/or dimethyl sulfoxide. Catenanes [19] are interlocked compounds consist of two or more interlocked rings and their name comes from the Latin word (catena), meaning (chain). Also, the nomenclature of catenanes like the way as for rotaxanes, it uses a naming rule thus, the number of macrocycles that comprise a catenane put in square brackets before the term. Rotaxenes and catenanes have several applications in different fields, such as molecular machines [20-23], polymers [24,25], prototypes of molecular machines [26-28] , serve as building blocks for interlocked supramolecular assemblies [29], preparation of molecular sensors [30] and as drug delivery [31].This review deals with interlocked compounds including rotaxenes, pseudorotaxanes and catenanes and describes their formation and uses.

2 Rotaxanes and Pseudorotaxanes

Rotaxanes are supramolecular compounds [32] consists of a linear species and macrocyclic molecules linked together in a threaded architecture by non-covalent interaction. There are two types of these compounds which are rotaxanes and pseudorotaxanes [33]. Pseudorotaxanes or semirotaxane means half rotaxanes and the word rotaxane comes from the Latin word for a wheel (**rota**) and an axle (***axis***).

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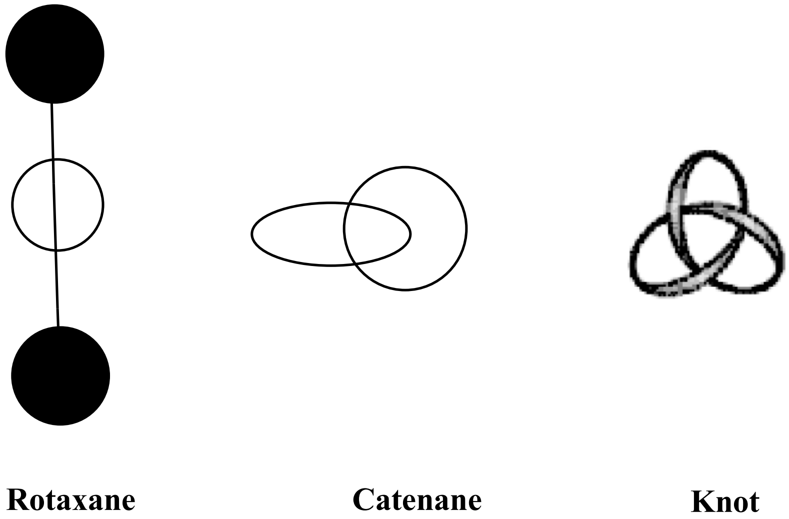

Fig. 1: Simplest forms of rotaxane, catenane, and knot.

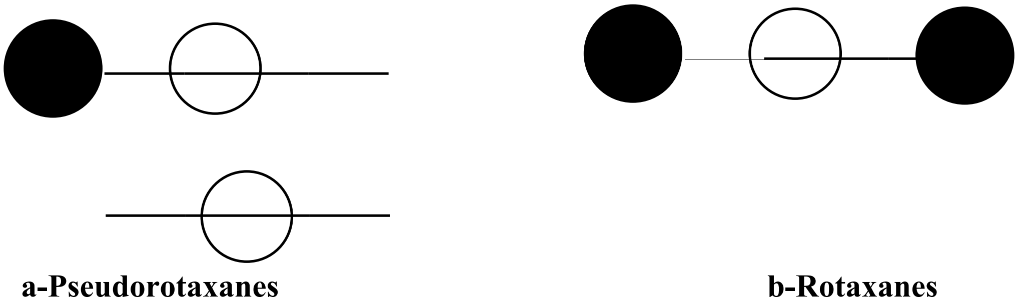

Fig. 2: Rotaxanes and pseudorotaxanes.

The black balls indicate caps or bulky groups which could prevent the slippage of cyclic molecules from the axis. Rotaxane compounds consist of two caps while the pseudorotaxane compounds contains of only one cap.

3 Synthesis of Rotaxanes

There are three different routes that can be used for building of rotaxanes. The first route is called threading [34,35] and includes the encircle macrocycle into the thread, then bulky group work as stopper. The second route is called clipping [36] and includes the cutting of macrocycle segments into two parts then the macrocyclic molecule inserts into axle which has already been covered in the first way. The third route is called slippage [37] in which the selectivity of macrocyclic size is highly necessary, as the identical size or at least fit size of macrocycle allow to slip over caps through the thread at high temperatures.

4 Types of Forces Lead to Formation of Rotaxanes

There are seven types of forces that effect on the synthesis of pseudorotaxanes and rotaxanes by threading method are noncovalent bonding interactions: statistical threading, chemical conversion, hydrogen bonding, hydrophilic-hydrophobic interaction, metal-ligand complexation, π-π stacking and charge transfer.

4.1 Statistical Threading Route

The synthesis of pseudorotaxanes and rotaxanes by this approach [38] depends only on statistical development without any obvious attractive force between the linear species and the cyclic molecules. The use of this method is limited due to the small value of ΔH which is nearly zero, in addition, ΔS is always negative toward threading. At present time, there is no use of this method except the use in conjugation with other synthetic methods [39].

4.2 Chemical Conversion Methods

Chemical conversion method [38]is not widely used for the preparation of rotaxanes and pseudorotaxanes due to the long time consumed and the small yield.

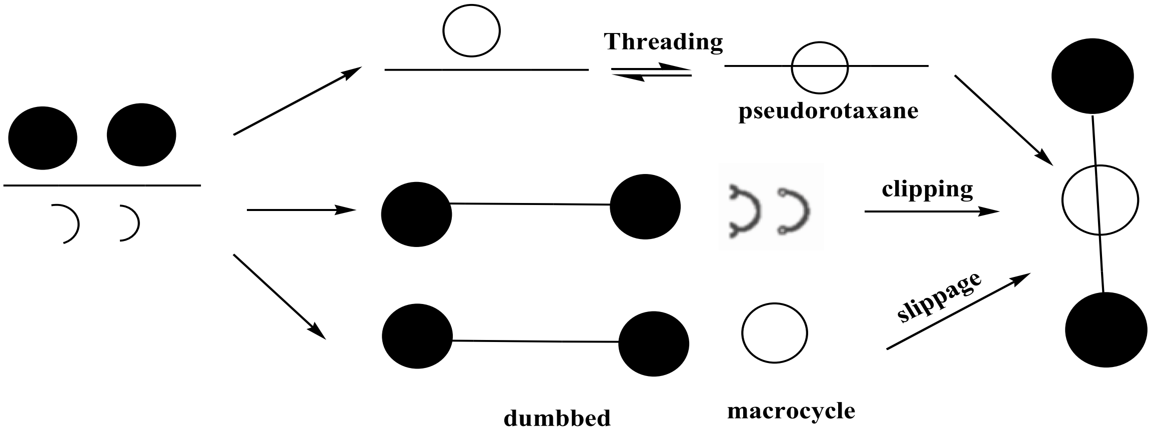

Fig.3: Different supramolecular strategies for making rotaxanes.

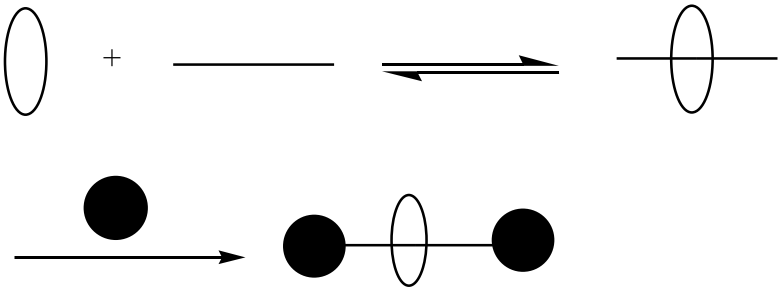

Fig. 4: Synthesis of a pseudorotaxane and rotaxane by statistical threading.

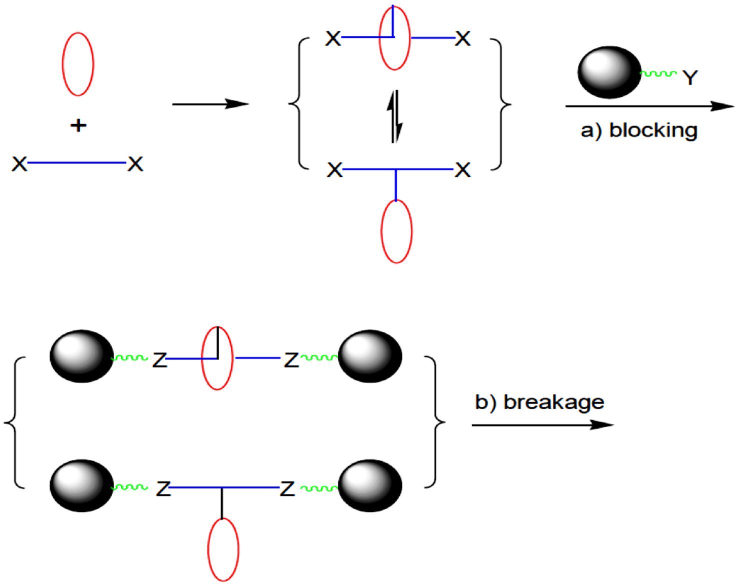

Fig. 5: Steps of Chemical conversion method [38].

4.3 Hydrogen Bonding Methods

This approach [39] depend on presence of electronegativity atoms on macrocyclic and/or linear species that can form hydrogen bond with hydrogen atoms of some groups, such as OH,–NH and NH_2on linear/cyclic molecules. Recently, this method is used widely in the preparation of pseudorotaxanes and rotaxanes.

4.4 Hydrophilic-Hydrophopic-Interaction Method

This method depends on using of cyclodextrins in synthesis of rotaxanes and pseudorotaxanes. Cyclodextrins are a group of cyclic oligosaccharides formed during bacterial digestion of cellulose. Cyclodextrins are example of supramolecular structure which associated natural products. There are several types of CDs, the most popular CDs includes six (α-cyclodextrin), seven (β-cyclodextrin) and eight (γ-cyclodextrin) glucopyranose units. There is no existence of CDs that consists of less than six glucopyranose units. There are many CDs that have been reported such as δ, €, £, η and θ-CDs which contain nine, ten, eleven, twelve, and thirteen glucopyranose units[40-42] All these structures of CDs consist of lipophilic inner cavity and a hydrophilic external surface. The chair conformation of the glucopyranose units is the reason of creating this structure. CDs are almost as formed as a truncated cone instead of perfect cylinders. The structure of CDs has got also two types of hydroxyl groups, the first primary which placed in narrow edge of the cone. The second type of hydroxyl groups are secondary that located at wider edge of the cone. The central cavity is created by the carbon chain and peptide linkage of the glucose residues that causes a lipophilic nature The torus of CDs has got the same structure of macrocyclic molecules, but CDs are less soluble in water and have got lipophilic cavity comparing with super molecule ring. The synthesis and stability of CDs complexes can be affected by several factors such as, hydrophobic forces and size of both cavity and guest molecule [44]. CDs have almost limitation in solubility, especially β-cyclodextrin owning to the relative strength of binding between CDs molecules in crystal configuration [45]. The synthesis of rotaxane requires an axis to penetrate through a CD ring, leading to axial inclusion compound.

4.5 Metal-ligand Complexation Methods [47]

This method depends on the presence of electron-doner and electron-acceptor substances. The mechanism for constructing of rotaxanes compounds requires the process of electron transfer from the electron donor to the electron acceptor substance which may proceed through covalent bonds or through space (mechanical bonds).

4.6. π-π Stacking and Charge Transfer Methods

This route is used to synthesize rotaxanes [49] and similar pseudorotaxanes [50] which is used for manufacturing of molecular machines. The Formation of pseudorotaxanes and rotaxanes depends on presenting linear species containing a π-electron-rich and a π-electron-deficient macrocycle. Moreover, rotaxanes which are synthesized by this route are usually used to construct molecular based electronically switchable tunnel junction devices.

Fig.6: Example for preparing rotaxane by hydrogen bonding method [39]

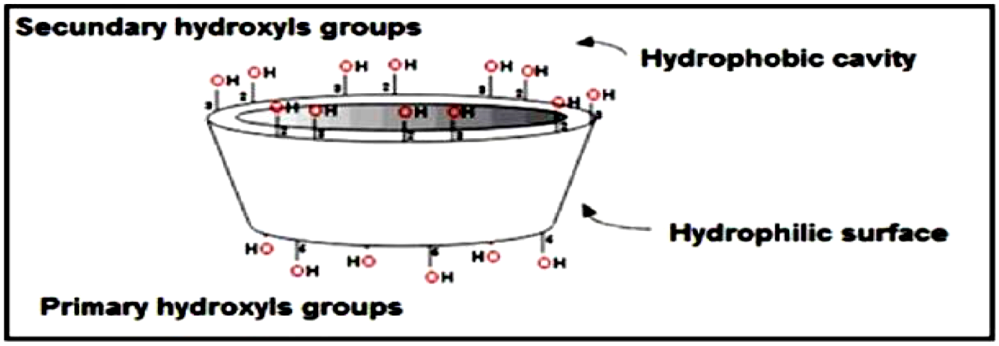

Fig.7: Cyclodextrins structure in torus similar to macro ring shape with the hydroxyl groups [43]

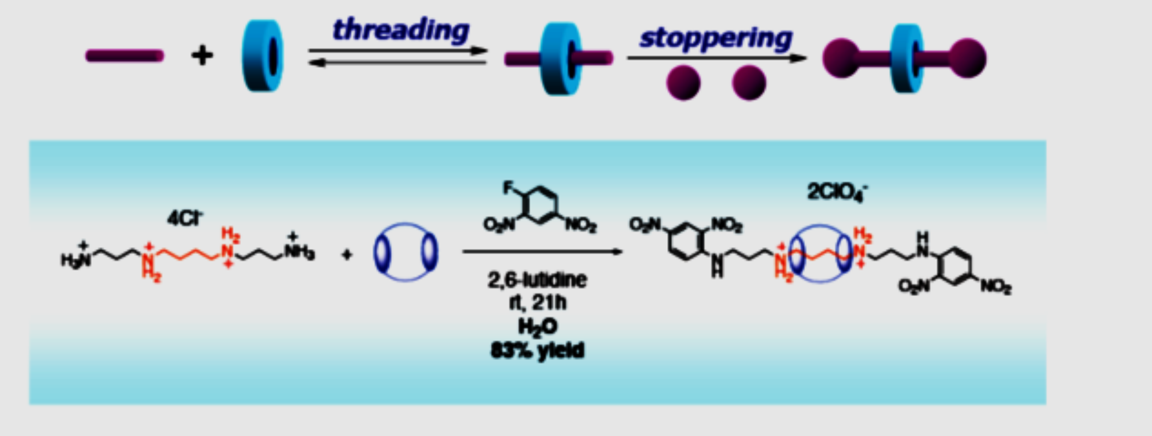

Fig. 8: Formation of rotaxane by hydrophilic- hydrophobic interaction [46].

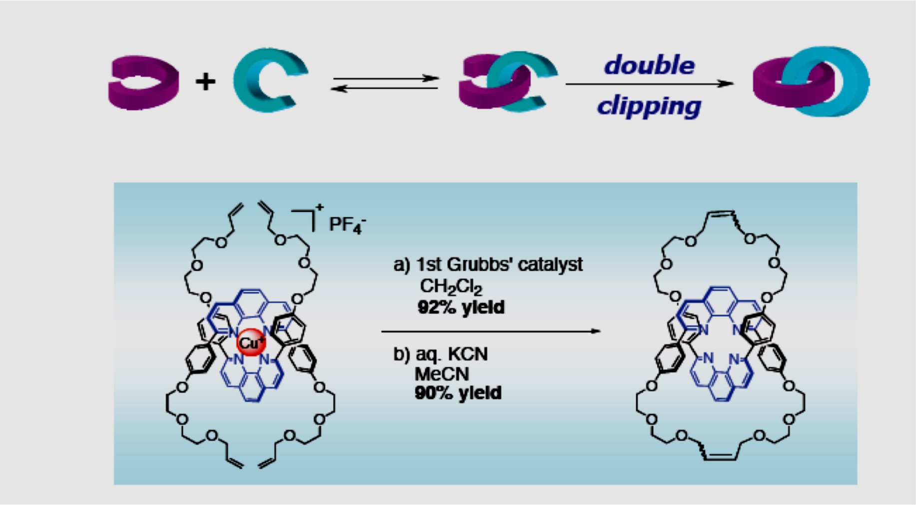

Fig.9: Formation of catenans by metal-ligand complexation methods[48]

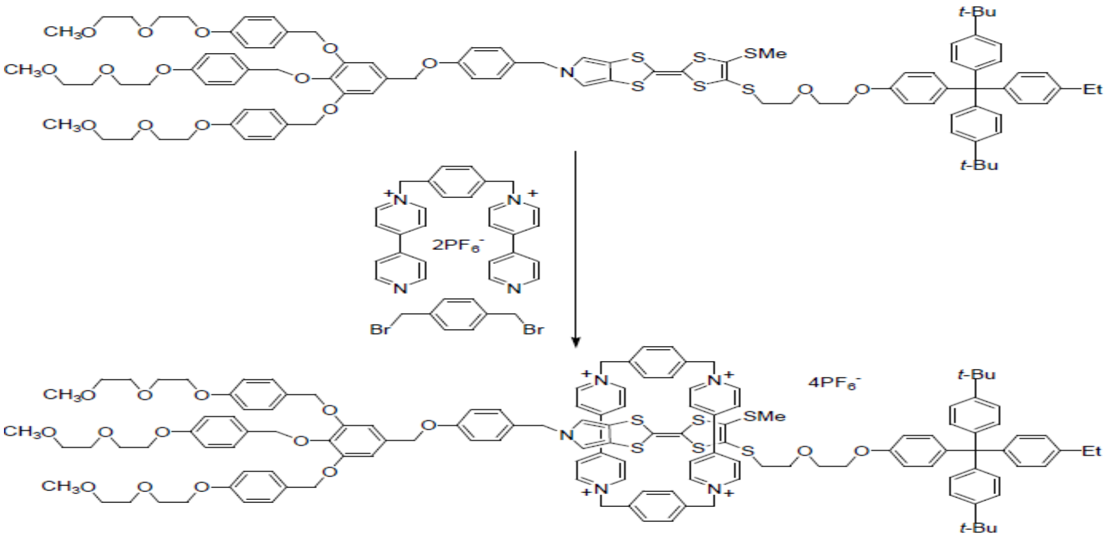

Fig. 10:A rotaxane which can be used to construct molecular-based electronically switchable tunnel junction devices [51]

5 Catenanes

Catenanes [52] are examples of essentially interlocked molecules that consists of two or more overlapping interlocked rings. Catenanes have steady architectures unless a covalent bond is broken. Catenane is derived from the Latin word (catena) that means (chain). The nomenclature of these type of supramolecular compounds is similar to the rotaxanes, since the number of macrocycles that involve a catenane appears in square brackets before the term, thus, [*n*] is the number of macrocycles that formed catenane.

5.1 Synthesis of Catenanes

The preparation of catenanes can be carried out using many different methods that depend on the noncovalent bonding interactions. These methods include statistical threading, chemical conversion, hydrogen bonding, hydrophilic-hydrophobic interaction, metal-ligand complexation, π-π stacking and charge transfer and donor/acceptor interactions. In the statistical technique, the formation of catenanes is affected with extra-annular ring closures which is not preferred in catenation developments in addition to the very small yield. Therefore, to enhance the yield of catenanes, the covalent bonds must be utilized. This strategy can be applied by using strict control to avoid the extra-annular ring closures. Catenanes have been formed for the first time by statistical processes and by multistep-directed synthesis. Using of transition metals recently as templates has permitted the relatively facile creation of a large range of different catenanes, rotaxanes and knots.

6 Rotaxanes and Catenanes as Artificial Molecular Machines

Machines are distinctive sorts of devices their component categories indicated modifications in their relative positions as a result of some external motivation. Recently, most of researches focused on reduction of the parts that were constructed of devices and machines principally in field of information processing. The miniaturization process can be occurred by decreasing the size with increasing the power of computers. Also, this fact can be used in variety of fields such as medicine, environment, energy, and materials. In last twenty years rotaxanes and catenanes are played significance role in manufacture of artificial molecular machines and motors [54] because of the motions of their molecular components can be easily imagine. This property of these architectures derived from noncovalent interactions between their components. This interaction is responsible for the efficient template directed.

Molecules are more stable species than atoms, so that, most of chemistry labs prefers the use of molecules rather than atoms. Molecules have many advantages compared to atoms, including the ability of control by photochemical and electrochemical inputs in addition to the ease of link them together to make bigger and distinctive structures. As a result, many factors use molecules nowadays in nanoscale devices and machines [56]. There are two main methods for generation of molecular machines and motors. First method has been occurred in solutions in an incoherent manner. The second route for the generation of molecular machines and motors should be ordered at Interfaces [57], deposited on surfaces or immobilized into membranes [58]

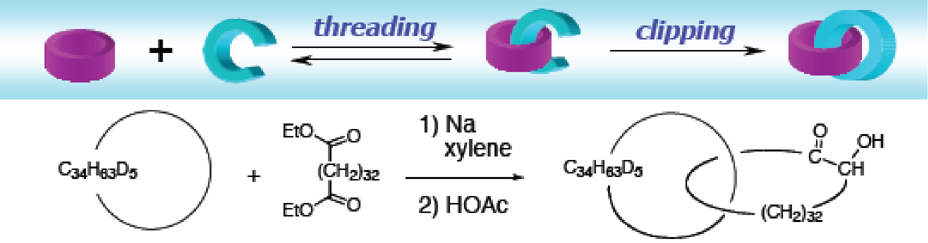

Fig.11: Synthesis of catenanes by threading method [53].

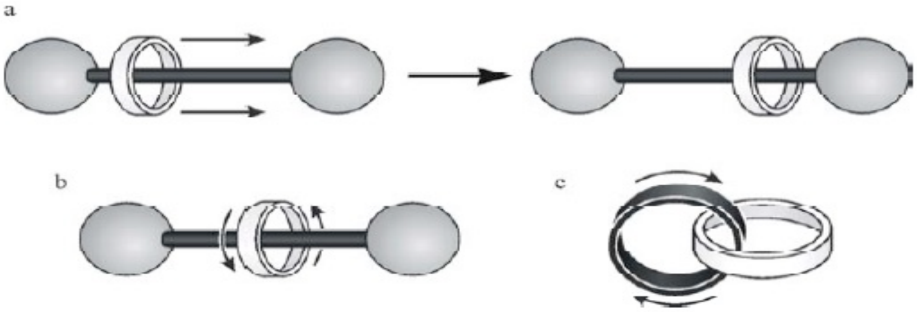

Fig. 12: Schematic representation of some of the intercomponent motions that can be obtained with rotaxanes and catenanes: shuttling (a) and ring rotation (b, c) [55]

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