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Artificial Molecular Motors and Machines: Design Principles and Prototype Systems

Vincenzo Balzani · Alberto Credi (✉) · Belen Ferrer · Serena Silvi ·
Margherita Venturi

Dipartimento di Chimica "G. Ciamician", Università di Bologna, via Selmi 2,
40126 Bologna, Italy
alberto.credi@unibo.it

Abstract A molecular machine can be defined as an assembly of a discrete number of molecular components (that is, a supramolecular structure) designed to perform a function through the mechanical movements of its components, which occur under appropriate external stimulation. Hence, molecular machines contain a motor part, that is a device capable of converting energy into mechanical work. Molecular motors and machines operate via nuclear rearrangements and, like their macroscopic counterparts, are characterized by the kind of energy input supplied to make them work, the manner in which their operation can be monitored, the possibility to repeat the operation at will, i.e., establishing a cyclic process, the time scale needed to complete a cycle of operation, and the performed function. Owing to the progress made in several branches of Chemistry, and to the better understanding of the operation mechanisms of molecular machines of the biological world, it has become possible to design and construct simple prototypes of artificial molecular motors and machines. The extension of the concept of machine to the molecular level is of great interest not only for basic research, but also for the growth of nanoscience and the development of nanotechnology. We will illustrate some basic features and design principles of molecular machines, and we will describe a few recent examples of artificial systems, based on rotaxanes, catenanes and related species, taken from our own research.

Keywords Catenane · Electron transfer · Photochemistry · Rotaxane · Supramolecular chemistry

Abbreviations

AMH	ammonium center
BPM	4,4′-bipyridinium unit
CT	charge transfer
DB24C8	dibenzo[24]crown-8
DON	1,5-dioxynaphthalene unit
SCE	saturated calomel electrode
TTF	tetrathiafulvalene unit

1
Basic Principles

1.1
Introduction

Movement is one of life's central attributes. Nature provides living systems with complex molecules called motor proteins which work inside a cell like ordinary machines built for everyday needs. The development of civilization has always been strictly related to the design and construction of devices, from wheel to jet engine, capable of facilitating movement and travel. Presently, the miniaturization race leads scientists to investigate the possibility of designing and constructing motors and machines at the nanometer scale, i.e. at the molecular level. Chemists, by the nature of their discipline, are able to manipulate atoms and molecules and are therefore in an ideal position to develop bottom-up strategies for the construction of nanoscale devices.

Natural molecular motors are extremely complex systems; their structures and detailed working mechanisms have been elucidated only in a few cases and any attempt to construct systems of such a complexity by using a molecular approach would be hopeless. What can be done, at present, in the field of artificial molecular motors is (i) to learn the design principles by constructing simple prototypes consisting of a few molecular components, capable of moving in a controllable way; and (ii) to investigate the challenging problems posed by interfacing artificial molecular devices with the macroscopic world, particularly as far as energy supply and information exchange are concerned. Surely, the study of motion at the molecular level is a fascinating topic from the viewpoint of basic research and a promising field for novel applications.

In the first section of this chapter we shall introduce the concepts of molecular motors and machines, and we will describe the bottom-up (i.e.

supramolecular) approach to their construction. We will then discuss the characteristics of molecular motors, with reference to those of macroscopic ones. The second section deals with artificial molecular motors and machines based on rotaxanes, catenanes and related species. For space reasons, we shall only describe a few recent examples taken from our own research. Finally, we will critically discuss some perspectives and limitations of these kinds of systems.

1.2
The Bottom-Up (Supramolecular) Approach to Nanodevices

In everyday life we make extensive use of devices. A *device* is something invented and constructed for a special purpose. More specifically, it is an assembly of components designed to achieve a specific *function*, resulting from the cooperation of the (simple) *acts* performed by each component (Fig. 1a). A *machine* is a particular type of device in which the component parts display changes in their relative positions as a result of some external stimulus.

Depending on the purpose of its use, a device can be very big or very small. In the last fifty years, progressive miniaturization of the components employed for the construction of devices and machines has resulted in outstanding technological achievements, particularly in the field of information processing. A common prediction is that further progress in miniaturization

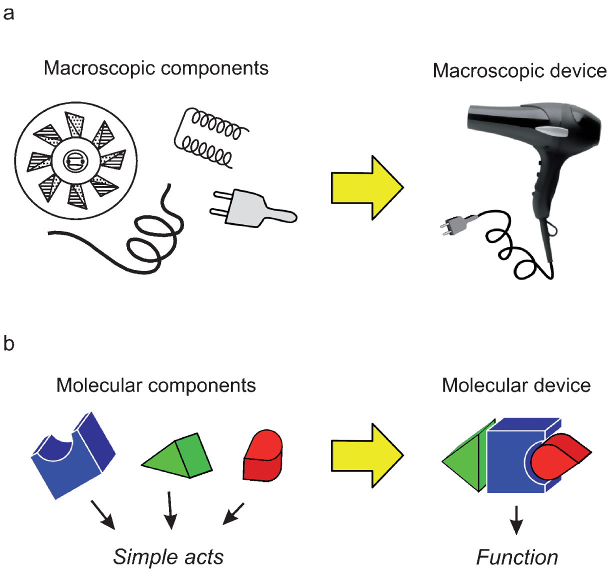

Fig. 1 Extension of the concept of macroscopic device to the molecular level

will not only decrease the size and increase the power of computers, but could also open the way to new technologies in the fields of medicine, environment, energy, and materials.

Until now miniaturization has been pursued by a large-downward (top-down) approach, which is reaching practical and fundamental limits (presumably ca. 50 nanometers) [1]. Miniaturization, however, can be pushed further since "there is plenty of room at the bottom", as Richard Feynman stated in a famous talk to the American Physical Society in 1959 [2, 3]. The key sentence of Feynman's talk was the following: *"The principle of physics do not speak against the possibility of manoeuvring things atom by atom".* The idea of the "atom-by-atom" bottom-up approach to the construction of nanoscale devices and machines, however, which was so appealing to some physicists [4, 5] did not convince chemists who are well aware of the high reactivity of most atomic species and of the subtle aspects of the chemical bond. Chemists know [6] that atoms are not simple spheres that can be moved from one place to another at will. Atoms do not stay isolated; they bind strongly to their neighbors and it is difficult to imagine that the atoms can be taken from a starting material and transferred to another material.

In the late 1970s a new branch of chemistry, called *supramolecular chemistry*, emerged and expanded very rapidly. In the frame of research on supramolecular chemistry, the idea began to arise in a few laboratories [7–9] that molecules are much more convenient building blocks than atoms to construct nanoscale devices and machines (Fig. 1b). The main reasons for this idea are: (i) molecules are stable species, whereas atoms are difficult to handle; (ii) nature starts from molecules, not from atoms, to construct the great number and variety of nanodevices and nanomachines that sustain life; (iii) most of the laboratory chemical processes deal with molecules, not with atoms; (iv) molecules are objects that exhibit distinct shapes and carry device-related properties (e.g. properties that can be manipulated by photochemical and electrochemical inputs); (v) molecules can self-assemble or can be connected to make larger structures. In the same period, research on molecular electronic devices began to flourish [10–12].

In the following years supramolecular chemistry grew very rapidly [13–16] and it became clear that the bottom-up approach based on molecules opens virtually unlimited possibilities concerning the design and construction of artificial molecular devices and machines. Recently, the concept of molecules as nanoscale objects exhibiting their own shape, size, and properties has been confirmed by new, very powerful techniques, such as single-molecule fluorescence spectroscopy and the various types of probe microscopies, capable of visualizing [17–19] or manipulating [20–22] single molecules, and even investigating bimolecular chemical reactions at the single molecule level [23].

Much of the inspiration to construct molecular devices and machines comes from the outstanding progress of molecular biology that has begun to reveal the secrets of the natural nanodevices which constitute the material base of life [24]. The bottom-up construction of devices as complex as those present in Nature is, of course, an impossible task. Therefore, chemists have tried to construct much simpler systems, without mimicking the complexity of the biological structures. In the last few years the synthetic talent, that has always been the most distinctive feature of chemists, combined with a device-driven ingenuity evolved from chemists' attention to functions and reactivity, have led to outstanding achievements in this field [25–29].

1.3
Characteristics of Molecular Motors and Machines

A *molecular motor* can be defined as an assembly of a discrete number of molecular components designed to perform mechanical-like movements under the control of appropriate energy inputs. This definition excludes the molecular motions caused simply by thermal energy [30–36]. The words *motor* and *machine* are often used interchangeably when referred to molecular systems. It should be recalled, however, that a motor converts energy into mechanical work, while a machine is a device, usually containing a motor component, designed to accomplish a function. Molecular motors and machines operate via electronic and/or nuclear rearrangements and make use of thermal fluctuations (Brownian motion) [37–39]. Like the macroscopic counterparts, they are characterized by (i) the kind of energy input supplied to make them work; (ii) the type of motion (linear, rotatory, oscillatory, ...) performed by their components; (iii) the way in which their operation can be monitored; (iv) the possibility to repeat the operation at will (cyclic process); and (v) the time scale needed to complete a cycle. According to the view described above, an additional and very important distinctive feature of a molecular machine with respect to a molecular motor is (vi) the function performed [26].

1.3.1
Energy Supply

The problem of the energy supply to make artificial molecular motors work [point (i)] is of the greatest importance [40]. The most obvious way to supply energy to a chemical system is through an exergonic chemical reaction. In the previously mentioned address [2, 3] to the American Physical Society, Richard Feynman observed: *"An internal combustion engine of molecular size is impossible. Other chemical reactions, liberating energy when cold, can be used instead"*. This is exactly what happens in our body, where the chemical energy supplied by food is used in a long series of slightly exergonic reactions to power the biological machines that sustain life.

If an artificial molecular motor has to work by inputs of chemical energy, it will need the addition of fresh reactants ("fuel") at any step of its working cycle, with the concomitant formation of waste products. Accumulation of waste products, however, will compromise the operation of the device unless they are removed from the system, as happens in our body as well as in macroscopic internal combustion engines. The need to remove waste products introduces noticeable limitations in the design and construction of artificial molecular motors based on chemical fuel inputs.

Chemists have long since known that photochemical and electrochemical energy inputs can cause the occurrence of *endergonic* and *reversible* reactions. In recent years, the outstanding progress made by supramolecular photochemistry [41–43] and electrochemistry [44, 45] has thus led to the design and construction of molecular machines powered by light or electrical energy, which work without the formation of waste products. In the case of photoexcitation, the commonly used endergonic and reversible reactions are isomerization and redox processes. In the case of electrochemical energy inputs, the induced endergonic and reversible reactions are, of course, heterogeneous electron transfer processes. Photochemical and electrochemical techniques offer further advantages, since lasers provide the opportunity of working in very small spaces and very short time domains, and electrodes represent one of the best ways to interface molecular-level systems with the macroscopic world.

A very important feature of molecular motors, related to energy supply [point (i)] and cyclic operation [point (iv)], is their capability to exhibit an *autonomous* behavior; that is, to keep operating, in a constant environment, as long as the energy source is available. Natural motors are autonomous, but the vast majority of the artificial molecular motors reported so far are *not autonomous* since, after the mechanical movement induced by a given input, they need another, opposite input to reset.

Needless to say, the operation of a molecular machine is accompanied by partial conversion of free energy into heat, regardless of the chemical, photochemical, and electrochemical nature of the energy input.

1.3.2
Other Features

The motions performed by the component parts of a molecular motor [point (ii)] may imply rotations around covalent bonds or the making and breaking of intercomponent non-covalent bonds, as we shall see later on.

In order to control and monitor the device operation [point (iii)], the electronic and/or nuclear rearrangements of the component parts should cause readable changes in some chemical or physical property of the system. In this regard, photochemical and electrochemical techniques are very useful since both photons and electrons can play the dual role of *writing* (i.e. causing a change in the system) and *reading* (i.e. reporting the state of the system). Luminescence spectroscopy, in particular, is a most valuable reading technique since it is easily accessible and offers good sensitivity and selectivity, along with the possibility of time-resolved studies.

The operation time scale of molecular machines [point (v)] can range from microseconds to seconds, depending on the type of rearrangement and the chemical nature of the components involved.

Finally, as far as point (vi) is concerned, the functions that can be performed by exploiting the movements of the component parts in molecular motors and machines are various and, to a large extent, still unpredictable. In natural systems the molecular motions are always aimed at obtaining specific functions, e.g., catalysis, transport, gating. As will be described in the following sections, the mechanical movements taking place in molecular machines, and the related changes in the spectroscopic and electrochemical properties, usually obey binary logic and can thus be taken as a basis for information processing at the molecular level. Artificial molecular machines capable of performing logic operations have been reported [46].

1.4
Natural Molecular Motors and Machines

In the last few years, much progress has been made in the elucidation of the moving mechanisms of motor biomolecules, owing to the fact that—in addition to the established physiological and biochemical methods—novel in vitro techniques have been developed which combine optical and mechanical methods to observe the behavior of a single protein.

The most important and best known natural molecular motors are ATP synthase, myosin, and kinesin [47, 48]. ATP synthase is the ubiquitous enzyme that manufactures adenosine triphosphate (ATP) and is a rotary motor powered by a proton gradient [49–52]. The enzymes of the myosin and the kinesin families are linear motors that move along polymer substrates (actin filaments for myosin and microtubules for kinesin), converting the energy of ATP hydrolysis into mechanical work [53, 54]. Motion derives from a mechanochemical cycle, during which the motor protein binds to successive sites along the substrate in such a way as to move forward on average.

Several other biological processes are based on motions, including protein folding and unfolding. Another example is RNA polymerase, which moves along DNA while carrying out transcriptions, thus acting as a molecular motor.

Suitable engineering of natural molecular motors and/or integration of motor proteins within artificial nanodevices has also been obtained [55–57], thereby opening up the possibility of building functional hybrid devices.

For space reasons, we cannot discuss in more detail the basic principles and operation mechanisms of natural molecular motors, and the reader should refer to the cited references.

1.5
Rotaxanes and Catenanes as Artificial Molecular Machines

In principle, molecular motors and machines can be designed starting from several kinds of molecular [58–62] and supramolecular [63–66] systems, including DNA [67–74]. However, most of the systems constructed so far are based on rotaxanes, catenanes, and related structures. Some relevant features of these multicomponent systems will therefore be summarized.

The names of these compounds derive from the Latin words *rota* and *axis* for wheel and axle, and *catena* for chain. Rotaxanes [75] are minimally composed (Fig. 2a) of a dumbbell-shaped molecule surrounded by a macrocyclic compound and terminated by bulky groups (stoppers) that prevent disassembly; catenanes [75] are made of (at least) two interlocked macrocycles or "rings" (Fig. 2b). Rotaxanes and catenanes are appealing systems for the construction of molecular machines because of the peculiar mechanical bonds that keep the molecular components together; hence, relative motions of such molecular components can be easily imagined (Fig. 3).

Important features of these systems derive from non-covalent interactions between components that contain complementary recognition sites. Such interactions, that are also responsible for the efficient template-directed syntheses of rotaxanes and catenanes [76–81], include electron donor-acceptor ability, hydrogen bonding, hydrophobic-hydrophilic character, π-π stacking, coulombic forces and, on the side of the strong interaction limit, metal-ligand bonding. The stability of a specific structure for rotaxanes and

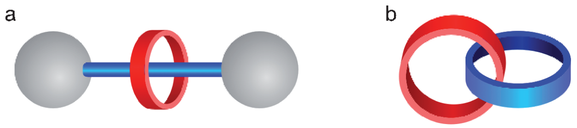

Fig. 2 Schematic representation of a rotaxane (**a**) and a catenane (**b**)

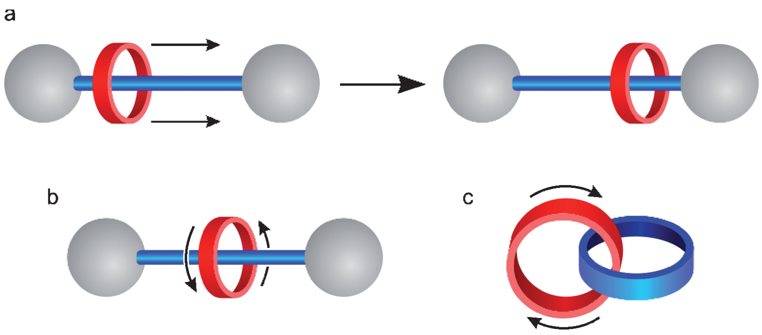

Fig. 3 Some of the intercomponent motions that can be obtained with rotaxanes and catenanes: shuttling (**a**) and ring rotation (**b**, **c**)

catenanes is determined by the intercomponent interactions that can take place. In general, in order to cause controllable mechanical movements, these interactions have to be modulated by means of external stimulation.

Among the most common types of rotaxanes and catenanes are those characterized by (i) charge-transfer (CT) intercomponent interactions between a π-electron acceptor (e.g. a 4,4′-bipyridinium derivative) and a π-electron donor (e.g. a dioxyaromatic unit or a tetrathiafulvalene derivative), and/or (ii) $N^+-H\cdots O$ intercomponent hydrogen bonding between secondary ammonium functions (e.g. dibenzylammonium ion) and a suitable crown ether (e.g. dibenzo[24]crown-8, DB24C8). The leading group in the synthesis and characterization of these compounds is that of Prof. Fraser Stoddart at the University of California, Los Angeles. All the examples described in this chapter are fruits of a long-lasting collaboration between our group and the Stoddart team.

The charge-transfer interactions between electron donor and electron acceptor units introduce low energy CT excited states (Fig. 4a) which are responsible not only for the presence of broad and weak absorption bands in the visible region, but also for the quenching of the potentially luminescent excited states localized on the molecular components. It should be noted that, when engaged in CT interactions, the electron donor and electron acceptor units become more difficult to oxidize and to reduce, respectively (Fig. 4b). Furthermore, units which are topologically equivalent in an isolated component may not be so when such a component is engaged in non-symmetric interactions with another component. In rotaxanes and catenanes based on CT interactions, mechanical movements can be promoted by destroying such interactions, i.e. reducing the electron acceptor unit(s) or oxidizing the electron donor one(s). This result can be achieved by chemical, electrochemical, or photochemical reactions. In most cases, the CT interactions can be restored by an opposite redox process, which thus promotes a reverse mechanical movement leading back to the original structure.

Contrary to what happens in the case of CT interactions, hydrogen bonds between secondary ammonium centers and crown ethers do not introduce low lying energy levels. Therefore, even if the absorption bands of the molecular components of rotaxanes and catenanes based on this kind of interaction are often perturbed compared with the corresponding absorption bands of the isolated molecular components, no new band is present in the visible region. As far as luminescence is concerned, in the multicomponent architecture each component maintains its potentially luminescent levels, but intercomponent photoinduced energy- and electron-transfer processes can also occur [82, 83]. The electrochemical properties of the separated components are more or less modified when the components are assembled. In these compounds, mechanical movements can be caused by acid-base chemical inputs that strengthen/weaken the hydrogen bonding interactions which

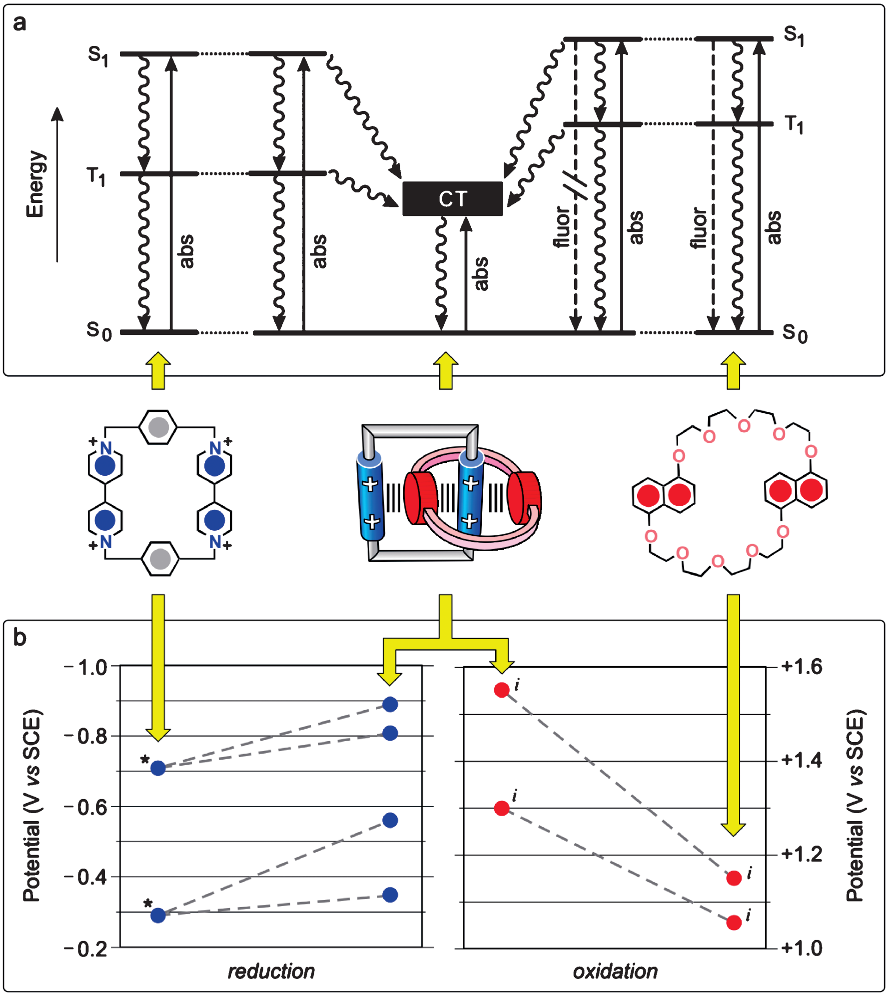

Fig. 4 **a** Schematic energy level diagram for a catenane based on charge-transfer (CT) interactions and for its separated components. The *wavy lines* indicate non-radiative decay paths of the electronic excited states. **b** Correlations between potential values obtained for the catenane and its separated components (Conditions: acetonitrile solution, room temperature, 5×10^{-4} mol L^{-1}, tetraethylammonium hexafluorophosphate 0.05 mol L^{-1} as the supporting electrolyte, glassy carbon working electrode, scan rate 0.2 V s^{-1}). Processes marked with * involve the exchange of two electrons, while those marked with *i* are irreversible processes

are responsible for assembly and spatial organization. The easiest way to produce an acid-base input is, of course, the addition of suitable chemical species, but photochemical and electrochemical inputs can also be used in principle.

2
Prototypes

2.1
Linear Motions in Rotaxanes

Because of their peculiar structure, at least two interesting molecular motions can be envisaged in rotaxanes, namely (i) translation, i.e. shuttling [84], of the ring along the axle (Fig. 3a); and (ii) rotation of the macrocyclic ring around the axle (Fig. 3b). Hence, rotaxanes are good prototypes for the construction of both rotary and linear molecular motors. Systems of type (i), termed molecular shuttles, constitute indeed the most common implementation of the molecular motor concept with rotaxanes.

If two identical recognition sites for the ring, i.e., "stations", are located within the dumbbell component, the result is a degenerate, conformational equilibrium state in which the ring spontaneously shuttles back and forth along the axle [84]. When the two recognition sites on the dumbbell component are different, a rotaxane can exist as two different equilibrating conformations, the population of which reflects their relative free energy as determined primarily by the strengths of the two different sets of non-covalent bonding

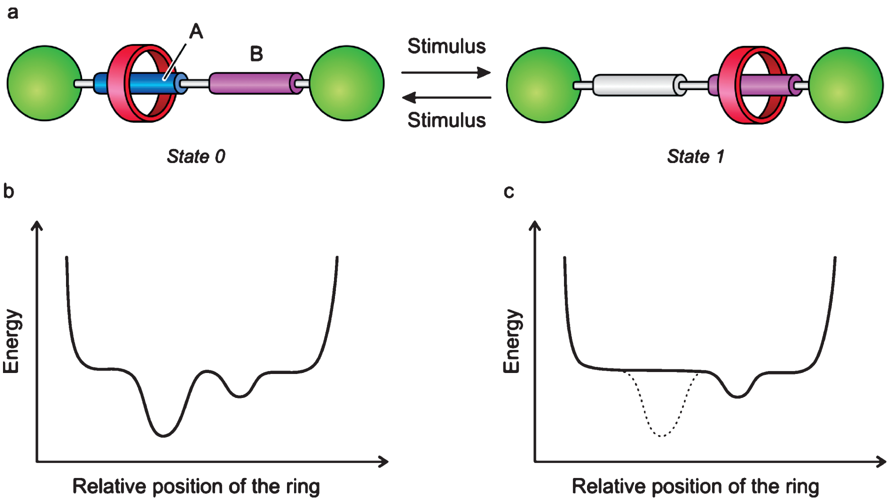

Fig. 5 Schematic representation of a two-station rotaxane and its operation as a controllable molecular shuttle (**a**). The graphs are a simplified representation of the potential energy of the system as a function of the position of the ring relative to the axle before (**b**) and after (**c**) switching off station A. An alternative approach would be to modify station B through an external stimulus in order to make it a stronger recognition site compared to station A

interactions. In the schematic representation shown in Fig. 5, the molecular ring resides preferentially around station A (state 0), until a stimulus is applied that switches off this recognition site. The rotaxane then equilibrates according to the new potential energy landscape, and the molecular ring moves by Brownian motion to the second recognition site (station B, state 1). If station A is switched on again by an opposite stimulus, the original potential energy landscape is restored, and another conformational equilibration occurs through the shuttling of the ring back to station A by Brownian motion. In appropriately designed rotaxanes, the switching process can be controlled by reversible chemical reactions (protonation-deprotonation, reduction-oxidation, isomerization) caused by chemical, electrochemical, or photochemical stimulation.

2.2
An Acid-Base Controlled Molecular Shuttle

The first example of a controllable molecular shuttle was reported in 1994 [85]. Since then, many molecular shuttles relying on chemical [25–28, 86–89], electrochemical [25–28, 90, 91], and photochemical [25–28, 92–94] stimulation have been described in the literature. A chemically driven system with good performance in terms of switching and stability is compound $\mathbf{1}H^{3+}$ shown in Fig. 6 [95]. It is made of a dumbbell component containing an ammonium (AMH) and an electron acceptor bipyridinium (BPM) units that can establish hydrogen-bonding and CT interactions, respectively, with the ring component DB24C8, which is a crown ether with electron donor properties. An anthracene moiety is used as a stopper because its absorption, luminescence, and redox properties are useful to monitor the state of the system. Since the $N^+ - H\cdots O$ hydrogen bonding interactions between the macrocyclic ring and the ammonium center are much stronger than the CT interactions of the ring with the bipyridinium unit, the rotaxane exists as only one of the two possible translational isomers (Fig. 6a, state 0). Deprotonation of the ammonium center of $\mathbf{1}H^{3+}$ with a base (Fig. 6b) causes 100% displacement of the DB24C8 ring by Brownian motion to the BPM unit (Fig. 6c, state 1); reprotonation of $\mathbf{1}^{2+}$ with an acid (Fig. 6d) directs the ring back on the ammonium center. Such a switching process was investigated in solution by ^{1}H NMR spectroscopy and by electrochemical and photophysical measurements [95]. Very recently, the kinetics of ring shuttling were also studied in detail by stopped-flow spectroscopic experiments [96]. The full chemical reversibility of the energy supplying acid-base reactions guarantees the reversibility of the mechanical movement, in spite of the formation of waste products. Notice that this rotaxane could be useful for information processing since it is a bistable system and can exhibit a binary logic behavior. It should also be noted that, in the deprotonated rotaxane $\mathbf{1}^{2+}$, it is possible to displace the ring from the bipyridinium station by destroying the CT interactions through re-

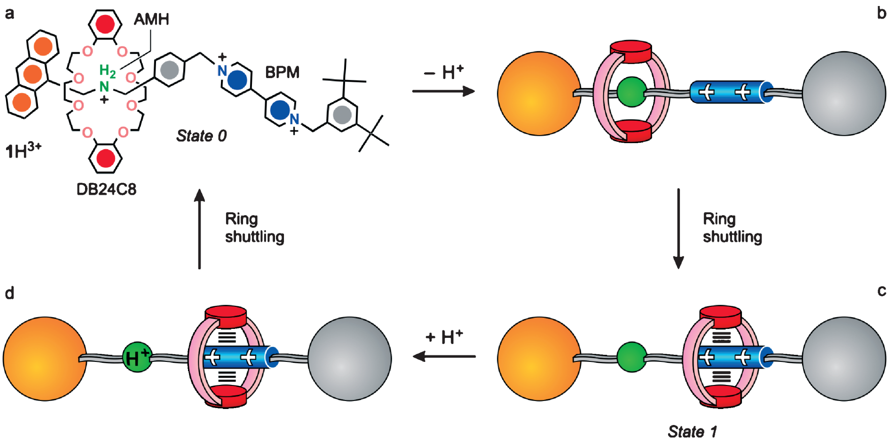

Fig. 6 Schematic representation of the operation of the acid-base controllable molecular shuttle $1H^{3+}$ in solution

duction of the bipyridinium station. Therefore, in this system, mechanical movements can be induced by two different types of stimuli (acid-base and reduction-oxidation).

2.3
A Molecular Elevator

In pursuit of a better fundamental understanding of the nature of multivalency in polytopic hosts and guests, as well as of the intercomponent electronic interactions that occur in complex supramolecular species, we have recently investigated [97] the acid-base controlled (Fig. 7) assembly and disassembly of a triply threaded two-component superbundle. This 1 : 1 adduct consists of a tritopic host **2**, in which three DB24C8 rings are fused together within a triphenylene core, and a trifurcated guest $3H_3^{3+}$ wherein three

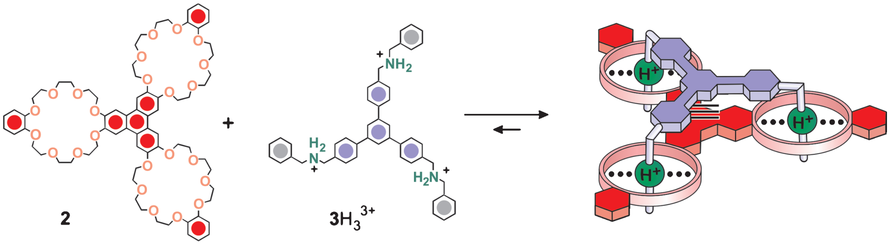

Fig. 7 The self-assembly of the tritopic host **2** and tripod component $3H_3^{3+}$ to afford a triply threaded supramolecular bundle. The adduct can be disassembled and reassembled in solution by addition of base and acid, respectively

dibenzylammonium ions are linked to a central benzenoid core. Fluorescence titration experiments (including Job plots), as well as electrochemical and ^{1}H NMR spectroscopic data in solution, have established the remarkable strength of the superbundle encompassing the triply cooperative binding motif revealed by X-ray crystallography in the solid state. In acetonitrile solution, the dethreading-rethreading of the 1 : 1 adduct can be controlled by addition of base and acid.

By using an incrementally staged strategy, we incorporated the architectural features of the acid-base switchable rotaxane $\mathbf{1}H^{3+}/\mathbf{1}^{2+}$ (Fig. 6) into those of the trifurcated trication $\mathbf{3}H_3{}^{3+}$ (Fig. 7) and we came up with the de-

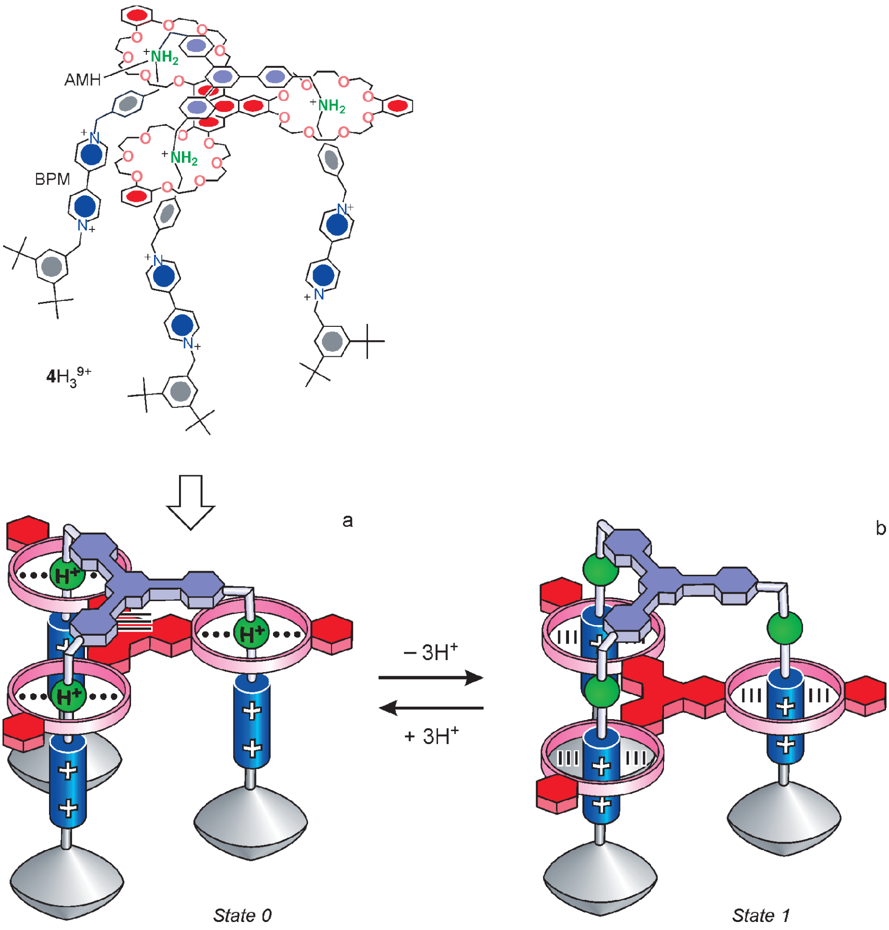

Fig. 8 Chemical formula and operation scheme in solution of the molecular elevator $\mathbf{4}H_3{}^{9+}$, obtained by interlocking the tripod component $\mathbf{5}H_3{}^{3+}$ with the platform-like species **2**

sign and construction of a two-component molecular device, **4**H_3^{9+} (Fig. 8), that behaves like a nanometer-scale elevator [98]. This nanomachine, which is ca. 2.5 nm in height and has a diameter of ca. 3.5 nm, consists of a tripod component **5**H_3^{9+} containing two different notches—one ammonium center (AMH) and one bipyridinium unit (BPM)—at different levels in each of its three legs. The latter are interlocked by the tritopic host **2**, which plays the role of a platform that can be made to stop at the two different levels. The three legs of the tripod carry bulky feet that prevent the loss of the platform. Initially, the platform resides exclusively on the "upper" level [99], i.e., with the three rings surrounding the AMH centers (Fig. 8a, state 0). This preference results from strong $N^+ - H\cdots O$ hydrogen bonding and weak stabilizing π-π stacking forces between the aromatic cores of the platform and tripod components. Upon addition of a strong, non-nucleophilic phosphazene base to an acetonitrile solution of **4**H_3^{9+}, deprotonation of the ammonium center occurs and, as a result, the platform moves to the "lower" level, that is, with the three DB24C8 rings surrounding the bipyridinium units (Fig. 8b, state 1). This structure is stabilized mainly by CT interactions between the electron rich aromatic units of the platform and the electron deficient BPM units of the tripod component. Subsequent addition of acid to $\mathbf{4}^{6+}$ restores the AMH centers, and the platform moves back to the upper level.

The "up and down" elevator-like motion, which corresponds to a quantitative switching and can be repeated many times, can be monitored by spectroscopic techniques (^{1}H NMR, absorption, and fluorescence) and, very conveniently, by electrochemistry. It is well known [100] that the BPM unit exhibits two consecutive reversible one-electron reduction processes at potential values of around − 0.4 and − 0.8 V versus SCE, and that when such a unit is surrounded by electron donors, such as the dioxybenzene units in DB24C8, its reduction potentials shift to more negative values (see Sect. 1.5). The voltammetric analysis of **4**H_3^{9+} shows the occurrence of two consecutive reversible reduction processes, each involving the exchange of three electrons (Fig. 9a), at potential values identical to those found for the tripod component **5**H_3^{9+}. This observation indicates that the three BPM units of **4**H_3^{9+} (and of **5**H_3^{9+}) are equivalent, behave independently from one another, and do not interact with the platform, which consistently resides on the "upper" level. After addition of three equivalents of base, two reversible three-electron reduction processes are still observed in cyclic voltammetric experiments, but they are displaced to more negative values (Fig. 9b). Such a change cannot be due simply to deprotonation of the AMH centers, because the potential values for reduction of the BPM units in the deprotonated tripod component $\mathbf{5}^{6+}$ are identical to those of **5**H_3^{9+}. Hence, the results obtained show that the BPM units in the three legs are surrounded by the electron donor DB24C8 rings of the platform. The changes in reduction potential can be fully reversed by the addition of acid and the cycle can be repeated without any apparent loss of reversibility.

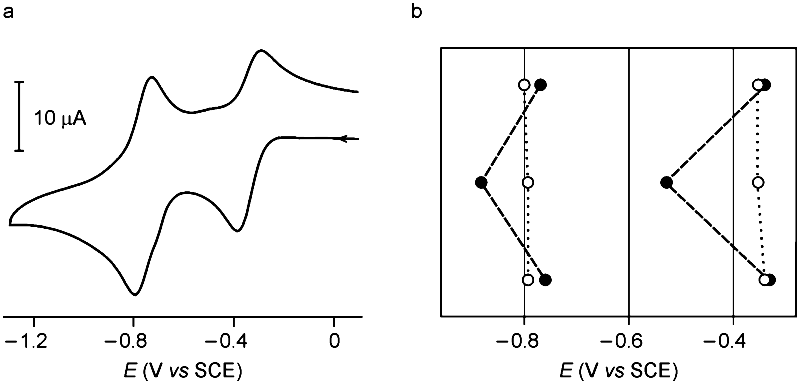

Fig. 9 **a** Cyclic voltammetry of $4H_3{}^{9+}$, showing the two reversible three-electron reduction processes of the three bipyridinium units. (Conditions: acetonitrile solution, room temperature, 4×10^{-4} mol L^{-1}, tetrabutylammonium hexafluorophosphate 0.05 mol L^{-1} as the supporting electrolyte, glassy carbon working electrode, scan rate 0.1 V s^{-1}). **b** Correlation diagram of the potential values, in V versus SCE, for the reduction processes of the bipyridinium units of $4H_3{}^{9+}$ (•) and $5H_3{}^{9+}$ (○) (*top*), upon addition of a base to afford 4^{6+} and, respectively, 5^{6+} (*middle*), and after reprotonation with an acid—stoichiometric amount with respect to the added base (*bottom*)

The distance traveled by the platform is about 0.7 nm, and from thermodynamic considerations it can be estimated that the elevator movement from the upper to lower level could in principle generate a force of up to 200 pN—one order of magnitude higher than that developed by myosin and kinesin [47, 48].

It should be noted that the acid-base controlled mechanical motion in $4H_3{}^{9+}$ is associated with interesting structural modifications, such as the opening and closing of a large cavity and the control of the positions and properties of the bipyridinium legs. This behavior can in principle be used to control the uptake and release of a guest molecule, a function of interest for the development of drug delivery systems.

2.4
An Autonomous Light-Powered Molecular Motor

The chemically powered artificial motors described in the previous sections are *not autonomous* since, after the mechanical movement induced by a chemical input, they need another, opposite chemical input to reset, which also implies generation of waste products. However, as illustrated in Sect. 1.3, addition of a reactant (fuel) is not the only means by which energy can be supplied to a chemical system. In fact, Nature shows that, in green plants, the energy needed to sustain the machinery of life is ultimately provided by sunlight. Energy inputs in the form of photons can indeed cause mechanical movements by reversible chemical reactions without formation of waste products. Only a few examples of light driven artificial molecular motors exhibiting autonomous behavior have been reported so far [59, 61, 101].

The design and construction of molecular shuttles powered exclusively by light energy is therefore a fascinating yet challenging subject. On the basis of the experience gained with previous studies on pseudorotaxane model systems [102–105], the rotaxane $\mathbf{6}^{6+}$ (Fig. 10) was specifically designed to achieve photoinduced ring shuttling in solution [106]. This compound is made of the electron donor ring *R*, and a dumbbell component which contains several units: a Ruthenium(II) polypyridine complex (P) that plays the dual role of a light-fueled motor [107] and a stopper, a *p*-terphenyl-type rigid spacer (S), a 4,4′-bipyridinium unit (A_1) and a 3,3′-dimethyl-4,4′-bipyridinium unit (A_2) as electron accepting stations, and a tetraarylmethane group as the second stopper (T). The stable translational isomer of rotaxane $\mathbf{6}^{6+}$ is the one in which the *R* component encircles the A_1 unit, in keeping with the fact that this station is a better electron acceptor than the other one.

The strategy devised in order to obtain the photoinduced abacus-like movement of the *R* macrocycle between the two stations A_1 and A_2, illustrated in Fig. 11, is based on the following four operations:

(a) *Destabilization of the stable translational isomer*: light excitation of the photoactive unit P (process 1) is followed by the transfer of an electron from the excited state to the A_1 station, which is encircled by the ring *R* (process 2), with the consequent "deactivation" of this station; such

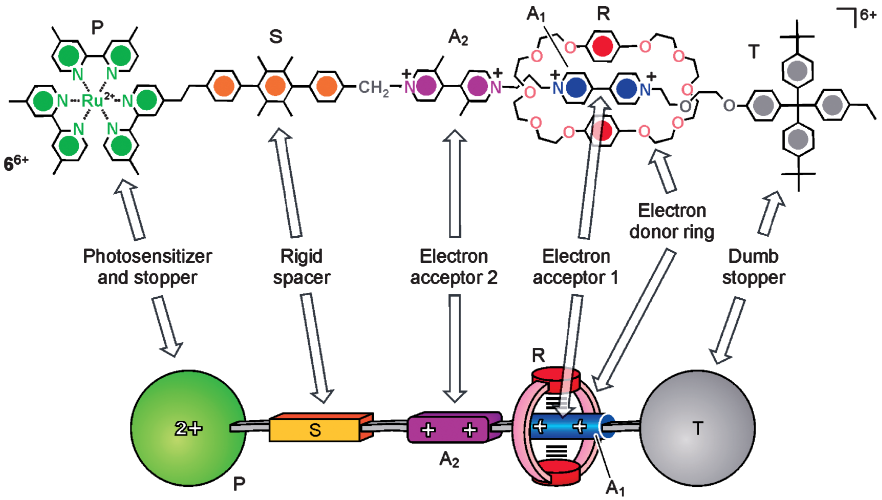

Fig. 10 Chemical formula and cartoon representation of the rotaxane 6^{6+}, showing its modular structure

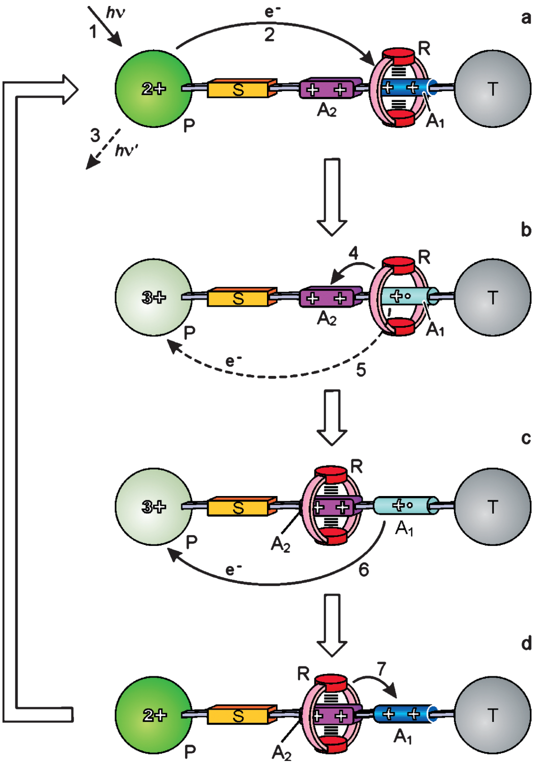

Fig. 11 Schematic representation of the operation of rotaxane **6**$^{6+}$ as an autonomous "four stroke" linear nanomotor powered by light

a photoinduced electron-transfer process has to compete with the intrinsic decay of the P excited state (process 3).

(b) *Ring displacement*: the ring moves by Brownian motion (process 4) from the reduced A_1 station to A_2, a step that has to compete with the back electron-transfer process from reduced A_1 (still encircled by *R*) to the oxidized P unit (process 5).

(c) *Electronic reset*: a back electron-transfer process from the "free" reduced A_1 station to the oxidized P unit (process 6) restores the electron acceptor power to the A_1 station.

(d) *Nuclear reset*: as a consequence of the electronic reset, back movement of the ring by Brownian motion from A_2 to A_1 takes place (process 7).

The crucial point for such a mechanism is indeed the favorable competition between ring displacement (process 4) and back electron transfer (process 5). The rate constants of the relevant electron-transfer processes were measured in acetonitrile solution by laser flash photolysis [106]; however, direct time-resolved observation of the ring displacement proved to be quite elusive. Very recently, we performed laser flash photolysis experiments in the presence of an electron relay in order to slow down the back electron-transfer process and facilitate the observation of ring displacement [108]. We observed that the transient absorption spectrum of the photogenerated one-electron reduced A_1 unit in the rotaxane changes slightly with time, while it does not change at all for the dumbbell component. Such changes have been attributed to the motion of the ring *R*, which immediately after light excitation surrounds the reduced A_1 unit and subsequently moves away from it to encircle the A_2 station.

These investigations revealed that in acetonitrile at room temperature the ring shuttling rate is one order of magnitude slower than the back electron transfer. Hence, the absorption of a visible photon can cause the occurrence of a forward and back ring movement (i.e. a full cycle) without generation of waste products, but with a low (around 2%) quantum efficiency. The low efficiency is compensated by the fact that the operation of the system relies *exclusively* on intramolecular processes. Therefore, this artificial molecular motor does not need the assistance of external species and, in principle, it can work at the single-molecule level. In other words, $\mathbf{6}^{6+}$, performs as a "four stroke" autonomous artificial linear motor working by an *intramolecular* mechanism powered by *visible* light.

2.5
Systems Based on Catenanes

Catenanes are chemical compounds consisting minimally of two interlocked macrocycles [75]. When one of the two rings carries two different recognition sites, then the opportunity exists to control the dynamic processes in a manner reminiscent of the controllable molecular shuttles. By switching *off* and *on* again the recognition properties of one of the two recognition sites of the non-symmetric ring by means of external energy stimuli, it is indeed possible to induce conformational changes that can be viewed as the rotation of the non-symmetric ring.

An example of such a behavior is offered by the catenane $\mathbf{7}^{4+}$ shown in Fig. 12 [109, 110]. This compound is made of a symmetric tetracationic ring containing two electron acceptor bipyridinium units and a non-symmetric ring comprising two different electron donor units, namely a tetrathiafulvalene (TTF) group and a 1,5-dioxynaphthalene (DON) unit. Since the TTF unit is a better electron donor than the DON one, as witnessed by the potentials values for their oxidation, the thermodynamically stable conformation of the catenane is that in which the symmetric ring encircles the TTF unit of the non-symmetric one (Fig. 12a, state 0). On electrochemical oxidation in solution, the TTF unit loses its electron donor power and acquires a positive charge (Fig. 12b). As a consequence it is expelled from the cavity of the tetracationic ring and is replaced by the neutral DON unit (Fig. 12c, state 1). At this stage, subsequent reduction of the oxidized TTF unit restores its electron donor ability and the

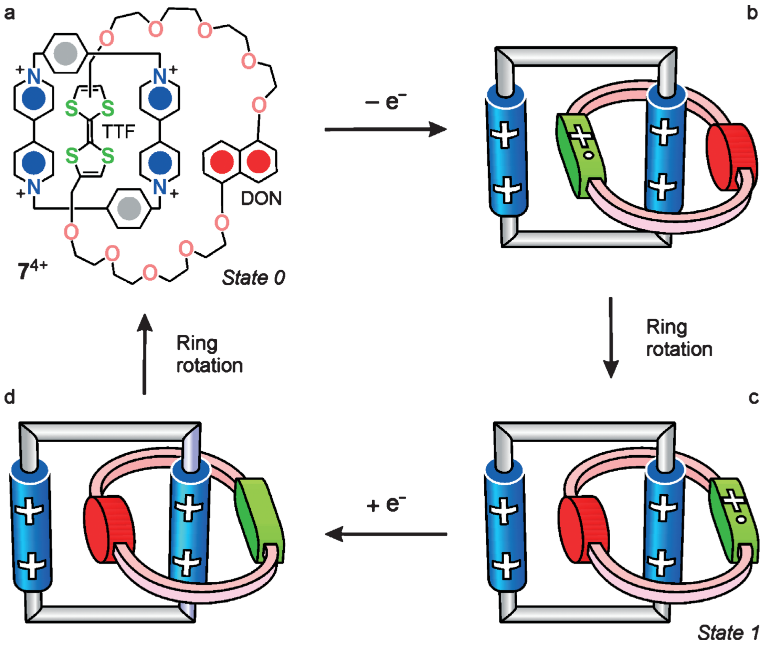

Fig. 12 Redox controlled ring rotation in solution for catenane 7^{4+}, which contains a non-symmetric ring

system goes back to its original conformation. A variety of techniques, including cyclic voltammetry, were employed to characterize the system. The catenane 7^{4+} was also incorporated in a solid state device that could be used for random access memory (RAM) storage [111, 112]. Additionally, this compound could be employed for the construction of electrochromic systems, because its various redox states are characterized by different colors [109, 110, 113].

It should be pointed out that in the catenane system described above, repeated switching between the two states does not need to occur through a full rotation. In fact, because of the intrinsic symmetry of the system, both the movement from state 0 to state 1 and that from state 1 to state 0 can take place, with equal probabilities, along a clockwise or anticlockwise direction. A full (360°) rotation movement, which would be much more interesting from a mechanical viewpoint, can only occur in ratchet-type systems, i.e. in the presence of asymmetry elements which can be structural or functional in nature [40, 114]. This idea was recently implemented with a carefully designed catenane by relying on a sequence of photochemical, chemical, and thermally activated processes [115] and employing ^{1}H NMR spectroscopy to characterize the system.

By an appropriate choice of the functional units that are incorporated in the catenane components, more complex functions can be obtained. An example is represented by catenane $8H^{5+}$ (Fig. 13), composed of a symmetric crown ether ring and a cyclophane ring containing two bipyridinium (BPM) and one ammonium (AMH) recognition sites [116]. The absorption spectra and electrochemical properties show that the crown ether ring surrounds a BPM unit of the other ring both in $8H^{5+}$ (Fig. 13a) and in its deprotonated form 8^{4+} (Fig. 13b), indicating that deprotonation-protonation of the AMH unit does not cause any displacement of the crown ether ring (state 0). Electrochemical measurements show that, after one-electron reduction of both the BPM units of $8H^{5+}$, the crown ether ring is displaced on the AMH function (Fig. 13c, state 1), which means that an electrochemically induced conformational switching does occur. Furthermore, upon deprotonation of the two-electron reduced form $8H^{3+}$ (Fig. 13d), the macrocyclic polyether moves to one of the monoreduced BPM units (state 0). Therefore, in order to achieve the motion of the crown ether ring in the deprotonated catenane 8^{4+}, it is necessary *both* to reduce (switch off) the BPM units *and* protonate (switch on) the amine function.

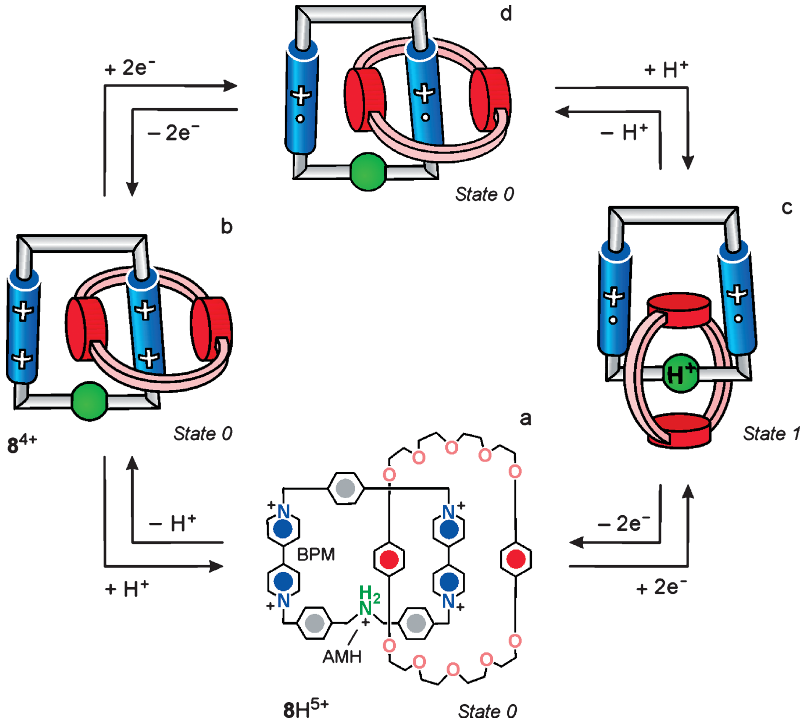

Fig. 13 Switching processes of catenane $8H^{5+}$ in solution. Starting from the deprotonated catenane 8^{4+}, the position of the crown ether ring switches under acid-base and redox inputs according to AND logic

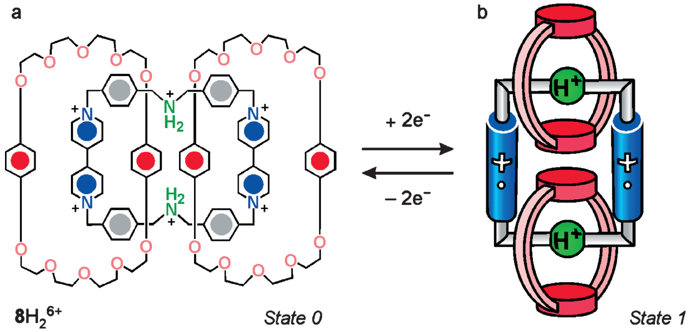

Fig. 14 Redox controlled movements of the ring components in a catenane composed of three interlocked macrocycles. These motions are obtained upon reduction-oxidation of the bipyridinium units of the cyclophane ring in solution

The mechanical motion in such a catenane takes place according to an AND logic [46], a function associated with two energy inputs of different nature.

Controlled rotation of the molecular rings has been achieved also in catenanes composed of three interlocked macrocycles. For example, catenane $9H_2^{6+}$ (Fig. 14) is made up of two identical crown ether rings interlocked with a cyclophane ring containing two BPM and two AMH units [116]. Because of the type of crown ethers used, the stable conformation of $9H_2^{6+}$ is that where the two crown ether rings surround the BPM units (Fig. 14a, state 0). Upon addition of one electron in each of the BPM units, the two macrocycles move on the AMH stations (Fig. 14b, state 1), and move back to the original position when the bipyridinium units are reoxidized. A clever—albeit complex—way to obtain a unidirectional full rotation in a catenane having the same topology of $9H_2^{6+}$ was devised by another research group [117]. Other examples of molecular motors based on catenanes can be found in the literature [25–28, 118].

3
Conclusion and Perspectives

The results described here show that, by taking advantage of careful incremental design strategies, of the tools of modern synthetic chemistry, of the paradigms of supramolecular chemistry, as well as inspiration from natural systems, it is possible to produce compounds capable of performing nontrivial mechanical movements and exercising a variety of different functions upon external stimulation.

In the previously mentioned address to the American Physical Society [2, 3], R. P. Feynman concluded his reflection on the idea of constructing molecular machines as follows: *"What would be the utility of such machines? Who knows? I cannot see exactly what would happen, but I can hardly doubt that when we have some control of the rearrangement of things on a molecular scale we will get an enormously greater range of possible properties that substances can have, and of different things we can do"*. This sentence, pronounced in 1959, is still an appropriate comment to the work described in this chapter. The results achieved sowed the seeds for future developments, which are under investigation in our laboratory: (i) the design and construction of more sophisticated artificial molecular motors and machines; (ii) the use of such systems to do tasks such as molecular-level transportation, catalysis, and mechanical gating of molecular channels; and (iii) the possibility of exploiting their logic behavior for information processing at the molecular level and, in the long run, for the construction of chemical computers.

It should also be noted that the majority of the artificial molecular motors developed so far operate in solution, that is, in an incoherent fashion and without control of spatial positioning. The studies in solution of complicated chemical systems such as molecular motors and machines are indeed of fundamental importance to understand their operation mechanisms; moreover, for some uses (e.g., drug delivery) molecular machines will have to work in liquid solution. In this regard, it should be recalled that motor proteins operate in—or at least in contact with —an aqueous solution. However, it seems reasonable that, before artificial molecular motors and machines can find applications in many fields of technology, they have to be interfaced with the macroscopic world by ordering them in some way. The next generation of molecular machines and motors will need to be organized at interfaces, deposited on surfaces, or immobilized into membranes or porous materials [111–113, 119–126] so that they can behave coherently and can be addressed in space. Indeed, the preparation of modified electrodes represents one of the most promising ways to achieve this goal.

Apart from more or less futuristic applications, the extension of the concepts of motor and machine to the molecular level is of interest not only for the development of nanotechnology, but also for the growth of basic research. Looking at molecular and supramolecular species from the viewpoint of functions with references to devices of the macroscopic world is indeed a very interesting exercise which introduces novel concepts into Chemistry as a scientific discipline.

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References

1. Keyes RW (2001) Proc IEEE 89:227, see also the International Technology Roadmap for Semiconductors (ITRS), 2004 Edition, available at http://public.itrs.net
2. Feynman RP (1960) Eng Sci 23:22
3. Feynman RP (1960) Saturday Rev 43:45; see also: http://www.feynmanonline.com
4. Drexler KE (1986) Engines of Creation—The Coming Era of Nanotechnology. Anchor Press, New York
5. Drexler KE (1992) Nanosystems. Molecular Machinery, Manufacturing, and Computation. Wiley, New York
6. Smalley RE (2001) Sci Am 285:76
7. Joachim C, Launay JP (1984) Nouv J Chem 8:723
8. Balzani V, Moggi L, Scandola F (1987) In: Balzani V (ed) Supramolecular Photochemistry. Reidel, Dordrecht, p 1
9. Lehn JM (1990) Angew Chem Int Ed Engl 29:1304
10. Aviram A, Ratner MA (1974) Chem Phys Lett 29:277
11. Carter FL (ed) (1982) Molecular Electronic Devices. Dekker, New York
12. Metzger RM (2003) Chem Rev 103:3803 and references therein
13. Lehn JM (1995) Supramolecular Chemistry—Concepts and Perspectives. VCH, Weinheim
14. Lehn JM, Atwood JL, Davies JED, MacNicol DD, Vögtle F (eds) (1996) Comprehensive Supramolecular Chemistry. Pergamon, Oxford
15. Steed JW, Atwood JL (2000) Supramolecular Chemistry. Wiley, New York
16. Atwood JL, Steed JW (eds) (2004) Encyclopedia of Supramolecular Chemistry. Dekker, New York
17. Rigler R, Orrit M, Talence I, Basché T (2001) Single Molecule Spectroscopy. Springer, Berlin Heidelberg New York
18. Moerner WE (2002) J Phys Chem B 106:910
19. Zander C, Enderlein J, Keller RA (2002) Single Molecule Detection in Solution. Wiley-VCH, Weinheim
20. Gimzewski JK, Joachim C (1999) Science 283:1683
21. Hla SW, Meyer G, Rieder KH (2001) Chem Phys Chem 2:361
22. Samorì B, Zuccheri G, Baschieri P (2005) Chem Phys Chem 6:29
23. See e.g.: Christ T, Kulzer F, Bordat P, Basché T (2001) Angew Chem Int Ed 40:4192
24. Goodsell DS (2004) Bionanotechnology—Lessons from Nature. Wiley, New York
25. Balzani V, Credi A, Raymo FM, Stoddart JF (2000) Angew Chem Int Ed 39:3348
26. (2001) Acc Chem Res 34, no 6. Special Issue on Molecular Machines
27. (2001) Struct Bond 99. Special Volume on Molecular Machines and Motors
28. Balzani V, Credi A, Venturi M (2003) Molecular Devices and Machines—A Journey into the Nano World. Wiley-VCH, Weinheim
29. Sauvage JP (2005) Chem Comm 1507
30. Akkerman OS, Coops J (1967) Rec Trav Chim Pays-Bas 86:755
31. Cozzi F, Guenzi A, Johnson CA, Mislow K, Hounshell WD, Blount JF (1981) J Am Chem Soc 103:957
32. Bedard TC, Moore JS (1995) J Am Chem Soc 117:10662
33. Dominguez Z, Khuong TAV, Dang H, Sanrame CN, Nunez JE, Garcia-Garibay MA (2003) J Am Chem Soc 125:8827
34. Shima T, Hampel F, Gladysz JA (2004) Angew Chem Int Ed 43:5537
35. Khuong TAV, Zepeda G, Sanrame CN, Dang H, Bartbeger MD, Houk KN, Garcia-Garibay MA (2004) J Am Chem Soc 126:14778

36. Kottas GS, Clarke LI, Horinek D, Michl J (2005) Chem Rev 105:1281
37. Astumian RD, Hänggi P (2002) Phys Today 55:33
38. Parisi G (2005) Nature 433:221
39. Astumian RD (2005) Proc Natl Acad Sci USA 102:1843
40. Ballardini R; Balzani V, Credi A, Gandolfi MT, Venturi M (2001) Acc Chem Res 34:445
41. Balzani V, Scandola F (1991) Supramolecular Photochemistry. Horwood, Chichester
42. Armaroli N (2003) Photochem Photobiol Sci 2:73
43. Balzani V (2003) Photochem Photobiol Sci 2:479
44. Kaifer AE, Gómez-Kaifer M (1999) Supramolecular Electrochemistry. Wiley-VCH, Weinheim
45. Marcaccio M, Paolucci F, Roffia S (2004) In: Pombeiro AJL, Amatore C (eds) Trends in Molecular Electrochemistry. Dekker, New York, p 223
46. Balzani V, Credi A, Venturi M (2003) ChemPhysChem 4:49
47. Schliwa M (ed) (2003) Molecular Motors. Wiley-VCH, Weinheim
48. Schliwa M, Woehlke G (2003) Nature 422:759
49. Boyer PD (1993) Biochim Biophys Acta 1140:215
50. Boyer PD (1998) Angew Chem Int Ed 37:2296
51. Walker JE (1998) Angew Chem Int Ed 37:2308
52. Stock D, Leslie AGW, Walker JE (1999) Science 286:700
53. Vale RD, Milligan RA (2000) Science 288:88
54. Frey E (2002) ChemPhysChem 3:270
55. Steinberg-Yfrach G, Rigaud JL, Durantini EN, Moore AL, Gust D, Moore TA (1998) Nature 392:479
56. Soong RK, Bachand GD, Neves HP, Olkhovets AG, Craighead HG, Montemagno CD (2000) Science 290:1555
57. Hess H, Bachand GD, Vogel V (2004) Chem Eur J 10:2110
58. Kelly TR, De Silva H, Silva RA (1999) Nature 401:150
59. Koumura N, Zijlstra RWJ, van Delden RA, Harada N, Feringa BL (1999) Nature 401:152
60. Kelly TR, Silva RA, De Silva H, Jasmin S, Zhao YJ (2000) J Am Chem Soc 12:6935
61. van Delden RA, Koumura N, Schoevaars A, Meetsma A, Feringa BL (2003) Org Biomol Chem 1:33
62. Zheng XL, Mulcahy ME, Horinek D, Galeotti F, Magnera TF, Michl J (2004) J Am Chem Soc 126:4540
63. Shinkai S, Ikeda M, Sugasaki A, Takeuchi M (2001) Acc Chem Res 34:494
64. Gray M, Cuello AO, Cooke G, Rotello VM (2003) J Am Chem Soc 125:7882
65. Moon K, Grindstaff J, Sobransingh D, Kaifer AE (2004) Angew Chem Int Ed 43:5496
66. Jeon WS, Kim E, Ko YH, Hwang IH, Lee JW, Kim SY, Kim HJ, Kim K (2005) Angew Chem Int Ed 44:87
67. Mao C, Sun W, Shen Z, Seeman NC (1999) Nature 397:144
68. Yurke B, Turberfield AJ, Mills AP Jr, Simmel FC, Neumann JL (2000) Nature 406:605
69. Yan H, Zhang X, Shen Z, Seeman NC (2002) Nature 415:82
70. Li JJ, Tan W (2002) Nano Lett 2:315
71. Chen Y, Wang M, Mao C (2004) Angew Chem Int Ed 43:3554
72. Chen Y, Mao C (2004) J Am Chem Soc 126:8626
73. Yin P, Yan H, Daniell XG, Turberfield AJ, Reif JH (2004) Angew Chem Int Ed 43:4906
74. Sherman WB, Seeman NC (2004) Nano Lett 4:1203
75. Sauvage JP, Dietrich-Buchecker C (eds) (1999) Molecular Catenanes, Rotaxanes and Knots. Wiley-VCH, Weinheim

76. Chambron JC, Dietrich-Buchecker CO, Sauvage JP (1993) Top Curr Chem 165:131
77. Gibson HW, Bheda MC, Engen PT (1994) Prog Polym Sci 19:843
78. Amabilino DB, Stoddart JF (1995) Chem Rev 95:2725
79. Johnston AG, Leigh DA, Pritchard RJ, Degan MD (1995) Angew Chem Int Ed Engl 34:1209
80. Jäger R, Vögtle F (1997) Angew Chem Int Ed 36:930
81. Fujita M (1999) Acc Chem Res 32:53
82. Ishow E, Credi A, Balzani V, Spadola F, Mandolini L (1999) Chem Eur J 5:984
83. Ballardini R, Balzani V, Clemente-Léon M, Credi A, Gandolfi MT, Ishow E, Perkins J, Stoddart JF, Tseng HR, Wenger S (2002) J Am Chem Soc 124:12786
84. Anelli PL, Spencer N, Stoddart JF (1991) J Am Chem Soc 113:5131
85. Bissell A, Córdova E, Kaifer AE, Stoddart JF (1994) Nature 369:133
86. Elizarov AM, Chiu SH, Stoddart JF (2002) J Org Chem 67:9175
87. Tseng HR, Vignon SA, Stoddart JF (2003) Angew Chem Int Ed 42:1491
88. Keaveney CM, Leigh DA (2004) Angew Chem Int Ed 43:1222
89. Leigh DA, Perez EM (2004) Chem Comm 2262
90. Tseng HR, Vignon SA, Celestre PC, Perkins J, Jeppesen JO, Di Fabio A, Ballardini R, Gandolfi MT, Venturi M, Balzani V, Stoddart JF (2004) Chem Eur J 10:155
91. Altieri A, Gatti FG, Kay ER, Leigh DA, Martel D, Paolucci F, Slawin AMZ, Wong JKY (2003) J Am Chem Soc 125:8644
92. Willner I, Pardo-Yssar V, Katz E, Ranjit KT (2001) J Electroanal Chem 497:172
93. Wang QC, Qu DH, Ren J, Chen KC, Tian H (2004) Angew Chem Int Ed 43:2661
94. Abraham W, Grubert L, Grummt UW, Buck K (2004) Chem Eur J 10:3562
95. Ashton PR, Ballardini R, Balzani V, Baxter I, Credi A, Fyfe MCT, Gandolfi MT, Gomez-Lopez M, Martinez-Diaz MV, Piersanti A, Spencer N, Stoddart JF, Venturi M, White AJP, Williams DJ (1998) J Am Chem Soc 120:11932
96. Garaudée S, Credi A, Silvi S, Venturi M, Stoddart JF (2005) ChemPhysChem 6:2145
97. Balzani V, Clemente-Leon M, Credi A, Lowe JN, Badjic JD, Stoddart JF, Williams DJ (2003) Chem Eur J 9:5348
98. Badjic JD, Balzani V, Credi A, Silvi S, Stoddart JF (2004) Science 303:1845
99. The molecular elevator operates in solution, i.e. with no control of the orientation of the molecules relative to a fixed reference system. Therefore, in the present context the words “upper” and “lower” are used only for descriptive purposes
100. Monk PMS (1998) The Viologens—Physicochemical Properties, Synthesis and Application of the Salts of 4,4′-Bipyridine. Wiley, Chichester
101. Brouwer AM, Frochot C, Gatti FG, Leigh DA, Mottier L, Paolucci F, Roffia S, Wurpel GWH (2001) Science 291:2124
102. Ballardini R, Balzani V, Gandolfi MT, Prodi L, Venturi M, Philp D, Ricketts HG, Stoddart JF (1993) Angew Chem Int Ed Engl 32:1301
103. Ashton PR, Ballardini R, Balzani V, Boyd SE, Credi A, Gandolfi MT, Gomez-Lopez M, Iqbal S, Philp D, Preece JA, Prodi L, Ricketts HG, Stoddart JF, Tolley MS, Venturi M, White AJP, Williams DJ (1999) Chem Eur J 3:152
104. Ashton PR, Ballardini R, Balzani V, Constable EC, Credi A, Kocian O, Langford SJ, Preece JA, Prodi L, Schofield ER, Spencer N, Stoddart JF, Wenger S (1998) Chem Eur J 4:2413
105. Ashton PR, Balzani V, Kocian O, Prodi L, Spencer N, Stoddart JF (1998) J Am Chem Soc 120:11190
106. Ashton PR, Ballardini R, Balzani V, Credi A, Dress R, Ishow E, Kleverlaan CJ, Kocian O, Preece JA, Spencer N, Stoddart JF, Venturi M, Wenger S (2000) Chem Eur J 6:3558

107. Ballardini R, Balzani V, Credi A, Gandolfi MT, Venturi M (2001) Int J Photoenergy 3:63
108. Balzani V, Clemente-León M, Credi A, Ferrer B, Venturi M, Flood AH, Stoddart JF (submitted)
109. Asakawa M, Ashton PR, Balzani V, Credi A, Hamers C, Mattersteig G, Montalti M, Shipway AN, Spencer N, Stoddart JF, Tolley MS, Venturi M, White AJP, Williams DJ (1998) Angew Chem Int Ed 37:333
110. Balzani V, Credi A, Mattersteig G, Matthews OA, Raymo FM, Stoddart JF, Venturi M, White AJP, Williams DJ (2000) J Org Chem 65:1924
111. Collier CP, Mattersteig G, Wong EW, Luo Y, Beverly K, Sampaio J, Raymo FM, Stoddart JF, Heath JR (2000) Science 289:1172
112. Luo Y, Collier CP, Jeppesen JO, Nielsen KA, Delonno E, Ho G, Perkins J, Tseng HR, Yamamoto T, Stoddart JF, Heath JR (2002) ChemPhysChem 3:519
113. Steuerman DW, Tseng HR, Peters AJ, Flood AH, Jeppesen JO, Nielsen KA, Stoddart JF, Heath JR (2004) Angew Chem Int Ed 43:6486
114. Ref [28], ch 16
115. Hernández JV, Kay ER, Leigh DA (2004) Science 306:1532
116. Ashton PR, Baldoni V, Balzani V, Credi A, Hoffmann HDA, Martinez-Diaz MV, Raymo FM, Stoddart JF, Venturi M (2001) Chem Eur J 7:3482
117. Leigh DA, Wong JKY, Dehez F, Zerbetto F (2003) Nature 424:174
118. Mobian P, Kern JM, Sauvage JP (2004) Angew Chem Int Ed 43:2392
119. Cavallini M, Biscarini F, Leon S, Zerbetto F, Bottari G, Leigh DA (2003) Science 299:531
120. Long B, Nikitin K, Fitzmaurice D (2003) J Am Chem Soc 125:5152
121. Álvaro M, Ferrer B, García H, Palomares EJ, Balzani V, Credi A, Venturi M, Stoddart JF, Wenger S (2003) J Phys Chem B 107:14319
122. Huang TJ, Tseng HR, Sha L, Lu WX, Brough B, Flood AH, Yu BD, Celestre PC, Chang JP, Stoddart JF, Ho CM (2004) Nano Lett 4:2065
123. Hernandez R, Tseng HR, Wong JW, Stoddart JF, Zink JI (2004) J Am Chem Soc 126:3370
124. Katz E, Lioubashevsky O, Willner I (2004) J Am Chem Soc 126:15520
125. Cecchet F, Rudolf P, Rapino S, Margotti M, Paolucci F, Baggerman J, Brouwer AM, Kay ER, Wong JKY, Leigh DA (2004) J Phys Chem B 108:15192
126. Flood AH, Peters AJ, Vignon SA, Steuerman DW, Tseng HR, Kang S, Heath JR, Stoddart JF (2004) Chem Eur J 10:6558