Shuttles and Muscles: Linear Molecular Machines Based on Transition Metals[†]

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ABSTRACT

Transition-metal-containing rotaxanes can behave as linear motors at the molecular level. The molecules are set into motion either by an electrochemical reaction or using a chemical signal. In a first example, a simple rotaxane is described that consists of a ring threaded by a two-coordination-site axle. The ring contains a bidentate ligand, coordinated to a copper center. The axle incorporates both a bidentate and a terdentate ligand. By oxidizing or reducing the copper center to Cu(II) or Cu(I) respectively, the ring glides from a given position on the axle to another position and vice versa. By generalizing the concept to a rotaxane dimer, whose synthesis involves a quantitative double-threading reaction triggered by copper(I) complexation, a molecular assembly reminiscent of a muscle is constructed. By exchanging the two metal centers of the complex (copper(I)/zinc(II)), a large-amplitude movement is generated, which corresponds to a contraction/stretching process. The copper(I)-containing rotaxane dimer is in a stretched situation (overall length ~8 nm), whereas the zinc(II) complexed compound is contracted (length ~6.5 nm). The stretching/contraction process is reversible and it is hoped that, in the future, other types of signals can be used (electrochemical or light pulse) to trigger the motion.

I. Introduction

In biology, molecular machines and motors play an essential role.[1] Many examples are known of proteins that undergo important shape changes, such as folding/defolding, after a signal has been sent to the molecules.[2] Molecular motors consist of several components, among which some parts will be considered as motionless and others will move continuously while energy is consumed (ATP hydrolysis or pH-gradient consumption). Biological motors can be classified as rotary or linear motors, ATP synthase being certainly the most important and best understood rotary motor.[3]

Artificial molecular machines and motors appear as one of the emerging fields of chemistry in the past decade.[4] Molecules or molecular assemblies, for which a certain part can be set into motion deliberately, have triggered great interest as "machines" in the course of the last 7 or 8 years.[5] Several such systems have been designed and elaborated recently, many of them being based on electroactive compounds whose shape will be modified at will by a redox process. Threaded or interlocking rings[6] are ideally suited to the construction of machines or motors since large-amplitude motions can be envisaged with such architectures without the risk of damaging the chemical structure of the system. If a ring is threaded onto a rod, it can either spin around the axle or undergo a translation movement. In a similar way, a ring can glide and spin within another ring in interlocking ring systems (catenanes).

Two representative examples of "molecular machines" are depicted in Figure 1. They are based on organic acceptor–donor and hydrogen-bonded complexes[5a] (Figure 1a) or transition-metal (copper) complexes[5b] (Figure 1b).
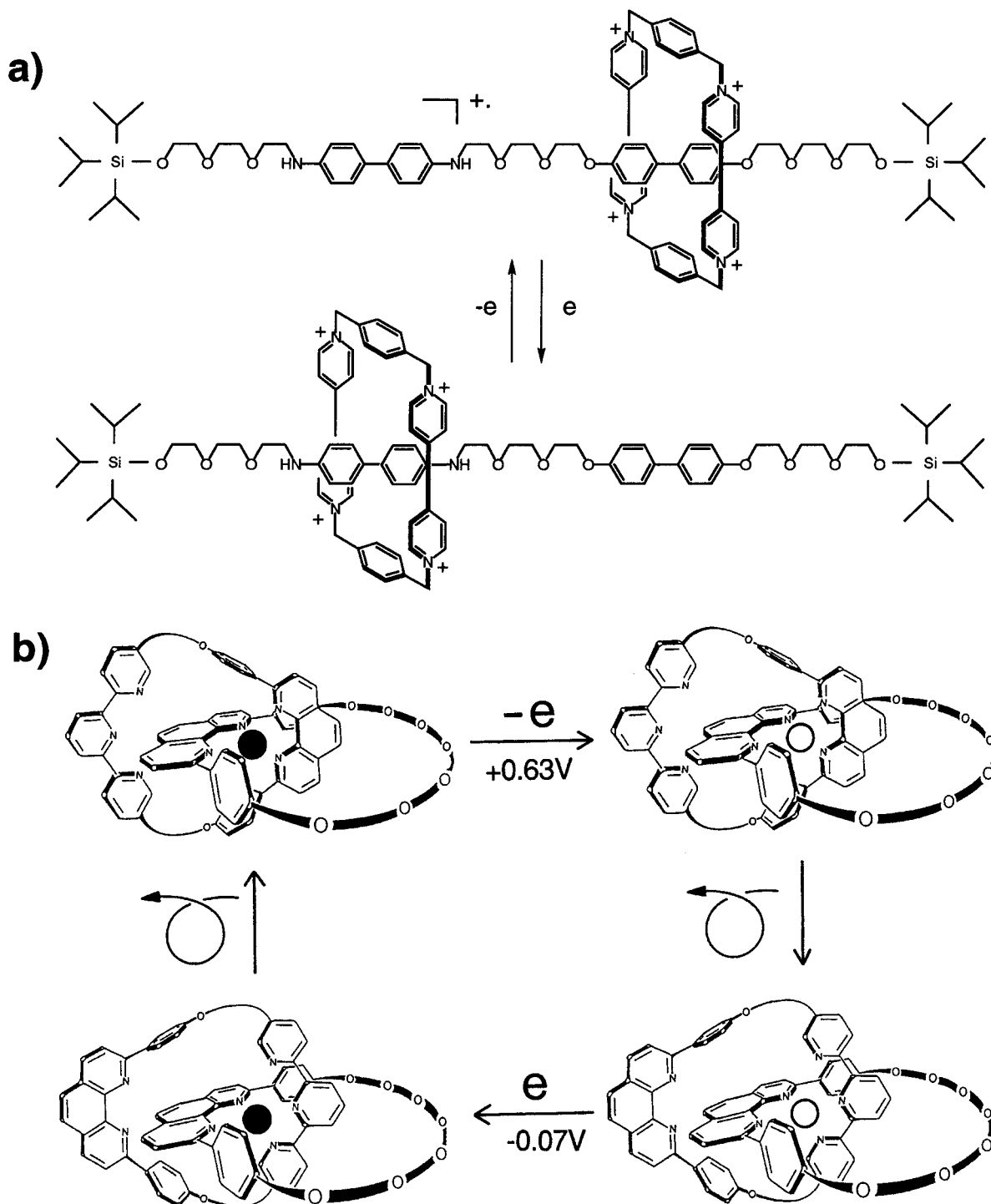
This Account is focused on linear machines and motors, which are essential in many biological processes. Recently, several linear motors have been given special attention, such as microtubule-associated ATPases. Kinesin and dynein play an essential role in organelles transport along the microtubules in cells.[7] These proteins travel in a controlled fashion, in a way reminiscent of trains on a rail.

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Maria Consuelo Jimenez-Molero was born in Valencia, Spain, in 1967. She graduated from the Universidad de Valencia and obtained her Ph.D. from the Universidad Politécnica de Valencia in 1997 in Organic Photochemistry. She spent two years in Strasbourg as postdoctoral researcher in Professor J.-P. Sauvage's group where she would achieve the synthesis of the first "molecular muscle" (1998–2000). After her stay in Strasbourg, she returned to Spain where she currently holds a research and teaching position at the Universidad Politécnica de Valencia.

Jean-Pierre Sauvage was born in Paris in 1944. He obtained his Ph.D. from the university of Strasbourg under the supervision of J.-M. Lehn. After postdoctoral research in Oxford (U.K.) with M. L. H. Green, he went back to Strasbourg where he is now a CNRS Director of Research. His current interests range from models of the photosynthetic reaction center using transition-metal complexes and porphyrins to topology (catenanes and knots) to molecular machines and motors. He is a member of the French Academy of Science.

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Christiane Dietrich-Buchecker was born in Strasbourg. She earned her Ph.D. from the Université Louis Pasteur in 1973 in Professor M. Frank-Neumann's laboratory, where she studied small rings (cyclopropanes, cyclopropenes, synthesis and reactivity) and the total synthesis of chrysanthemic acids. Dr. Dietrich-Buchecker has been a member of the CNRS since 1970, and she did postdoctoral work with Professor K. B. Sharpless (MIT, Cambridge, MA, 1973–1974) on the study of new organoselenium compounds. She joined Professor Sauvage's group in 1981, and her present research field is the synthesis of topologically novel molecules, catenanes and molecular knots.

FIGURE 1. (a) The molecular "shuttle" elaborated and studied by Stoddart, Kaifer, and co-workers is based on electroactive organic functions (aromatic amine) and electron donor and acceptor groups. (b) A two-geometry [2]catenane constructed around copper(I); the gliding motion of one ring within the other is triggered by oxidizing or reducing the metal center (Cu^I/Cu^{II}).

Clearly, the functioning of skeletal muscles is the best understood linear motor.[8] The actin/myosin linear motor, which constitutes the most important part of muscles, has been extensively studied in the past three decades. There is obviously some analogy between the motion of actin filaments with respect to myosin-containing filaments (thick filament) and classical motors consisting of a piston moving in a cylinder (see Figure 2).

In terms of molecular synthetic models, shuttles,[5a]

consisting of rings gliding on the filaments (or rods) on which they have been threaded, also display functional analogy with the myosin−actin complex.

II. Molecular Shuttle: Gliding of the Ring on Its Axle under the Action of an Electrochemical or Photochemical Signal

A [2]rotaxane is a molecular system consisting of a ring threaded by a string with two blocking groups attached
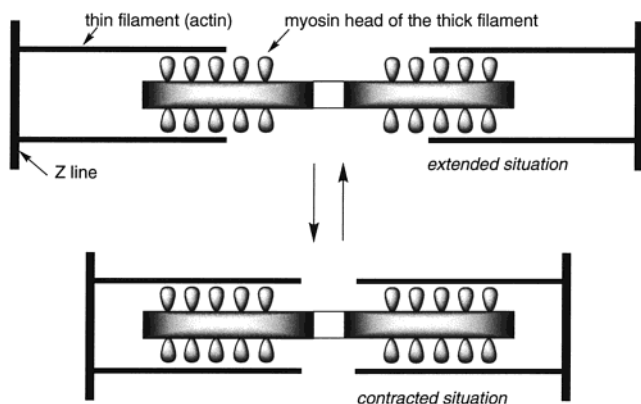
FIGURE 2. Schematic representation of a muscle in action. From the stretched situation, the contracted situation is obtained by a gliding process of the thick filament (myosin) along the thin filament (actin polymer).

at both ends of the string to prevent dethreading.[6a] Such compounds have been made long ago,[9,10] but they have been mostly considered as chemical curiosities. Recently, rotaxanes underwent a real revival due to the newly developed efficient procedures that make them relatively easy to prepare,[11−13] and also because of their electro- and photochemical properties[14−16] and their aptitude to undergo controlled molecular motions.[5a,17,18] In previous work on catenanes, the gliding motion of a ring within the other was studied by setting in motion either one cycle or both rings.[5b,19,20] In the rotaxanes described here, a ring is translated along a rodlike component on which it is threaded (Figure 3).
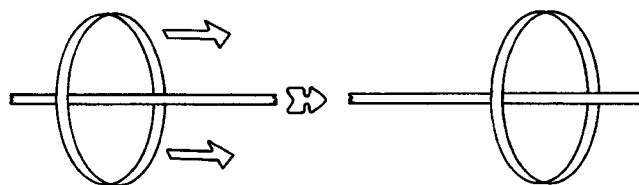

FIGURE 3. Motion of a ring on its axle.

The synthetic strategy developed in our group for making rotaxanes relies on the ability of copper(I) to gather the two constitutive organic fragments (a ring incorporating a bidentate chelate and an open chain component) and to force the string to thread through the ring. This threading step is generally quantitative provided the stoichiometry of the reaction is carefully respected due to the selective formation of very stable tetrahedral copper(I) complexes. It can be extended to strings containing two *different* sites, such as *bi*dentate and *ter*dentate coordinating units.

Our approach toward threaded linear systems displaying electrochemically and photochemically induced molecular motions involves the synthesis of the copper(I) rotaxane as represented in Figure 4.

This system and most of the other "molecular machines" elaborated and studied in our group function on the same principle. Among the first row transition-metal ions, copper displays unusual features related to the geometrical properties of its complexes: the stereoelectronic requirements of copper(I) and copper(II) are markedly different. This characteristic will provide the driving
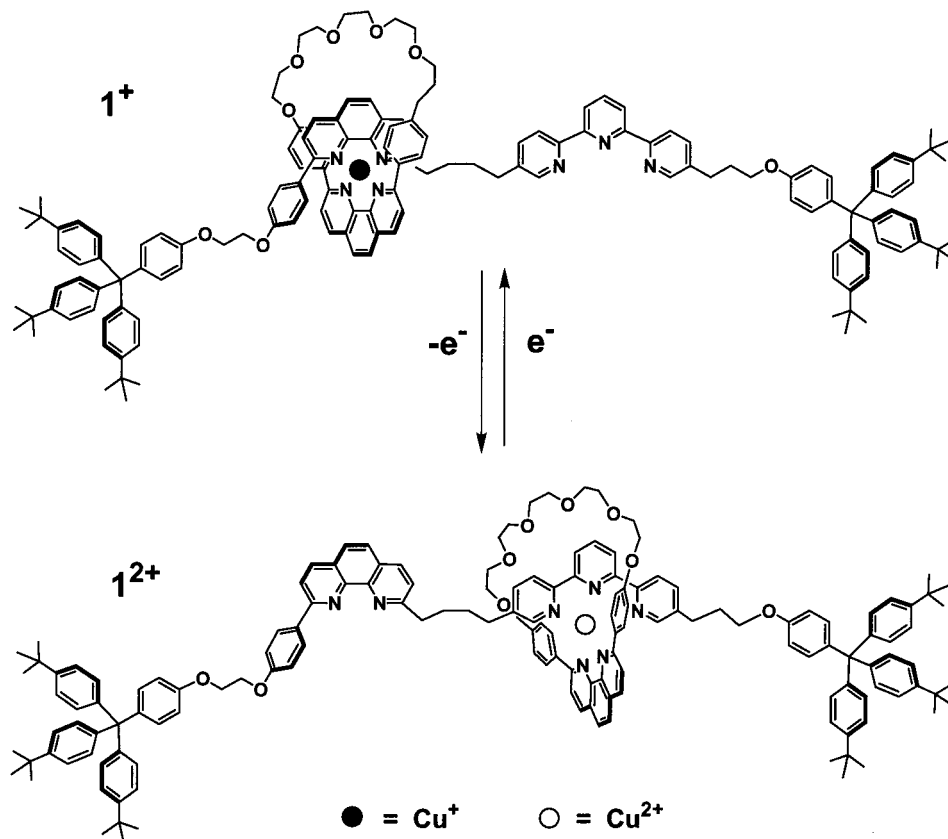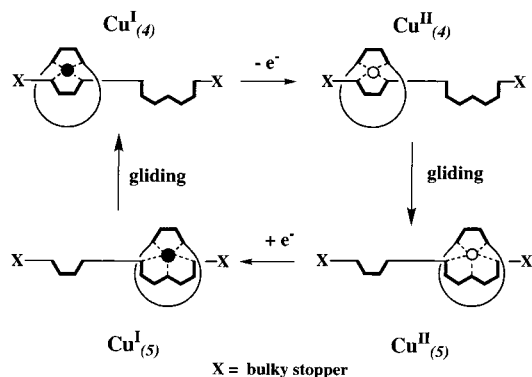

FIGURE 4. The copper(I) rotaxane: the four-coordinate situation (upper line) and the five-coordinate arrangement (lower line).

FIGURE 5. *Square scheme* in the threaded compound. The subscripts (4) and (5) indicate the copper coordination number in each complex. The stable $Cu^I_{(4)}$ complex is oxidized to an intermediate tetrahedral divalent species $Cu^{II}_{(4)}$ which undergoes a rearrangement to afford the stable $Cu^{II}_{(5)}$ complex. Upon reduction, a $Cu^I_{(5)}$ species is formed as a transient, which finally reorganizes to regenerate the starting complex. The black circle represents Cu(I), and the white circle represents Cu(II).

force for setting our systems in motion. Whereas a coordination number of 4 (usually with a roughly tetrahedral arrangement of the ligands) corresponds to stable monovalent systems, copper(II) requires higher coordination numbers. The most commonly encountered copper-(II) complexes have a coordination number of 5 (square pyramidal or trigonal bipyramidal geometries) or 6 (octahedral arrangement, with Jahn–Teller distortion). Thus, by switching alternatively from copper(I) to copper(II), one should be able to induce changes in the molecule so as to afford a coordination situation favorable to the corresponding oxidation state. The square scheme illustrating this principle is given in Figure 5.
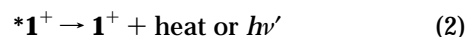
Electrochemically Driven Motion. The electrochemical behavior of 1^+ is particularly clean and interesting since only the four- and the five-coordinate geometries can be obtained by translating the metal-complexed ring from the phenanthroline site to the terpyridine site. The electrochemically induced molecular motions (square scheme[21]) similar to those represented in Figure 5 can be monitored by cyclic voltammetry (CV) and controlled potential electrolysis experiments.

From the CV measurements at different scan rates (from 0.005 to 2 V s^{-1}) both on the copper(I) and copper-(II) species, it could be inferred that the chemical steps (motions of the ring from the phenanthroline to the terpyridine sites and vice versa) are slow on the time scale of the experiments. It is noteworthy that oxidation of 1^+ to the divalent copper(II) state affords exclusively the five-coordinate species after rearrangement of the system. The bis-terpyridine complex, which would be formed by decomplexation of the copper(II) center and recoordination to the terpyridine fragments of two different strings, is not detected. This observation is important in relation to the general mechanism of the changeover step converting a four-coordinate Cu(II) species ($Cu^{II}_{(4)}$) into the corresponding stable five-coordinate complex ($Cu^{II}_{(5)}$). It tends to indicate that the conversion does not involve full demetalation of $Cu^{II}_{(4)}$ followed by recomplexation but is

rather an intramolecular reaction, probably consisting of several elemental dissociation–association steps involving the phenanthroline and terpyridine fragments of the string as well as solvent molecules and, possibly, counterions.

Photochemically Driven Motion. The Cu(I) complexes of polypyridine ligands display luminescence from the lowest triplet MLCT excited state and have a reasonably long lifetime which allows them to act as electron-transfer reductants.[22,24] In this instance, the characteristics of the Cu(I)-based chromophoric unit of rotaxane 1^+ are (i) UV absorption bands due to Π^* ligand-centered (LC) transitions, (ii) metal-to-ligand charge transfer (MLCT) bands in the 400–700 nm spectral region, and (iii) a MLCT emission band with $\lambda_{max} = 785$ nm and a lifetime of 34 ns in aerated acetonitrile solution at 298 K.[19b]

The first electron-transfer step of the overall swinging process, that is, the conversion of $*1^+$ into 1^{2+}, is possible despite the short excited-state lifetime of $*1^+$. Indeed, the light irradiation of 1^+ in the presence of a suitable electron acceptor (A) leads to the 1^{2+} species by an oxidative quenching. Equations 1–5 describe the different reactions which occur.

$$1^+ + h\nu \rightarrow *1^+ \tag{1}$$

$$*1^+ \rightarrow 1^+ + \text{heat or } h\nu' \tag{2}$$

$$*1^+ + A \rightarrow 1^{2+} + A^{-\bullet} \tag{3}$$

$$1^{2+} + A^{-\bullet} \rightarrow 1^+ + A \tag{4}$$

$$A^{-\bullet} \rightarrow \text{products} \tag{5}$$

In eq 3, the electron-transfer reaction competes with nonradiative deactivation and luminescence (eq 2). It is of course necessary that reaction 3 takes place with a negative free energy change. The reduction potential of the $1^{2+}/*1^+$ couple can be evaluated by the following equation:[25]

$$E^{\circ}(1^{2+}/*1^+) = E^{\circ}(1^{2+}/1^+) - \xi_{o-o} = -0.90 \text{ V} \tag{6}$$

where ξ_{o-o} is the energy of the $*1^+$ excited state (about 1.58 eV, as estimated from the onset of the maximum of the corrected emission band in the same solvent) and $E^{\circ}(1^{2+}/1^+)$ is the reduction potential of the ground state (+0.68 V in acetonitrile). This shows that even a mild oxidant should be capable of oxidizing the photoexcited $*1^+$ rotaxane (eq 3). The principle of the photochemically triggered rearrangement of the rotaxane 1^+ is given in Figure 6.

Photochemical experiments were performed by irradiating acetonitrile solutions containing 1^+ and p-NO$_2$C$_6$H$_4$CH$_2$Br in the presence of 0.1 M TBA(BF$_4$) with light of wavelength 464 nm. Under these conditions, light excitation leads to the disappearance of 1^+ and the concomitant formation of 1^{2+}($Cu^{II}_{(4)}$) as the only reaction product. At the end of the photoreaction, the irradiated solution was kept in the dark at 298 K. Spectrophotometric measurements showed that a slow reaction was occurring, causing a general decrease in absorbance, particularly in
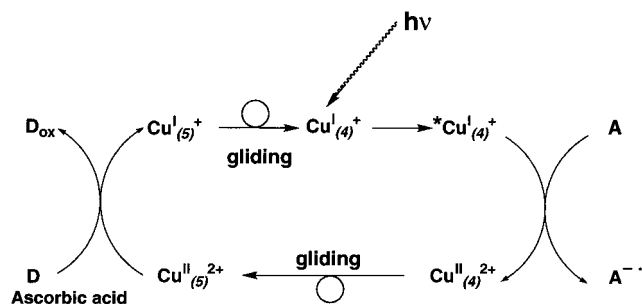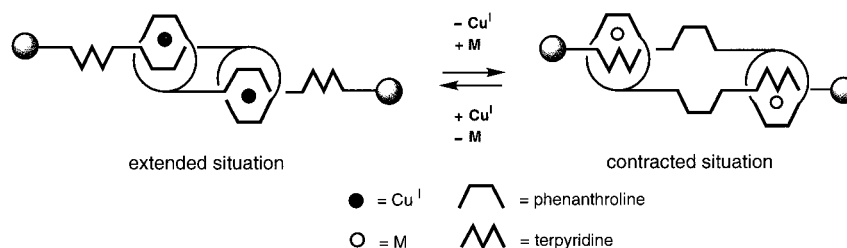
FIGURE 6. Principle of the photochemically and chemically triggered rearrangement of the rotaxane **1**+.

FIGURE 7. The topology and the shape of a linearly arranged pseudo-rotaxane dimer is adapted to a contraction/stretching motion.

the 600−800 nm region, as expected for the transformation of **1**$^{2+}$ (Cu^{II}$_{(4)}$) into the more stable **1**$^{2+}$ (Cu^{II}$_{(5)}$) species. After about 26 h, the spectrum of the solution corresponded to the stable Cu^{II}$_{(5)}$ species. To close the cycle (Figure 4), an excess of ascorbic acid was added to the solution. A gradual but complete reappearance of the spectrum of **1**$^+$ (Cu^{I}$_{(4)}$) was observed, as is also observed when oxidation and successive reduction are carried out electrochemically. After about 8 h, the spectrum was practically coincident with the initial spectrum, showing that the cyclic process (Figure 4) is fully reversible even when oxidation is photoinduced and reduction is chemically induced.
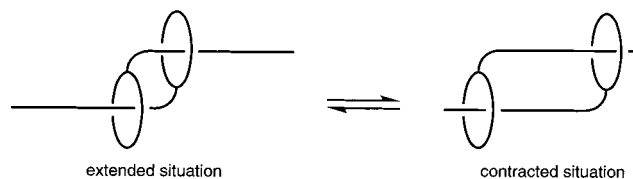
The motion of the ring and of the metal ion from the bidentate to the tridentate site on the string can be carried out electrochemically or by an oxidative photochemical process and can be fully reversed upon chemical reduction. However, in terms of response time, it is clear that the system requires substantial improvement.

III. Molecular Muscles

So far we have seen quite simple linear machines based on a [2]rotaxane. Nevertheless, to extend the number of working parts of future and more efficient machines, more elaborate topologies are needed. In particular, one-dimensional molecular assemblies able to undergo stretching and contraction motions under the action of an external signal, similar to those observed in the real muscles, appeared as an exciting target.

Before now, several interesting artificial systems have been described which aim at reproducing some essential properties of skeletal muscles. Polypyrrole-based devices are particularly promising, allowing one to bend a solid polymer film in one direction or another depending on the sign of an electric current applied to the film.[26] Another recent approach relies on single-walled nanotube sheets.[27] However, unimolecular linear arrays capable of undergoing contraction or stretching had so far not been made.

1. Design and Motion Principle. We designed and studied a multicomponent system able to contract or stretch under the action of an external chemical signal. Our system, based on a symmetrical doubly threaded topology and represented in a very schematic fashion in Figure 7, was originally assumed to fulfill the requirements to mimic the behavior of a muscle at the molecular level.

Double-threaded topologies were obtained by Stoddart and co-workers in the solid state by dimerization of a self-complementary monomer, whereas in solution single-threading processes led to the formation of various pseudo-oligomeric rotaxane topologies.[28a,b] By analogy with real muscles, a molecular assembly in which two filaments can glide along one another was designed. This is the very process taking place in the sarcomere, in which the thick filament (containing myosin) moves along the thin filament (actin polymer) in one direction or the other so as to induce contraction or stretching. In the double-threaded object of Figure 7, the motion is easy to visualize. Both strings (mimicking the muscle filaments) move along one another but stay together thanks to the rotaxane nature of the system.

So far, the machine-like compounds elaborated and studied in our group were mostly copper complexes, the motion being triggered by an electrochemical reaction

FIGURE 8. Functioning principle of the unimolecular synthetic "muscle" presently discussed. The two-component rotaxane dimer contains identical ring-and-string conjugates. Each component consists of a bidentate chelate (U-shaped symbol) embedded in a ring, the ring being covalently attached to a filament-like part. This string contains another bidentate ligand, a terdentate coordinating unit (schematically represented by a W-shaped symbol), and a bulky stopper (sphere on the drawings) whose function is to prevent dethreading of the filaments from the rings through which they are threaded. The four-coordinate situation (left-hand side) is such that the metal (black disk) is coordinated to two bidentate chelates. If the bidentate chelate belonging to the string is replaced by a terdentate fragment, a five-coordinate situation is reached, which corresponds to an overall contracted situation (right-hand side). The contracted situation is obtained by replacing the four-coordinate metal of the compound represented on the left (copper(I) in the present work) by a five-coordinate center (white disk; zinc(II) in the present report).
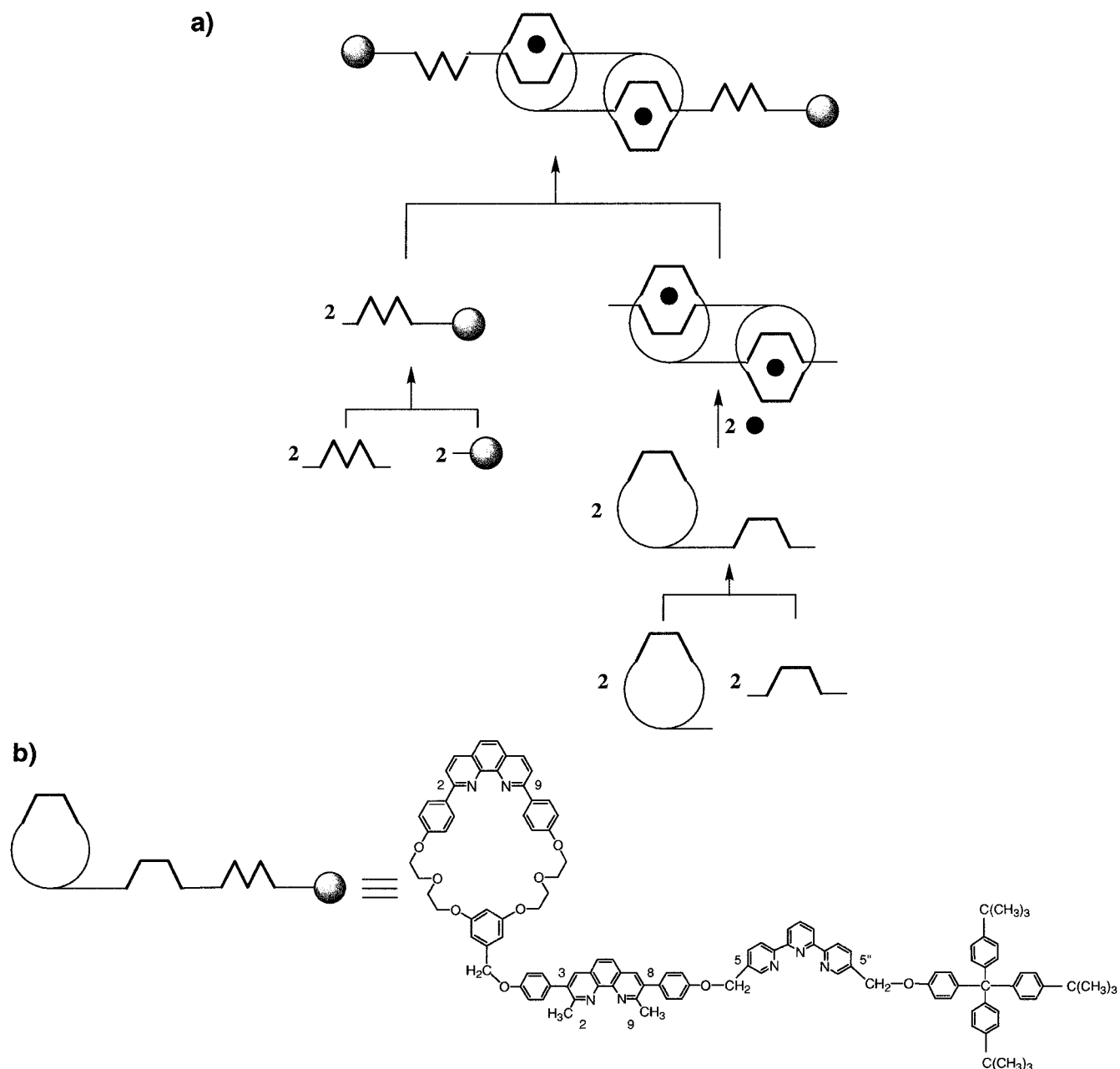
FIGURE 9. (a) Synthetic strategy used for the building up of the rotaxane dimer. (b) Chemical content of each subunit contained in the double-threaded assembly.

(Cu^I/Cu^{II}),[5b,18] although photochemically driven processes based on ruthenium(II) compounds seem also to be promising.[29] The present system contains copper(I) as the assembling and templating metal, but the movement is induced by a *chemical reaction*, corresponding to metal exchange. As shown in Figure 8, the double-threaded compound reported here can bind simultaneously two metal centers, either in a four-coordinate or a five-coordinate geometry. The four-coordinate situation results from the coordination of a copper(I) ion with two phenanthroline units and corresponds to an extended geometry (left part of Figure 8), whereas the five-coordinate situation results from the coordination of a divalent ion M with one phenanthroline and one terpyridine and leads to a contracted geometry (right part of Figure 8).

To reach such a rotaxane dimer, we envisaged the general synthetic strategy schematically represented in Figure 9a.

A macrocycle containing a 2,9-diaryl-1,10-phenanthroline was covalently linked to a linear 1,10-phenanthroline ended by a phenolic function which would allow the final stoppering process. Synthesis of the dinuclear double-threaded central core was performed using copper(I) as the gathering and threading actuator between two of the latter bis-bidentate ligands. After separate synthesis of a functionalized 2,2′:6′,2″-terpyridine bearing a bulky stopper, we reacted two such terdentate coordinating units with the phenolic functions of the double-threaded dicopper(I) complex. This last reaction not only allowed us to introduce terdentate sites into the molecular assembly,
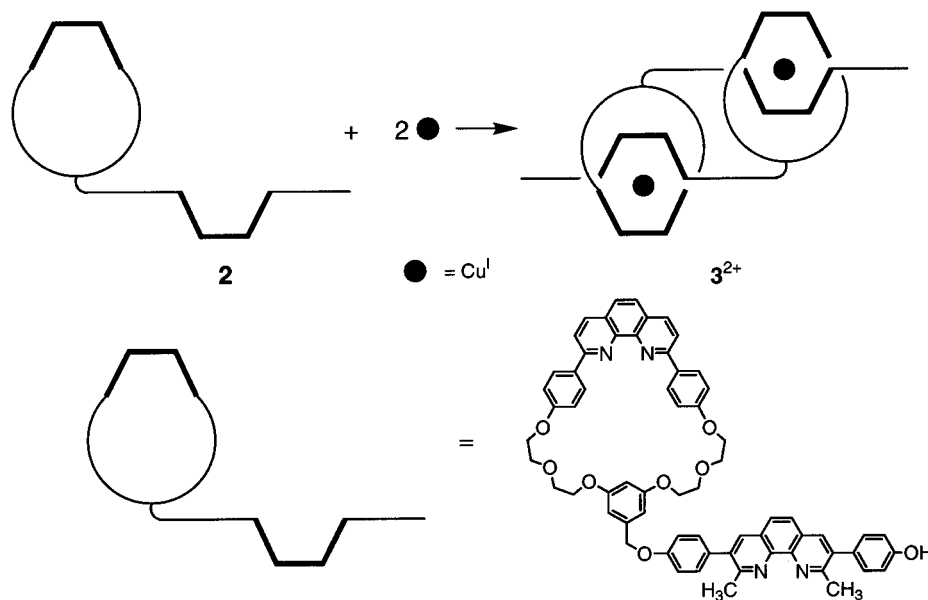
FIGURE 10. Schematic representation of the double-threading process induced by copper(I) (black dots) between two hermaphrodite ligands each containing a chelating ring, a coordinating stick, and a chemical structure of the target ligand **2**.
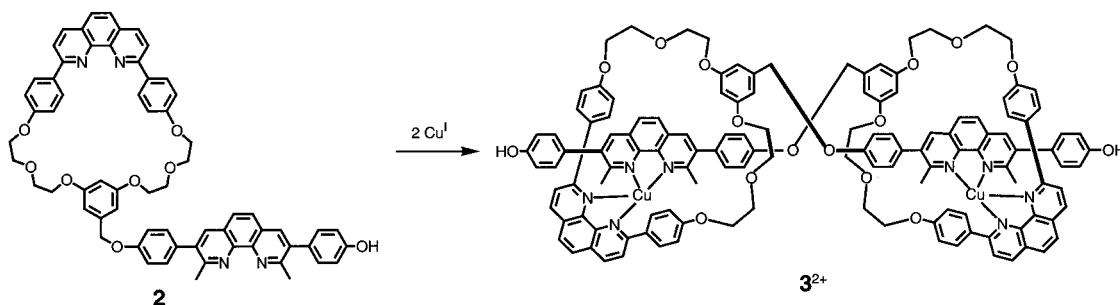

FIGURE 11. The copper(I)-induced threading process leading to the dimer **3**$^{2+}$.

but also gave access to a real rotaxane structure in which any dethreading process was prohibited due to the presence of the two bulky stoppers.

Once both principles (motion principle and construction principle) were defined, Corey–Pauling–Koltun (CPK) models helped us decide what should be the precise chemical structure of each symbolic fragment used in Figures 8 and 9a. Indeed, CPK models suggested that a 31-membered macrocycle should have the optimum size. It appeared large enough to allow the threading of a phenanthroline belonging to an opposite rod, but also small enough so that an intramolecular copper(I) complexation between the two phenanthrolines of the same unit would be avoided. In fact, such a kind of intramolecular complexation could occur with a large flexible macrocycle able to fold-up easily. For the rod, we chose a tetrasubstituted phenanthroline. Substitution in positions 2 and 9 was necessary for the formation of a stable diphenanthroline copper(I) complex, but here again the size was critical; these substituents should not be too bulky so that the threading process will not be inhibited for steric reasons. Methyl groups fulfill such requirements. Finally, the 3 and 8 positions were substituted by aromatic groups so that the rod would be as linear as possible, thus avoiding the formation of an intramolecular copper(I)

complex between the two adjacent phenanthrolines of the same subunit. A 5,5″-dimethyl-terpyridine able to be connected to the other fragments after functionalization of the methyl groups was chosen as the terdentate site. The large bulky tris(*tert*-butyl-phenyl)-methane derivative stoppers should avoid any dethreading. After all the connections between the various fragments were achieved, the precise chemical nature of the monomeric multisite ligand used in the present work is given in Figure 9b.

2. Synthesis of the Dinuclear Doubly Threaded Central Core. Using copper(I) as a gathering and threading center, it was possible to generate the double-threaded species shown schematically in Figure 10 both in solution and in the solid state. In this dinuclear dimer, each organic ligand is a self-complementary monomer of a chelating ring attached to a coordinating stick. Due to the structural features of the ring-and-stick ligand **2**, the complexation reaction that affords the double-threaded copper(I) complex **3**$^{2+}$ can be regarded as a double plugging-in process between the female (ring) and the male (coordinating stick) components; thus, the organic ligand has a hermaphrodite character.

As expected, **2** was not able to form an intramolecular tail-bitten complex. The rigid rod consisting of 3,8-diaryl-1,10-phenanthroline was too rigid and was connected to
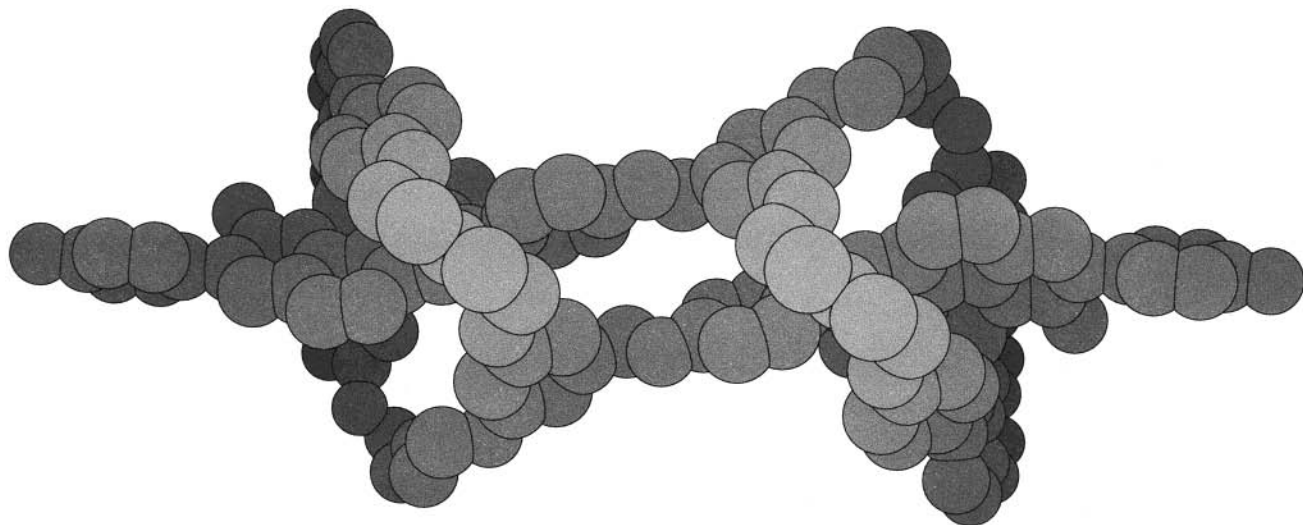
FIGURE 12. Crystal structure of the dicopper(I) dimer **3**$^{2+}$. ORTEP presentation.
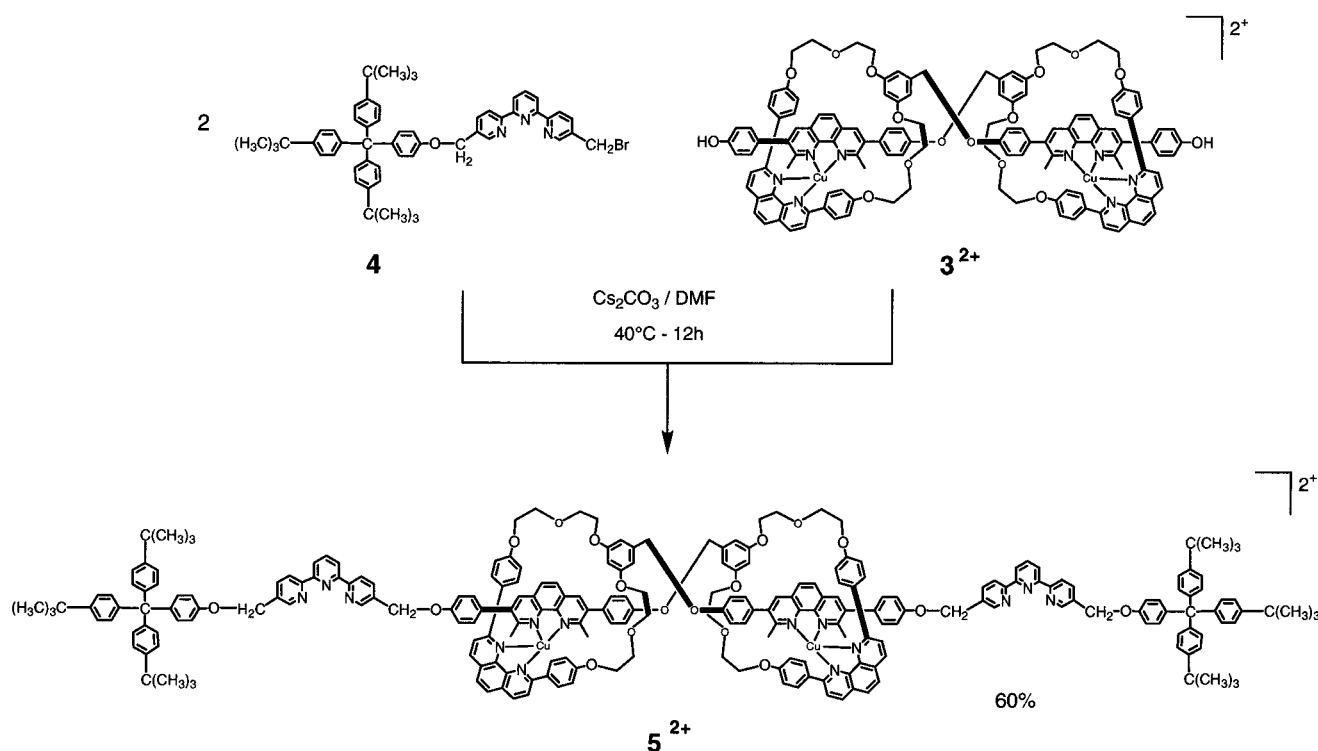

FIGURE 13. Synthesis of the "muscle" **5**$^{2+}$ in its extended situation.

the ring via too short a linker for **2** to fold-up so as to allow a self-threading process, comparable to what was observed in previously reported organic systems.[30] In fact, the dimerization reaction represented in Figure 10 occurred quantitavely in solution upon addition of a stoichiometric amount of Cu(CH$_3$CN)$_4^+$PF$_6^-$ to **2**. ^{1}H NMR and mass spectroscopy (MS) turned out to be particularly useful to demonstrate quantitative formation of the dimer **3**$^{2+}$ at room temperature[31] (see Figure 11).

Interestingly, ^{1}H NMR study as well as thin-layer chromatography clearly showed that the initial mixture of the kinetic copper(I) complexes obtained immediately after addition of the copper(I) salt to ligand **2** re-equilibrates. The various cyclic or linear oligomers initially present in the reaction mixture besides **3**$^{2+}$ are spontane-

ously converted to the thermodynamically more stable dimer **3**$^{2+}$ in quantitative yield over a period of 48 h at room temperature.

The dimer **3**$^{2+}$ was isolated as deep red crystals of its PF$_6^-$ salt, which allowed determination of its actual molecular structure by X-ray diffraction. The molecular structure of the dinuclear dimer **3**$^{2+}$, which possesses only a single C_2 axis, is shown in Figure 12.

The complex **3**$^{2+}$ contains two identical symmetry-related subunits each consisting of one macrocycle, one linear 3,8-diaryl-1,10-phenanthroline rod, and one copper ion. The most striking feature of this structure is its linear well-extended antiparallel arrangement that locates the two terminal phenolic oxygen at a distance as large as 36.3
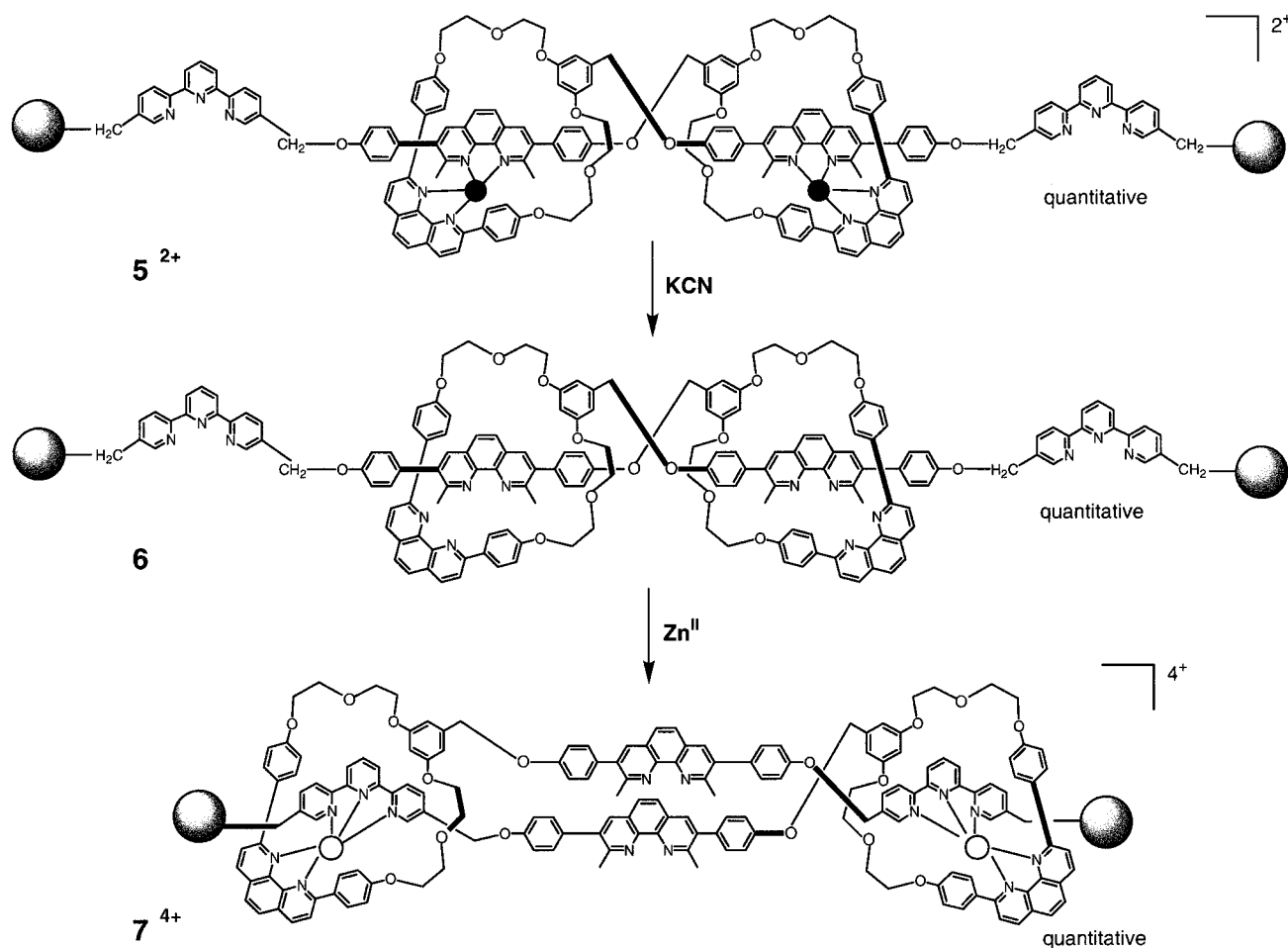
FIGURE 14. Reversible chemically induced motions between extended **5**$^{2+}$ and contracted **7**$^{2+}$. The black disk is copper(I); the white circles are zinc(II).

Å. The two copper atoms are 18.3 Å apart and have similar environments.

3. Synthesis of a Linear Rotaxane Dimer. The interesting topology of complex **3**$^{2+}$ prompted us to react its phenolic functions in DMF and Cs_2CO_3 at 40 °C with 2 equiv of bromide **4** (a stopper-bearing disymmetrical 2,2′:6′,2″-terpyridine that was obtained in a multistep synthesis). The latter coupling reaction led to the molecular "muscle" **5**$^{2+}$ in 60% yield as represented in Figure 13.

2D-ROESY NMR experiments as well as high-resolution mass spectroscopy (FAB) showed clearly that the stoppering procedure leading to **5**$^{2+}$ occurred without significant dethreading as evidenced by large interfragment interactions in its NMR spectrum and expected molecular ion peak at 3834.2 (calcd 3834.3).

4. Chemically Triggered Stretching and Contracting Motions. The free ligand **6** obtained in quantitative yield by reacting **5**$^{2+}$ with a large excess of KCN (in $CH_2Cl_2-H_2O$ at room temperature) was subsequently remetalated with $Zn(NO_3)_2$ (in CH_2Cl_2-MeOH) affording quantitatively **7**$^{4+}$ as a colorless solid, in the contracted situation (Figure 14). The reverse motion, leading back to the extended situation, that is, back to **5**$^{2+}$, could be easily induced upon addition of excess $Cu(CH_3CN)_4 \cdot PF_6$ in $CH_2Cl_2-CH_3CN$ at room temperature. If the dimeric nature of **5**$^{2+}$, **6**, and **7**$^{4+}$ could be easily evidenced by mass spectroscopy (FAB or

ES), then the contraction/stretching phenomenon accompanying the metal exchange (Cu^I/Zn^{II}) required demonstration by extensive NMR studies. The latter were mainly based on the unambiguous chemical shifts of some aromatic protons (belonging either to the phenanthroline or the terpyridine moieties) which turned out to be excellent probes in one- and two-dimensional ^1H NMR.[32]

The present rotaxane dimer represents the first example of an unimolecular linear array able to stretch and contract at will under the action of a chemical stimulus. From CPK model estimations, the length of the compound changes from 83 to 65 Å between both situations, that is, roughly of the same relative amount as natural muscles (~27%).

Conclusion

The field of molecules in motion, for which movements and shape changes are triggered and controlled from the outside, has indisputably been one of the most rapidly developing areas of the past decade. Transition-metal-containing rotaxanes and catenanes represent an interesting class of such compounds, due to the evident nondestructive nature of redox processes taking place on the metal, as opposed to the involvement of organic radicals. Electrochemical signaling is attractive, but photonic pro-

cesses are likely to be more important if future applications are to be found. Here again, transition-metal complexes will play an important role since many of them display rich and clean photochemistry. In this Account, we have discussed linear systems, the most elaborated example being that of a rotaxane dimer whose behavior is reminiscent of a muscle. The stretching/contraction process is triggered by a chemical reaction (metal exchange), but it is obviously hoped that electrochemical or photochemical reactions will also lead to the same mechanical effect in the future. Most of the work carried out in our group has been inspired by biology, and this is, of course, the case for the presently described compounds. Today, applications of transition-metal-based synthetic muscles seem to be relatively far away, but other systems may turn out to be practically important much sooner. Recent work[33] has demonstrated that molecular computers are perhaps not out of reach and could be proposed within one or two decades. In addition, the motion of a ring shuttling between two or several stations could easily be related to transport of various chemical species, the ring playing the role of a cargo in a way reminiscent of kinesin or dynein moving along microtubules in cells.[34] Another important step will be to transpose what has been perfomed on large collections of molecules in solution to ordered 2D and 3D arrays and single molecules on a surface.

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