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A Fast-Moving [2]Rotaxane Whose Stoppers Are Remote from the Copper Complex Core

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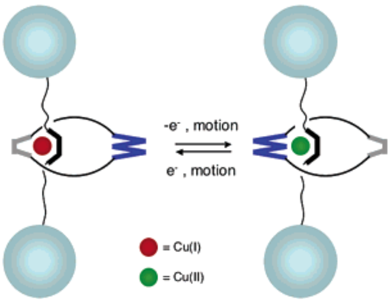
ABSTRACT



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

In the field of dynamic molecular systems, whose motions are triggered and controlled from the outside and which are often referred to as “molecular machines” or “molecular motors”,[1] catenanes and rotaxanes occupy a special position.[2]

Transition-metal-based molecular machines whose organic backbone is a catenane or a rotaxane have been prepared in the course of the past decade.[3a] These systems contain either a redox-active species[3b] or a ruthenium(II) central complex as photoactive unit.[3c] Since the first bistable copper-complexed [2]catenane reported by our group,[4] several related species, including [2]rotaxanes, have been described with shorter and shorter response times between the redox signal (copper(II)/copper(I)) and the subsequent motion leading to the most thermodynamically stable situation.[3b] From the

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[1] (a) Balzani, V.; Venturi, M.; Credi, A. *Molecular Devices and Machines*; Wiley-VCH: Weinheim, 2003. (b) Sauvage, J.-P. *Molecular Machines and Motors, Structure & Bonding*; Springer: Berlin, Heidelberg, 2001; Vol. 99 (c) Balzani, V.; Credi, A.; Raymo, F. M.; Stoddart, J. F. *Angew. Chem., Int. Ed.* **2000**, *39*, 3348. (d) Special issue on Molecular Machines. *Acc. Chem. Res.* **2001**, *34*, 341. (e) Fabbrizzi, L.; Licchelli, M.; Pallavicini, P. *Acc. Chem. Res.* **1999**, *32*, 846. (f) Kelly, T. R.; de Silva, H.; Silva, R. A. *Nature* **1999**, *401*, 150. (g) Koumura, N.; Zijistra, R. W. J.; van Delden, R. A.; Harada, N.; Feringa, B. L. *Nature* **1999**, *401*, 152. (h) Leigh, D. A.; Wong, J. K. Y.; Dehez, F.; Zerbetto, F. *Nature* **2003**, *424*, 174. (i) Jimenez-Molero, M. C.; Dietrich-Buchecker, C. O.; Sauvage, J.-P. *Chem. Commun*. **2003**, 1613. (j) Shipway, A. N.; Willner, I. *Acc. Chem. Res.* **2001**, *34*, 421. (k) Harada, A. *Acc. Chem. Res.* **2001**, *34*, 456.

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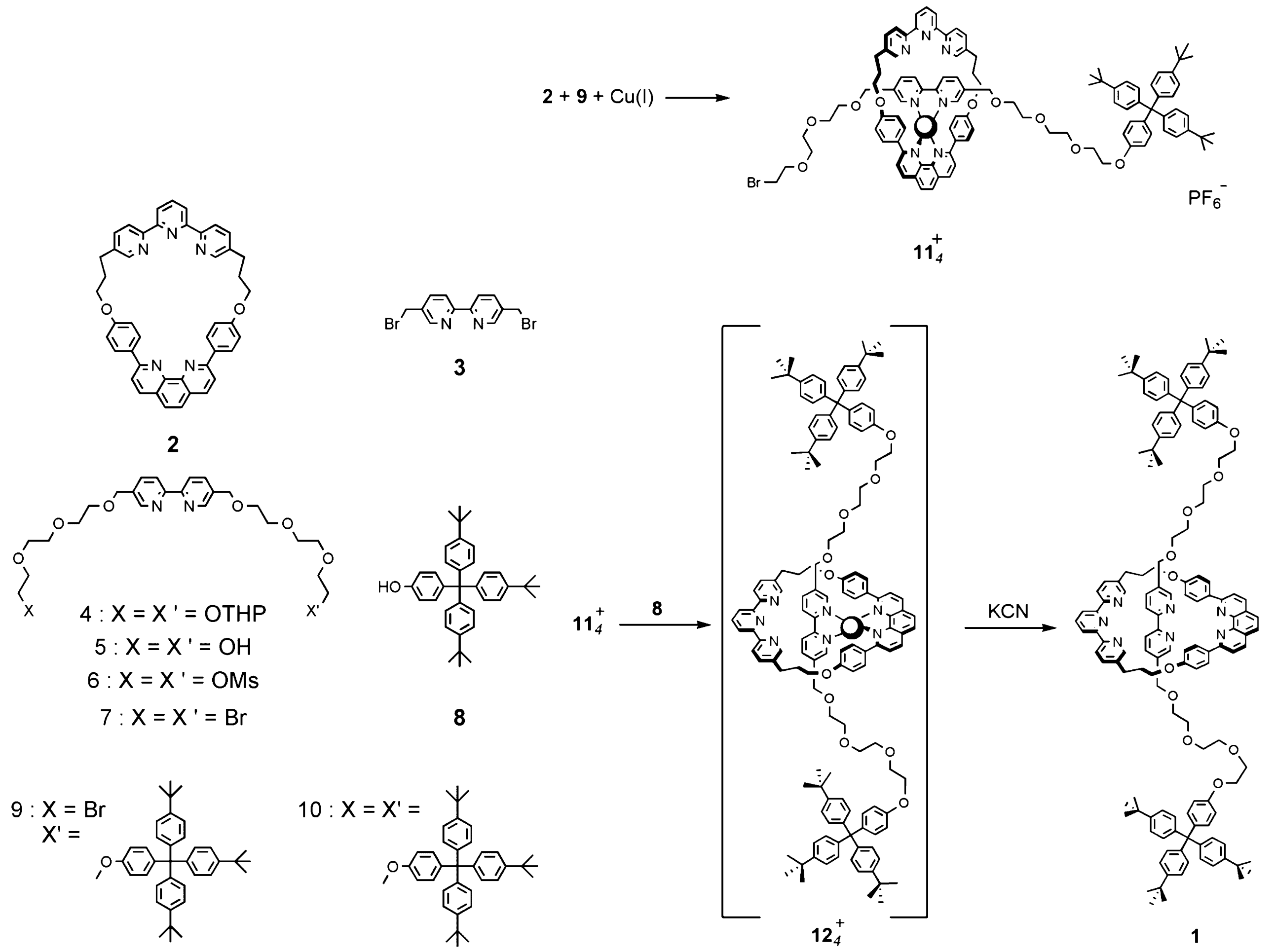

Figure 1. Synthesis of the free rotaxane **1**.

minutes or even hours required originally to set a given part of the compound in motion,[4] the time scale for the most recent compounds could be shifted toward hundreds of milliseconds ($Cu^{II}_4 \rightarrow Cu^{II}_5$, the subscript indicates the coordination number of the copper center) and even milliseconds ($Cu^{I}_5 \rightarrow Cu^{I}_4$).[5]

The rearrangement process involves several coordination/decoordination steps, an important factor being the accessibility of the copper center and its ability to undergo fast ligand exchange. To make the copper center as easy as possible to reach for entering ligands, we thought that the bulky stoppers should be located far away from the central complex. We thus prepared and studied a new bistable rotaxane whose general structure is similar to that of a previously published compound,[5] but whose stoppers are very remote from the copper center (see Figure 2). This new dynamic system can indeed be set in motion more rapidly than the previously described systems. In the present report, we would like to describe the synthetic procedure leading to this new rotaxane; the dynamic behavior of the copper-complexed rotaxane will also be discussed.

Synthesis of the Copper(I)-Complexed Rotaxane. The synthetic route leading to the free rotaxane **1** and the various starting compounds and intermediates are represented in Figure 1. We chose triethyleneglycol chains for the elongation of the axle. The axle of the rotaxane was synthesized starting from 5,5′-bis(bromomethyl)-2,2′-bipyridine **3**.[6] The Williamson ether synthesis with 2 equiv of 8-(2*H*-tetrahydropyran-2-yloxy)-3n$_6$^{3}-dioxaoctan-1-ol[7] in the presence of sodium hydride led to compound **4**. The THP protecting groups of **4** were removed upon treatment with HCl to give **5**. Diol **5** was mesylated on both hydroxyl groups with methanesulfonyl chloride to afford **6**, which was subsequently reacted with LiBr to give **7**. The stoppers were added to the molecule in two steps. Usually, the Williamson ether synthesis does not lead to very high yields, so it seemed more reasonable to have only one stoppering reaction to carry out once the macrocycle is threaded on the axle. The first stoppering reaction for the synthesis of **9**, which is a statistical reaction, was carried out with only 0.3 equiv of the stopper **8** in respect to the axle in order to minimize as much as

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(5) Poleschak, I.; Kern, J.-M.; Sauvage, J.-P. *Chem. Commun.* **2004**, 474.

(6) Schubert, U. S.; Eschbaumer, C.; Hochwimmer, G. *Synthesis* **1999**, *5*, 779.

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possible the formation of the dumbbell like molecule **10**. Compound **9** was obtained in 30% yield, and 62% of the nonconsumed starting material **7** could be recovered. In the next step, macrocycle **2** was threaded onto the axle by using Cu(I) as templating agent. The threading process leading to **11**$^{+}$ was shown to be quantitative by ^{1}H NMR. The phenyl ring protons in **2** show a significant shift to lower frequencies when the ring is threaded on the axle. This shift results from the cone of anisotropy of the bipyridine unit of the axle. Another equivalent of **8** for the second stoppering reaction was then added to the pre-rotaxane **11**$^{+}$ in the presence of Cs_2CO_3 and DMF[8] in order to obtain **12**$^{+}$. The copper complex **12**$^{+}$ revealed to be unstable on silica. This is understandable in view of the structure since the stability of copper(I) complexes is particularly sensitive to the hindering nature of the ligands used. Sterically hindering bidentate chelates such as 6,6′-disubstituted 2,2′-bipyridine or 2,9-disubstituted 1,10-phenanthroline lead to roughly tetrahedrally coordinated copper(I) complexes and, thus, highly stable compounds. By contrast, if the encumbering nature of the ligand is decreased, the complex stability of the ligand suffers as a result of the possibility of forming close-to-square planar complexes and to the increased accessibility of the metal center to O_2. To fabricate fast-moving molecular machines, it could be detrimental to build extremely stable and sterically protected copper complexes. This is clearly illustrated by the dynamic properties of the first copper-based molecular machines made in our group.[4] In other words, the ideal systems, combining fast rearrangement and reasonable stability, will have to be a compromise between these two features, as illustrated by the present rotaxane. Upon purification of **12**$^{+}$ partial loss of Cu(I) was observed, leading to mixtures of **12**$^{+}$ and the demetalated rotaxane **1**. To obtain pure **12**$^{+}$, we decided to demetalate it with KCN, purify the free rotaxane **1** on column chromatography, and subsequently remetalate it for the electrochemical studies. This strategy proved to be successful. Column chromatography of the demetalated rotaxane on silica using pentane, ethyl acetate, methanol, and triethylamine as eluents (70:28:1:1) led to pure **1** in 32% yield. The partial loss of copper on silica from **12**$^{+}$ as well as the isolation of one fraction containing the dumbbell **10** lacking the threaded macrocycle, where dethreading occurred during the second stoppering reaction, indicate that ligand exchange of copper in this system is rather facile. To show that the macrocycle is indeed able to pirouette around the axle, as shown schematically in Figure 2, and to determine the speed of this rotational motion, we carried out electrochemical studies on **12**$^{+}$.

Compound **1** was metalated with Cu(I) using $[Cu(MeCN)_4]PF_6$ in acetonitrile leading to pure **12**$_{4}^{+}$. The solution became deep red due to the metal-to-ligand charge transfer (MLCT) band in the visible region. The central metal Cu(I) is coordinated in a tetrahedral manner by the 2,9-substituted phenanthroline and the 2,2′-bipyridine moieties. The cyclic voltammetry (CV) study is presented in Figure 3. Experiments were carried out in acetonitrile using a platinum electrode as working electrode and $^{n}Bu_4NPF_6$ (0.1 M) as supporting electrolyte. A silver wire served as reference electrode.

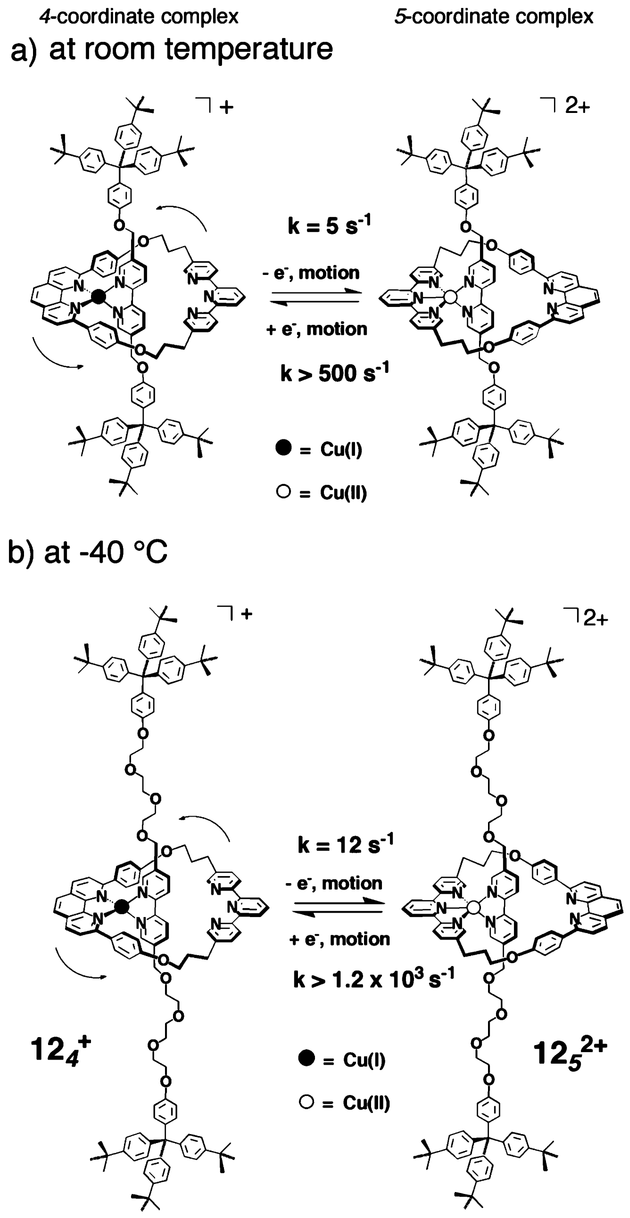

Figure 2. Schematic representation of the redox-driven pirouetting motion. In the drawing, the thread has been represented as fixed, whereas the ring undergoes the motion. This is of course arbitrary since the molecules are free to diffuse in solution and it is thus impossible to identify a motionless part and a mobile part. (a) Behavior of the previously published system[5] at room temperature; (b) behavior of the present system at −40 °C.

In the first series of scans (Figure 3) the potential sweep was applied between −400 and +800 mV at a scan rate of 200 mV s^{-1}. At −400 mV no current was observed, as **12**$_{4}^{+}$ is electrochemically inactive at this potential. When the potential sweep was continued toward the anodic region, an oxidation peak could be observed at a potential of +460 mV,

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[8] (a) Dietrich-Buchecker, C. O.; Sauvage, J.-P.; Kintzinger, J.-P. *Tetrahedron Lett.* **1983**, *24*, 5095. (b) Dietrich-Buchecker, C. O.; Sauvage, J.-P. *Chem. Rev.* **1987**, *87*, 795.

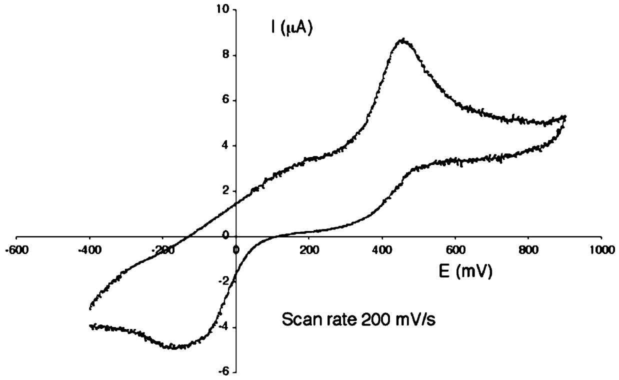

Figure 3. Cyclic voltammetric study. The electrochemical responses of the 4-coordinate and the 5-coordinate copper complexes are found around +460 and −140 mV, respectively (potential vs a silver quasi-reference electrode).

corresponding to the expected oxidation of Cu(I) to Cu(II) in agreement with related copper-complexed rotaxanes.[5] On the reverse scan, no corresponding reduction peak was observed. However, going to the cathodic region, a reduction peak corresponding to the reduction of the pentacoordinated $\mathbf{12}_5{}^{2+} \rightarrow \mathbf{12}_5{}^{+}$ could be observed at −140 mV. These results clearly show that, upon oxidation or reduction of the central metal Cu, the macrocycle is set in motion. Upon oxidation of $\mathbf{12}_4{}^{+}$, the resulting tetrahedrally coordinated Cu(II) is unstable as Cu(II) forms stable square planar complexes or higher coordination (five or six). Therefore, the macrocycle pirouettes around the axle permitting the restoration of a stable coordination, which is pentacoordination by the 2,2′, 6′2″-terpyridine and 2′,6′-bipyridine moiety, providing a stable coordination situation. The same phenomenon happens for the reduction of $\mathbf{12}_5{}^{2+}$: when the latter is reduced, the pentacoordinated situation $\mathbf{12}_5{}^{+}$ is unstable, and the ring is set in motion leading to the preferred tetrahedral coordination of Cu(I). To determine the velocity of the rearrangement of the macrocycle, we applied higher scan rates at various temperatures to the system. The maximal chosen scan rate was 2000 mV s^{-1} because at higher values the capacity currents became too important to be able to draw a reasonable conclusion from the cyclic voltammogramms. With these results in hand we have shown that the macrocycle is indeed pirouetting very fast around the axle. The system moves faster than the scan rate, which implies that we can only estimate an upper limit for the half-life time of the species $\mathbf{12}_4{}^{2+}$ using the method of Nicholson and Shain.[9] Using their reported equations we find a reaction rate $k = 12$ s^{-1} for the rearrangement $\mathbf{12}_4{}^{2+} \rightarrow \mathbf{12}_5{}^{2+}$ and a half-life time $t_{1/2} = 60$ ms at −40 °C. In agreement with previous studies on related compounds it can be assumed that this step is about 2−3 orders of magnitude slower than the rearrangement $\mathbf{12}_5{}^{+} \rightarrow \mathbf{12}_4{}^{+}$. We can thus estimate that the half-life time of $\mathbf{12}_5{}^{+}$ is in the range of 100 μs. Compared to the previously reported rotaxanes of ref 5, the motion of the macrocycle around the axle in $\mathbf{12}^{m+}$ is 2 orders of magnitude faster.

In conclusion, a new rotaxane has been synthesized, for which the stoppers attached at the ends of the axle are remote from the mobile central core and the chelate incorporated in the thread is sterically little hindering. These two features make the copper center very accessible and strongly facilitate ligand exchange within its coordination sphere. The mutual movements of the ring and the axle have been investigated by cyclic voltammetry, and it has been shown that the ring moves very fast around the axle (milliseconds) even at low temperature. The present system constitutes a prototype of a fast-moving molecular machine that will be used further to attach related species on electrode surfaces.

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Supporting Information Available: Exprimental procedure and characterization data for all new compounds. This material is available free of charge via the Internet at http://pubs.acs.org.

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