**Host–Guest Systems**

DOI: 10.1002/anie.201004008

# A Cyclic [4]rotaxane that Behaves as a Switchable Molecular Receptor: Formation of a Rigid Scaffold from a Collapsed Structure by Complexation with Copper(I) Ions**

*Jean-Paul Collin,* Fabien Durola, Valérie Heitz,* Felipe Reviriego, Jean-Pierre Sauvage,* and Yann Trolez*

The most efficient molecular receptors are usually rigid edifices with a hollow part that is able to accommodate the complexed species through an electronic and geometrical complementarity between the substrate and the complexing parts of the host.[1] By analogy with biological processes related to induced fit, other host–guest processes are based on flexible hosts that are able to adapt their geometry to that of the species to be recognized. In the very active field of catenanes, rotaxanes,[2] and molecular machines,[3] very few systems have been considered as interesting receptors for molecular guests.[4] One of the main contributions to this subfield of research is that of anion recognition by various interlocking compounds.[5] Our research group has also recently described a [3]rotaxane that is able to act as an adjustable receptor.[6] The system consists of two rings threaded by an axis on which the rings can move freely. The complexing units are zinc porphyrins that are firmly attached to the rotaxane rings and are able to interact with given substrates that consist of doubly end functionalized compounds bearing 4-pyridyl groups. It was shown that the marked geometrical adaptability of the host in its metal-free form allows interaction with guests of very different sizes. Herein we report the properties of a related compound, namely a cyclic bisporphyrin [4]rotaxane, the behavior of which is totally different from that of a previously studied linear [3]rotaxane.[6] Contrary to the latter compound, the metal-free [4]rotaxane collapses completely and does not show any complexation properties, whereas the copper(I)-complexed compound is a good and selective receptor for diamine and dipyridyl substrates because of the scaffolding effect of the four metal centers (Figure 1).[7] The recognition process can thus be switched on and off by complexing the free ligand to four Cu$^{I}$ ions or demetalating the metal-complexed species, respectively.

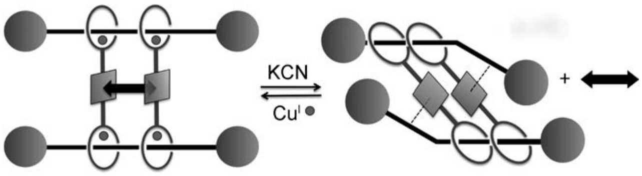


*Figure 1.* Principle of the recognition process that is switched on and off by metalation or demetalation. Small gray dots: Cu$^{I}$ ions; gray squares: porphyrins; black double arrow: guest compound. The chemical structures of **1**$^{4+}$ and **2** are shown in Scheme 1.

The synthesis of rotaxane **1**$^{4+}$[7] as well as that of its related [4]pseudorotaxane have already been reported.[8] **1**$^{4+}$ was demetalated using a large excess of KCN (ca. 50 equivalents) at room temperature. The reaction mixture was stirred for 2.5 hours, and the crude product was then purified by chromatography on silica gel to afford the demetalated rotaxane **2** in 88 % yield (Scheme 1).

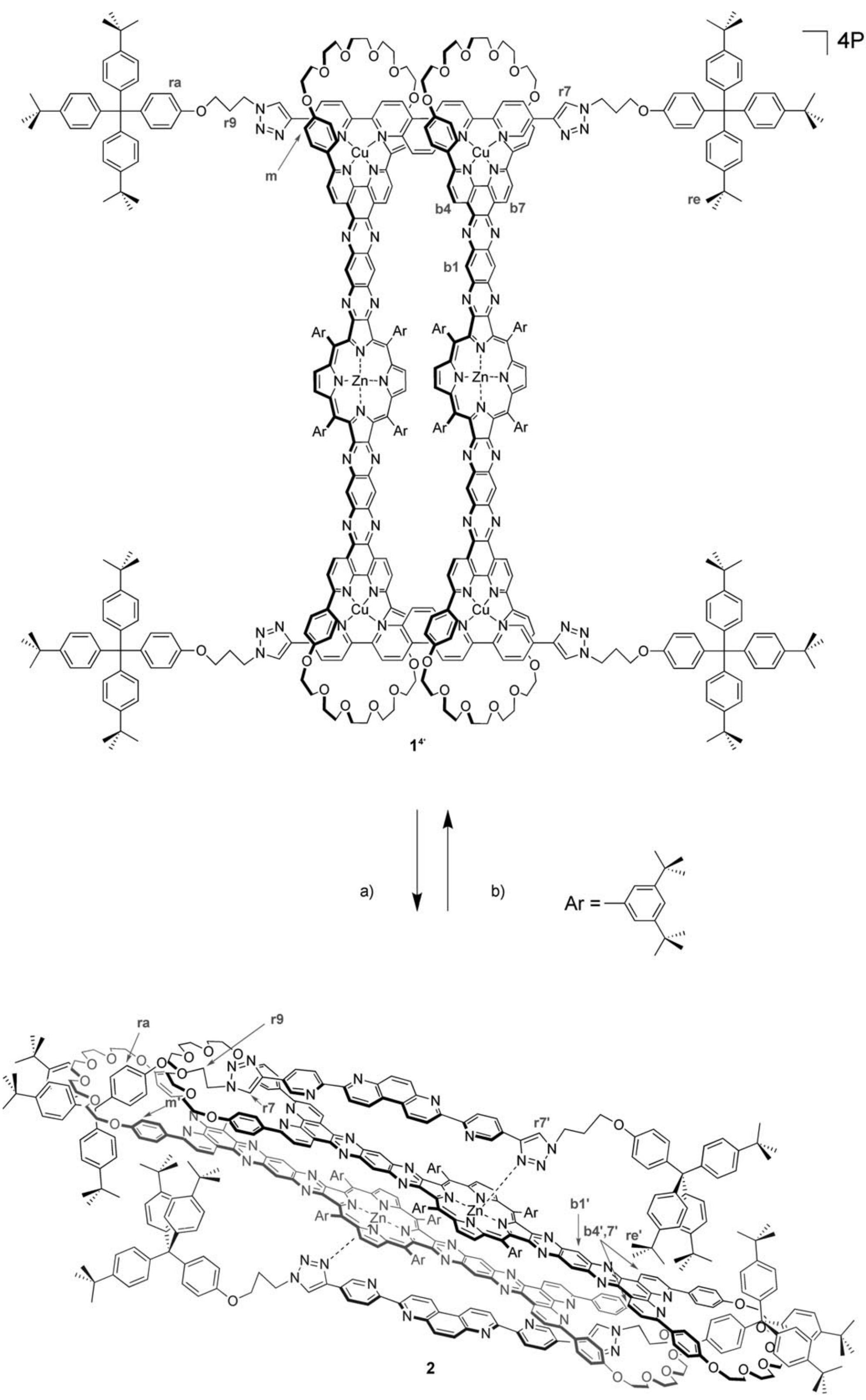
Rotaxane **2** was characterized by $^{1}$H NMR spectroscopy (COSY, ROESY, DOSY), electrospray mass spectrometry and UV/Vis spectroscopy. Very surprisingly, the $^{1}$H NMR spectrum of rotaxane **2** shows considerable loss of symmetry compared to the metalated system **1**$^{4+}$, in which all the Cu$^{I}$ centers as well as the four stoppers were chemically equivalent. A quarter of the rotaxane **1**$^{4+}$ only had thus to be considered for complete NMR assignment. By contrast, the $^{1}$H NMR signals of **2** were doubled compared to those of rotaxane **1**$^{4+}$. Two distinct stoppers with significantly different $^{1}$H NMR signals and thus markedly different environments can be identified. NOE interactions between some parts of **2** were clearly detected, whereas these fragments were too far away from one another in **1**$^{4+}$ to show any interaction. For instance, some protons of the *t*Bu groups of one type of stopper (H-re′; r = "rod") correlate to protons H-b4′ and H-b7′ (b = bismacrocycle) of the 1,10-phenanthroline unit in **2**, thus indicating that this stopper and a given 1,10-phenanthroline unit are located very close to one another. As the bismacrocycles and the axles are both rigid, the proximity between two such fragments tends to indicate that the topography of **2** is markedly different from that of **1**$^{4+}$, and that **2** has a totally collapsed structure. This hypothesis was confirmed by additional observations. For instance, one proton of the $-(CH_2)_3-$ linker (H-r9) is strongly shielded upon decomplexation; the corresponding signal moves from

---

[*] Dr. J.-P. Collin, Dr. F. Durola, Prof. V. Heitz, Dr. F. Reviriego, Prof. J.-P. Sauvage, Dr. Y. Trolez
Laboratoire de Chimie Organo-Minérale
Institut de Chimie, UMR 7177 du CNRS
Université de Strasbourg
4 rue Blaise Pascal, 67070 Strasbourg Cedex (France)
Fax: (+33) 88-607-312
E-mail: sauvage@chimie.u-strasbg.fr

[**] We thank the Agence Nationale de la Recherche (ANR no. 07-BLAN-0174, MolPress) for their support as well as the Ministry of Education for fellowships to Y.T. We are also grateful to Julien Frey for his contribution to the synthesis of compound **1**$^{4+}$ and to Lionel Allouche (Service Commun de RMN, Université de Strasbourg) for the NMR spectra.

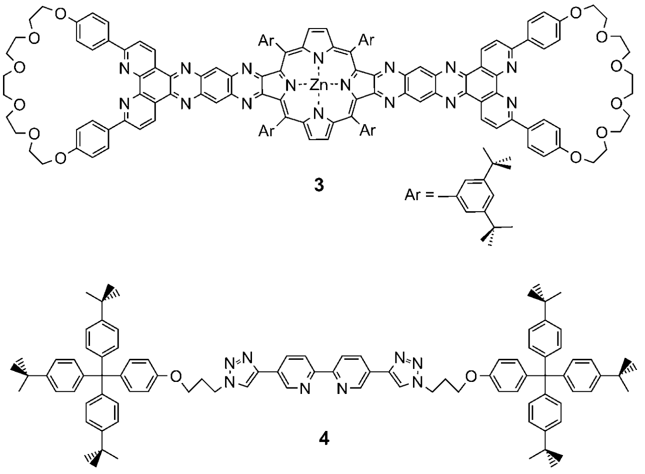
Supporting information for this article is available on the WWW under http://dx.doi.org/10.1002/anie.201004008.



***Scheme 1.*** Formation of **2** by decomplexation of $\mathbf{1}^{4+}$ and remetalation reaction that reforms the copper-complexed [4]rotaxane. The dashed lines represent coordination bonds between a triazole group and a Zn$^{II}$ ion. a) KCN, $CH_2Cl_2/CH_3CN/H_2O$ (2:1:1), 88%; b) $[Cu(CH_3CN)_4]PF_6$, $CH_2Cl_2/CH_3CN$ (2:1), 100%.

$\delta = 2.47$ ppm for rotaxane $\mathbf{1}^{4+}$ to $\delta = 0.47$ ppm for rotaxane **2**. Proton H-ra, which belongs to one type of stopper, is also strongly shifted upfield (from $\delta = 6.80$ ppm for rotaxane $\mathbf{1}^{4+}$ to $\delta = 5.81$ ppm for rotaxane **2**). This behavior was also observed for proton H-m′ ($\delta = 5.91$ ppm in **2**). These upfield shifts suggest that the corresponding protons are located close to aromatic nuclei and, again, point to a collapsed structure for rotaxane **2** (Scheme 1). The collapse of **2** was further evidenced by DOSY NMR experiments. Having measured the experimental diffusion coefficient, we estimated the size of the molecule in solution by using the Stokes–Einstein equation applied to an ellipsoid model with axes $a$ ($2a =$ length), $b$ ($2b =$ height), and $c$ ($2c =$ width). Rotaxane **2** has a diffusion coefficient of $(160 \pm 3)\ \mu m^2 s^{-1}$ in $C_6D_6$. The length of the axle ($2a$) was estimated to 55 Å from CPK models. By using this value in the Stokes–Einstein equation,[9] we deduced a height and a width of $2b = 2c = 19$ Å. The $a$, $b$, and $c$ values indicate that rotaxane **2** is significantly flattened compared to rotaxane $\mathbf{1}^{4+}$. This copper-complexed rotaxane fits a spherical model with a radius of 23 Å.

The unexpected collapsed structure of **2** can be explained by the coordination of the $Zn^{II}$ ions to two of the four triazole groups present in the molecule. The formation of complexes between triazole groups and zinc porphyrins has recently been reported by Osuka and co-workers.[10] The coordination of triazole groups to $Zn^{II}$ ions in [4]rotaxane **2** was demonstrated by UV/Vis and $^1$H NMR spectroscopy. The Soret band of compound **2** is centered at 471 nm, whereas it is located at 456 nm for compound $\mathbf{1}^{4+}$. There is thus a significant bathochromic shift, which is also observed when pyridines or amines are coordinated to zinc porphyrins in rotaxane $\mathbf{1}^{4+}$.[7] In order to confirm this hypothesis, the UV/Vis spectrum of bismacrocycle **3** alone and in the presence of an axle model, compound **4** (Scheme 2), were recorded. When 100 equivalents of **4** were added to a $2.5 \times 10^{-6}$ M solution of bismacrocycle **3** in $CH_2Cl_2$, a strong bathochromic shift from 456 nm to 474 nm was observed. This observation corroborates the hypothesis that in **2**, the triazole nuclei are coordinated to $Zn^{II}$ ions.



*Scheme 2.* Chemical structures of bismacrocycle **3** and bipyridine **4**.

The triazole protons H-r7 and H-r7′ for both types of triazoles are particularly shielded, and appear at $\delta = 7.22$ and 7.26 ppm, respectively. The expected chemical shift value for a normal triazole proton, as measured in related compounds such as **4**, is approximately 7.9 ppm. This notable upfield shift can be attributed to the proximity of a porphyrin to the first triazole group, and to the strong ring-current effect of the 1,10-phenanthroline fragments in a macrocyclic unit on the second triazole group. Two triazole groups are coordinated to zinc porphyrins, thus favoring the collapsed structure of rotaxane **2**. In addition to the coordination of two triazole nuclei to two $Zn^{II}$ ions, π stacking between aromatic fragments of macrocycles and axles could also contribute to stabilize the flattened structure of **2**. Interestingly, remetalation of rotaxane **2** using a stoichiometric amount of $Cu^I$ ions leads quantitatively to rotaxane $\mathbf{1}^{4+}$, as shown by $^1$H NMR spectroscopy (see the Supporting Information).

The host–guest properties of **2** towards diamines have also been investigated. A UV/Vis titration was performed with 1,4-diazabicyclo[2.2.2]octane (DABCO; Figure 2, spectra a and b), as well as an $^1$H NMR study, and no interaction between **2** and DABCO was observed. $^1$H NMR measurements also show that there is no interaction between **2** and 1,4-diaminobutane. The system completely loses its coordination properties towards basic ligands when demetalated. This behavior is certainly not surprising since the $Zn^{II}$ ions are already coordinated to triazole nuclei. When the system was remetalated with $Cu^I$ ions, the triazole groups were dissociated from their complexes with $Zn^{II}$ ions and the rotaxane returned to its initial conformation. As expected, its complexation properties were fully restored. Indeed, the $^1$H NMR spectra of 1:1 mixtures of $\mathbf{1}^{4+}$ (prepared from **2** and four equivalents of $Cu^I$ ions) and DABCO or 1,4-diaminobutane are identical to those of the originally prepared complexes [$\mathbf{1}^{4+}$•DABCO] or [$\mathbf{1}^{4+}$•1,4-diaminobutane] respectively.

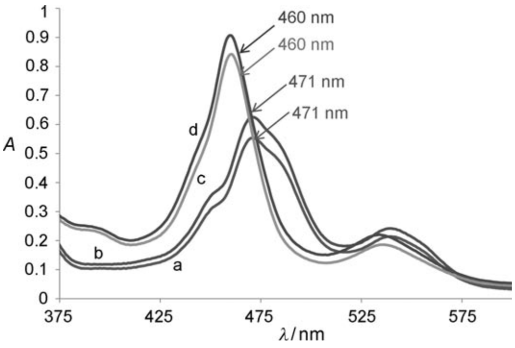


*Figure 2.* Absorption spectra of an equimolar mixture of rotaxane and DABCO : a) **2**; b) **2** and DABCO; c) **2** and DABCO after remetalation; d) $\mathbf{1}^{4+}$ and DABCO.

The reversibility of the metalation–demetalation process as well as the dramatic changes of the complexation properties that accompany these reactions have been confirmed for DABCO as guest by UV/Vis spectroscopy (Figure 2). When rotaxane **2** was metalated in presence of one equivalent of DABCO, the absorption spectrum changed and the same pattern as that of the absorption spectrum of a genuine sample of complex [$\mathbf{1}^{4+}$•DABCO] was obtained (Figure 2, spectrum c).

To conclude, the present system can be considered as a switchable receptor. The metalated system is able to strongly complex DABCO and 1,4-diaminobutane because of the scaffolding effect of the four $\mathrm{Cu^I}$ ions. Once demetalated, this ability is totally inhibited owing to the formation of an intramolecular complex involving two triazole groups and the porphyrinic $\mathrm{Zn^{II}}$ ions. A collapsed conformation is simultaneously formed. In the field of systems chemistry, this rotaxane could play a role in signaling (where cyanide input generates diamine output) within larger systems of supramolecules and molecular machines.[11]

Received: July 1, 2010

**Keywords:** host–guest systems · porphyrinoids · receptors · rotaxanes · supramolecular chemistry

---

[1] a) J.-M. Lehn, *Supramolecular Chemistry—Concepts and Perspectives*, VCH, Weinheim, **1995**; b) Y. Murakami, J.-I. Kikuchi, Y. Hisaeda, O. Hayashida, *Chem. Rev.* **1996**, *96*, 721; c) A. Ikeda, M. Ayabe, S. Shinkai, S. Sakamoto, K. Yamaguchi, *Org. Lett.* **2000**, *2*, 3707; d) M. Harmata, *Acc. Chem. Res.* **2004**, *37*, 862; e) D. Fiedler, D. H. Leung, R. G. Bergman, K. N. Raymond, *J. Am. Chem. Soc.* **2004**, *126*, 3674; f) S. Tashiro, M. Tominaga, M. Kawano, B. Therrien, T. Ozeki, M. Fujita, *J. Am. Chem. Soc.* **2005**, *127*, 4546; g) E. M. Pérez, N. Martín, *Chem. Soc. Rev.* **2008**, *37*, 1512; h) P. Mal, B. Breiner, K. Rissanen, J. R. Nitschke, *Science* **2009**, *324*, 1697; i) C. Caltagirone P. A. Gale, *Chem. Soc. Rev.* **2009**, *38*, 520; j) F. Huang, K. A. Switek, L. N. Zakharov, F. R. Fronczek, C. Slebodnick, M. Lam, J. A. Golen, W. S. Bryant, P. E. Mason, A. L. Rheingold, M. Ashraf-Khorassani, H. W. Gibson, *J. Org. Chem.* **2005**, *70*, 3231–3241.

[2] a) C. Dietrich-Buchecker, J.-P. Sauvage, *Chem. Rev.* **1987**, *87*, 795–810; b) D. B. Amabilino, J. F. Stoddart, *Chem. Rev.* **1995**, *95*, 2725- 2828; c) F. Vögtle, T. Dünnwald, T. Schmidt, *Acc. Chem. Res.* **1996**, *29*, 451–460; d) C. Dietrich-Buchecker, J.-P. Sauvage, *Catenanes, Rotaxanes and Knots. A Journey Through the World of Molecular Topology*, Wiley-VCH, Weinheim, **1999**; e) M. Fujita, *Acc. Chem. Res.* **1999**, *32*, 53–61.

[3] a) J.-P. Sauvage, *Acc. Chem. Res.* **1998**, *31*, 611–619; b) J. F. Stoddart, *Acc. Chem. Res.* **2001**, *34*; c) A. Harada, *Acc. Chem. Res.* **2001**, *34*, 456–464; d) V. Balzani, M. Venturi, A. Credi, *Molecular Devices and Machines. A Journey into the Nanoworld*, Wiley-VCH, Weinheim, **2003**; e) E. R. Kay, D. A. Leigh, F. Zerbetto, *Angew. Chem.* **2007**, *119*, 72–196; *Angew. Chem. Int. Ed.* **2007**, *46*, 72–191.

[4] a) I. Smukste, D. B. Smithrud, *J. Org. Chem.* **2003**, *68*, 2547–2558; b) R. T. S. Lam, A. Belenguer, S. L. Roberts, C. Naumann, T. Jarrosson, S. Otto, J. K. M. Sanders, *Science* **2005**, *308*, 667–669; c) J.-S. Marois, K. Cantin, A. Desmarais, J.-F. Morin, *Org. Lett.* **2008**, *10*, 33–36; d) D. I. Schuster, K. Li, D. M. Guldi, J. Ramey, *Org. Lett.* **2004**, *6*, 1919.

[5] P. Beer, M. R. Sambrook, D. Curiel, *Chem. Commun.* **2006**, 2105–2117.

[6] a) J. Frey, C. Tock, J.-P. Collin, V. Heitz, J.-P. Sauvage, *J. Am. Chem. Soc.* **2008**, *130*, 4592–4593; b) J.-P. Collin, J Frey, V. Heitz, J.-P. Sauvage, C. Tock, L. Allouche, *J. Am. Chem. Soc.* **2009**, *131*, 5609–5620.

[7] J.-P. Collin, F. Durola, J. Frey, V. Heitz, F. Reviriego, J.-P. Sauvage, Y. Trolez, K. Rissanen, *J. Am. Chem. Soc.* **2010**, *132*, 6840–6850.

[8] J.-P. Collin, F. Durola, J. Frey, V. Heitz, J.-P. Sauvage, C. Tock, Y. Trolez, *Chem. Commun.* **2009**, 1706–1708.

[9] P. T. Callaghan, *Aust. J. Phys.* **1984**, *37*, 359–387.

[10] a) C. Maeda, S. Yamaguchi, C. Ikeda, H. Shinokubo, A. Osuka, *Org. Lett.* **2008**, *10*, 549–552; b) C. Maeda, P. Kim, S. Cho, J. K. Park, J. M. Lim, D. Kim, J. Vura-Weis, M. R. Wasielewski, H. Shinokubo, A. Osuka, *Chem. Eur. J.* **2010**, *16*, 5052–5061.

[11] V. E. Campbell, X. de Hatten, N. Delsuc, B. Kauffmann, I. Huc, J. R. Nitschke, *Nat. Chem.* **2010**, *2*, 684–687.