Towards Synthetic Molecular Muscles: Contraction and Stretching of a Linear Rotaxane Dimer**

M. Consuelo Jiménez, Christiane Dietrich-Buchecker, and Jean-Pierre Sauvage*

In memoriam Olivier Kahn

Molecules whose shape and dynamic properties can be controlled at will have recently triggered great interest. Most of the systems specially designed and constructed for their movement properties contain interlocking rings (catenanes) or rings threaded by molecular stringlike components (pseudo-rotaxanes and rotaxanes). These compounds are often described as machines[1] or motors.[1, 2] The latter term applies more specifically to systems for which continuous movement can be induced while energy is consumed. Biological molecular motors are especially important.[3] They can be classified as rotary motors, ATP synthase being the most important and well understood example,[4] or linear motors.[5] Among the few natural linear motors identified to date, skeletal muscles[6] occupy a special position due to their universal character and to the importance of the mechanical properties they confer to vertebrates.

To date, several interesting artificial systems have been described which aim at reproducing some essential properties of skeletal muscles. Polypyrrole-based devices are particularly promising, since they allow one to bend a solid polymer film in one direction or another depending on the sign of an electric current applied to the film.[7] A more recent approach relies on single-walled nanotube sheets.[8]

To the best of our knowledge, unimolecular linear arrays capable of undergoing contraction or stretching have not been made as yet. Herein we describe such a multicomponent system, capable of contracting or stretching under the action of a chemical signal. It is based on a doubly threaded structure recently described.[9]

The principle of the contraction/stretching process is indicated in a very schematic fashion in Figure 1.

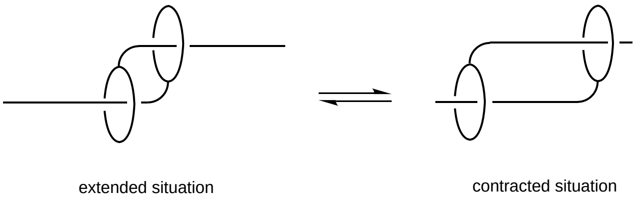


Figure 1. The topology and the shape of a linearly arranged pseudo-rotaxane dimer is adapted to a contraction/stretching motion.

By analogy with real muscles, we designed a molecular assembly for which two filaments can glide along one another. 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 1, 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 machinelike compounds elaborated and studied in our group are mostly copper complexes, the motion being triggered by an electrochemical reaction (Cu^I/Cu^{II}), although photochemically driven processes based on ruthenium(II) compounds seem also to be promising.[10] 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 2, the doubly threaded compound reported herein can bind simultaneously two metal centers, either in a four-coordinate or a five-coordinate geometry. The four-coordinate situation corresponds to an extended geometry, whereas the five-coordinate situation leads to a contracted geometry.

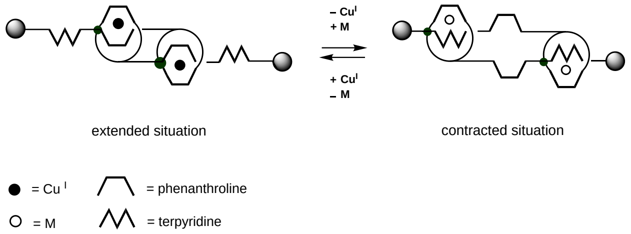


Figure 2. Functioning principle of the unimolecular synthetic "muscle" reported herein. The two-component rotaxane dimer contains identical ring-and-string conjugates. Each component consists of a bidentate chelate (U-shaped symbol) embedded in a ring, the ring being covalently attached to a filamentlike part. This string contains another bidentate ligand, a terdentate coordinating unit (schematically represented by a W-shaped symbol), and a bulky stopper (sphere) 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). A representative geometrical parameter measuring the level of contraction or stretching of the system can be the center-to-center distance between the two stoppers. 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).

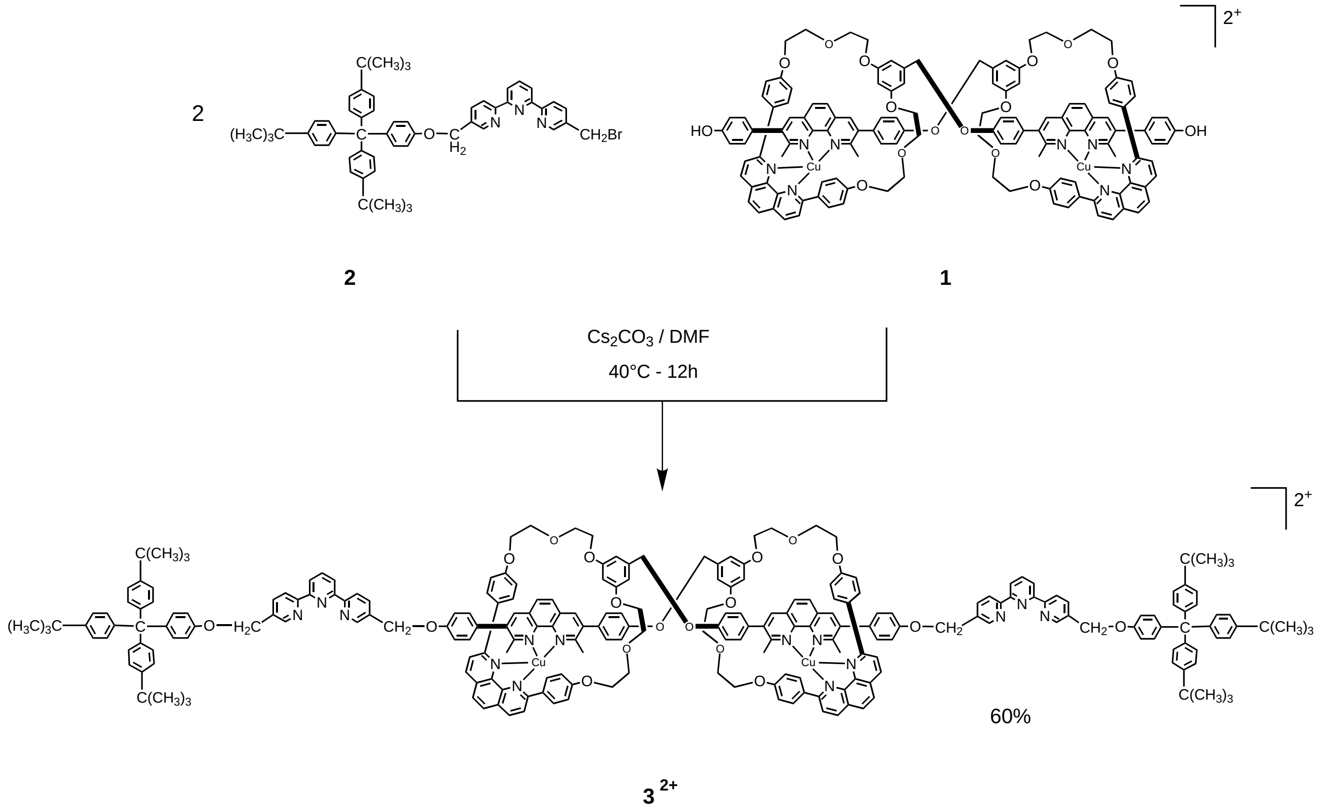
The molecular "muscle" of the present report was synthesized in its extended conformation (i.e., with a geometry corresponding to the left-hand side of Figure 2), from the dicopper(I) precursor **1** (Scheme 1). Compound **1** displays an interesting topology[11] which prompted us to call it a

---

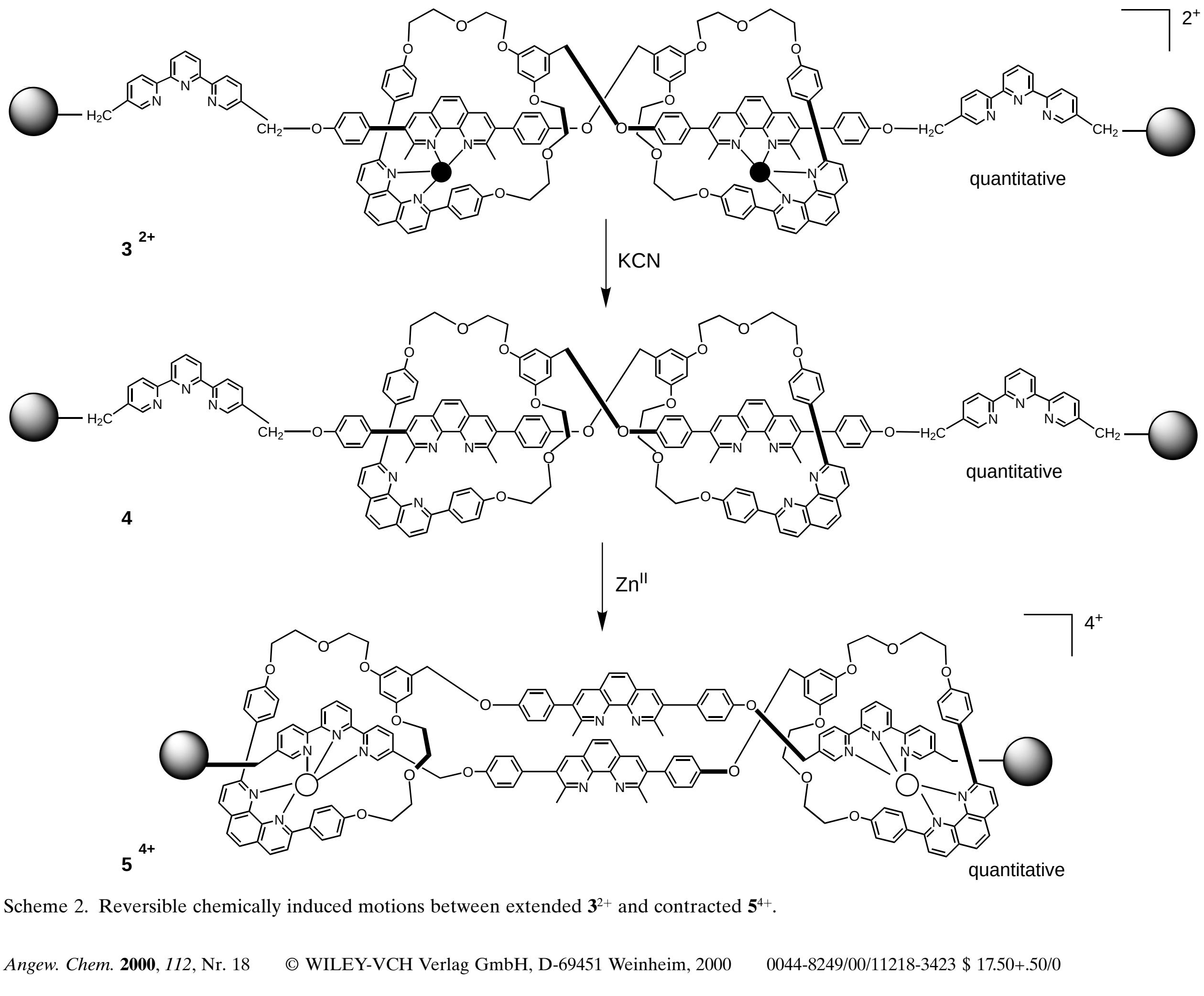
[*] Prof. J.-P. Sauvage, Dr. M. C. Jiménez, Dr. C. Dietrich-Buchecker
Laboratoire de Chimie Organo-Minérale
UMR 7513 du CNRS
Université Louis Pasteur
Faculté de Chimie
4, rue Blaise Pascal
67070 Strasbourg Cedex (France)
Fax: (+33) 3-88-60-73-12
E-mail: sauvage@chimie.u-strasbg.fr

[**] We are grateful to M. Jean-Daniel Sauer and Dr. Roland Graff for high-field NMR experiments, Hélène Nierengarten and Raymond Hubert for mass determinations. M.C.J. thanks the European Commission for a Grant (TMR Contract No. ERBFMBICT972547). We also thank the CNRS for financial support (Programme Physique et Chimie du Vivant).

Supporting information for this article is available on the WWW under http://www.wiley-vch.de/home/angewandte/ or from the author.



Scheme 1. Synthesis of the “muscle” 3^{2+} in its extended situation.



Scheme 2. Reversible chemically induced motions between extended 3^{2+} and contracted 5^{4+}.

"hermaphrodite" molecule.[9] Reaction of the phenolic functions of **1** in DMF and Cs_2CO_3 at 40 °C with two equivalents of bromide **2** (a stopper-bearing disymmetrical 2,2′,6′,2″-terpyridine whose synthesis will be described elsewhere), led to the desired complex $\mathbf{3}^{2+}$ in 60 % yield (Scheme 1).

2D-ROESY NMR experiments as well as high-resolution mass spectrometry (FAB) showed clearly that the stoppering procedure leading to $\mathbf{3}^{2+}$ occurred without significant dethreading as evidenced by large interfragment interactions in the NMR spectrum and by the expected molecular ion peak at m/z 3834.2 (calcd m/z 3834.3). The free ligand **4** obtained in quantitative yield by reacting $\mathbf{3}^{2+}$ 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 $\mathbf{5}^{4+}$ as a colorless solid, in the contracted situation (Scheme 2, page 3885). The reverse motion, leading back to the extended situation, that is back to $\mathbf{3}^{2+}$, could be easily induced upon addition of excess $Cu(CH_3CN)_4 \cdot PF_6$ in CH_2Cl_2/CH_3CN at room temperature. Although the dimeric nature of $\mathbf{3}^{2+}$, **4**, and $\mathbf{5}^{4+}$ could be easily demonstrated by mass spectrometry (FAB or ES),[13] demonstration of the contraction/stretching phenomenon accompanying the metal exchange (Cu^I/Zn^{II}) required extensive NMR studies. Some of the most characteristic chemical shifts are collected in Table 1.

Table 1. ¹H NMR spectroscopy: chemical shifts (δ, in ppm) of a few selected protons.[a]

Compounds	H_o	H_m	CH_3	6_{terpy}	$6''_{terpy}$	$4'_{terpy}$
2	–	–	–	8.68	8.72	7.96
$\mathbf{3}^{2+}$	7.48	6.04	2.09; 2.21	8.79	8.75	7.97
4	8.44	7.17	2.66; 2.72	8.80	8.71	7.97
$\mathbf{5}^{4+}$	6.85	6.29	2.71; 2.75	7.39	8.13	8.58

[a] 400 MHz in CD_2Cl_2.

From previous studies on the doubly threaded dicopper(I) precursor, it is clear that $\mathbf{3}^{2+}$ contains two pseudo-tetrahedral complexes, each metal center being coordinated to a dpp motif embedded in the ring (dpp = 2,9-diphenyl-1,10-phenanthroline) and a dmp fragment belonging to the filament (dmp = 2,9-dimethyl-1,10-phenanthroline). The data in Table 1 shows that various NMR probes can be considered (see Figure 3).

1) H_o and H_m are very indicative of the dpp situation. If this unit is free, the chemical shifts of the two protons are "normal" for an aromatic group attached to a 1,10-phenanthroline (phen) nucleus (δ = 7–8.5). On the other hand, once coordinated to a metal center in a 2-aromatic polyimine complex, H_o and H_m

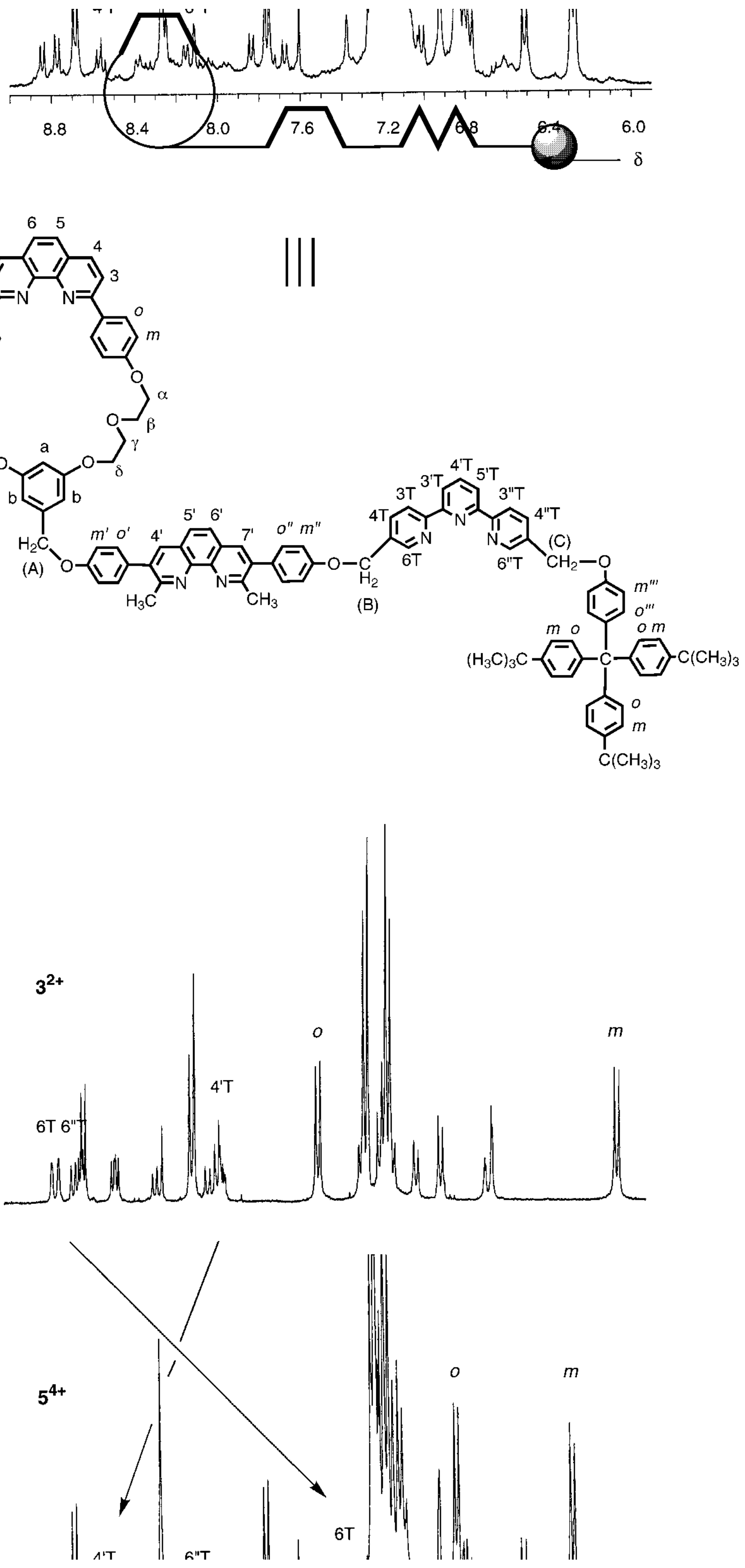


Figure 3. ¹H NMR spectra (aromatic part) of $\mathbf{3}^{2+}$ and $\mathbf{5}^{4+}$ (400 MHz in CD_2Cl_2).

undergo a strong upfield shift characteristic of "entwined" compounds, as evidenced long ago.[12] From the data in Table 1, it is evident that dpp is coordinated in both complexes $\mathbf{3}^{2+}$ and $\mathbf{5}^{4+}$. For instance, H_m undergoes an upfield shift with respect to the free ligand of $\Delta\delta = -1.13$ and -0.88 ppm for $\mathbf{3}^{2+}$ and $\mathbf{5}^{4+}$, respectively. For H_o, the shift is even more spectacular in $\mathbf{5}^{4+}$ ($\Delta\delta = -1.59$ ppm) probably because of the strong ring current exerted by the terpyridine (terpy) unit onto this proton.

2) The CH_3 groups borne by the phen chelate included in the filament are also strongly upfield shifted by complexation, owing to a similar "entwining" effect as that observed for H_o and H_m. The chemical shifts are strikingly similar for **4** and $\mathbf{5}^{4+}$, but they are significantly different from those of $\mathbf{3}^{2+}$: $\Delta\delta \sim -0.6$ ppm for $\mathbf{3}^{2+}$ with respect to **4** or $\mathbf{5}^{4+}$; thus, the dmp unit of $\mathbf{5}^{4+}$ is free.
3) H_6, $H_{6''}$, and $H_{4'}$ of the terpy part also undergo substantial chemical shift changes upon complexation. Whereas the corresponding chemical shift values are similar in **2**, $\mathbf{3}^{2+}$, and **4** ($\delta = 8.76 \pm 0.08$ for H_6; $\delta = 8.73 \pm 0.02$ for $H_{6''}$, and $\delta = 7.97 \pm 0.01$ for $H_{4'}$), they are noticeably different in $\mathbf{5}^{4+}$ (strong upfield shift for H_6 and $H_{6''}$; relatively strong downfield shift for $H_{4'}$). These observations are consistent with the "entwining" effect, placing H_6 and $H_{6''}$ in the shielding region of the dpp unit belonging to the ring for a (dpp)(terpy) complex. They also unambiguously demonstrate that both Zn^{2+} centers in $\mathbf{5}^{4+}$ are coordinated to the terpy fragments.

From the ^1H NMR data, it can be concluded that each Zn^{2+} ion of $\mathbf{5}^{4+}$ is coordinated to a dpp chelate and a terpy unit, that is the molecule is in the contracted situation, as represented in Scheme 2.

In conclusion, the present rotaxane dimer is the first unimolecular linear array capable of stretching and contracting at will under the action of a chemical stimulus. From CPK model estimations, the length of the compound changes from 83 Å to 65 Å between both situations, that is roughly by the same relative amount as natural muscles (~27%).

Received: March 13, 2000 [Z14842]

---

[1] a) V. Balzani, M. Gómez-López, J. F. Stoddart, *Acc. Chem. Res.* **1998**, *31*, 405–414; b) J.-P. Sauvage, *Acc. Chem. Res.* **1998**, *31*, 611–619; c) L. Raehm, J.-M. Kern, J.-P. Sauvage, *Chem. Eur. J.* **1999**, *5*, 3310–3317; d) A. S. Lane, D. A. Leigh, A. Murphy, *J. Am. Chem. Soc.* **1997**, *119*, 11092–11093; e) L. Zelikovich, J. Libman, A. Shanzer, *Nature* **1995**, *374*, 790–792; f) C. Canevet, J. Libman, A. Shanzer, *Angew. Chem.* **1996**, *108*, 2842–2845; *Angew. Chem. Int. Ed. Engl.* **1996**, *35*, 2657–2660; f) L. Fabbrizzi, M. Liccheli, P. Pallavicini, *Acc. Chem. Res.* **1999**, *32*, 846–853.

[2] Recent examples of compounds reminiscent of rotatory motors have been reported: a) T. R. Kelly, H. De Silva, R. A. Silva, *Nature* **1999**, *401*, 150–152; b) N. Koumura, R. W. J. Zijistra, R. A. van Deiden, N. Harada, B. L. Feringa, *Nature* **1999**, *401*, 152–155; c) for a Brownian rotor, see: J. K. Gimzewski, C. Joachim, R. R. Schlittler, V. Langlais, H. Tang, I. Johannsen, *Science* **1998**, *281*, 531–533.

[3] a) K. Kitamura, M. Tokunaga, A. H. Iwane, T. Yanagida, *Nature* **1999**, *397*, 129–134; b) J. Howard, *Nature* **1997**, *389*, 561–567.

[4] a) T. Elston, H. Wang, G. Oster, *Nature* **1998**, *391*, 510–513; b) H. Noji, R. Yasuda, M. Yoshida, K. Kinosita, Jr., *Nature* **1997**, *386*, 299–302; c) J. E. Walker, *Angew. Chem. **1998***, 110, 2438–2450; *Angew. Chem. Int. Ed.* **1998**, *37*, 2309–2319.

[5] J. Howard, *Nature* **1998**, *391*, 239–240.

[6] I. Rayment, H. M. Holden, M. Whittaker, C. B. Yohn, M. Lorenz, K. C. Holmes, R. A. Milligan, *Science* **1993**, *261*, 58–65.

[7] T. F. Otero, J. M. Sansiñera, *Adv. Mater.* **1998**, *10*, 491–494, and references therein.

[8] R. H. Baughman, C. Cui, A. A. Zakhidov, Z. Iqbal, J. N. Barisci, G. M. Spinks; G. G. Wallace, A. Mazzoldi, D. De Rossi, A. G. Rinzler, O. Jaschinski, S. Roth, M. Kertesz, *Science* **1999**, *284*, 1340–1344, and references therein.

[9] M. C. Jiménez, C. Dietrich-Buchecker, J.-P. Sauvage, *Angew. Chem.* **2000**, *112*, 1351–1354; *Angew. Chem. Int. Ed.* **2000**, *39*, 1295–1298.

[10] A. C. Laemmel, J.-P. Collin, J.-P. Sauvage, *Eur. J. Inorg. Chem.* **1999**, 383–386.

[11] A similar topology was observed, mostly in the solid state, by J. F. Stoddart and co-workers: a) P. R. Ashton, I. Baxter, S. J. Cantrill, M. C. T. Fyfe, P. T. Glink, J. F. Stoddart, A. J. P. White, D. J. Williams, *Angew. Chem.* **1998**, *110*, 1344–1347; *Angew. Chem. Int. Ed.* **1998**, *37*, 1294–1297; b) P. R. Ashton, I. W. Parsons, F. M. Raymo, J. F. Stoddart, A. J. P. White, D. J. Williams, R. Wolf, *Angew. Chem.* **1998**, *110*, 2016–2019; *Angew. Chem. Int. Ed.* **1998**, *37*, 1913–1916.

[12] C. Dietrich-Buchecker, P. A. Marnot, J.-P. Sauvage, J.-P. Kintzinger, P. Maltèse, *Nouv. J. Chim.* **1984**, *8*, 573–582.

[13] The synthesis of **2** will be reported elsewhere.

Conformation Control of Oligosilanes Based on Configurationally Constrained Bicyclic Disilane Units**

Kohei Tamao,* Hayato Tsuji, Masayoshi Terada,
Masahiro Asahara, Shigehiro Yamaguchi, and
Akio Toshimitsu

One of the most important properties of polysilane compounds is their electronic absorption in the UV region that provides a representative example of the σ-conjugation systems.[1] It is generally accepted that *both* the absorption wavelengths, λ_{max}, and the intensities depend on the chain length of the silicon backbone in the *anti* conformation, while the *gauche* conformations behave as defects in the σ conjugation. This idea has been successfully used to explain the thermochromic behavior of long-chain polysilanes.

However, little is understood about the origin of the conformation-dependency of the electronic absorptions. Recently, a new explanation has been proposed by Michl and coworkers[2] based on their pioneering theoretical and experimental studies on tetrasilane model systems. These systems

---

[*] Prof. Dr. K. Tamao, H. Tsuji, M. Terada, Dr. M. Asahara,
Dr. S. Yamaguchi, Dr. A. Toshimitsu
Institute for Chemical Research
Kyoto University
Uji, Kyoto, 611-0011 (Japan)
Fax: (+81) 774-38-3186
E-mail: tamao@scl.kyoto-u.ac.jp

[**] Financial support by a Grant-in-Aid from the Ministry of Education, Science, Sports, and Culture of Japan (09239103) is gratefully acknowledged. We thank Prof. R. West and Prof. J. Michl for their helpful discussions to this work.

Supporting information for this article is available on the WWW under http://www.wiley-vch.de/home/angewandte/ or from the author.