ORGANIC
LETTERS

2011
Vol. 13, No. 6
1326–1329

A Triangular Macrocycle Altering Planar and Bulky Sections in Its Molecular Backbone

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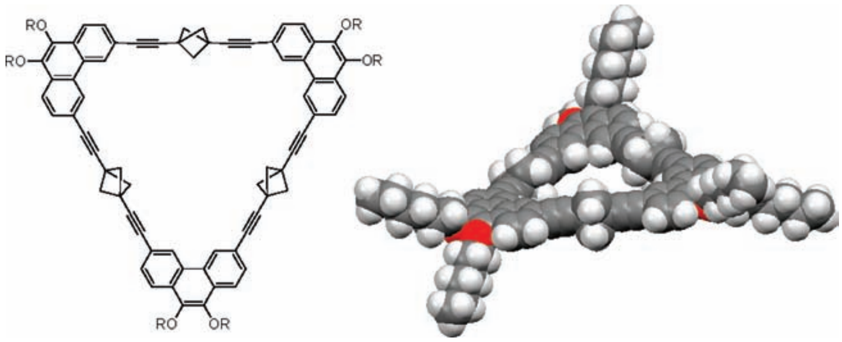
Received January 3, 2011

ABSTRACT



A triangular macrocyclic molecule has been synthesized which consists of substituted phenanthrene vertices interconnected by 1,3-diethynylbicyclo[1.1.1]pentane sides. The molecule is the very first example of exploiting the bicyclopentane motif in the construction of a shape persistent macrocycle's backbone. It carries new features such as bulkiness, nonconjugated σ-bonding, and a certain conformational flexibility due to its easy longitudinal rotation. We have used some of the features in order to rationalize the observed tendency of the compound to form films on various surfaces.

Macrocyclic molecules of persistent shape have proven their suitableness for various applications in the field of supramolecular chemistry and material science attracting thus the increasing attention of many research groups.[1] Probably the most rewarding synthetic approach to the shape persistent macrocycles (SPMs) uses acetylene arylene chemistry, which offers a variety of coupling methods to construct carbon−carbon bonds of the macrocyclic backbone. Sonogashira, Negishi, Heck, Glaser, Suzuki, and Castro−Stevens coupling reactions have thus been used successfully as well as the alkyne metathesis.[2] This approach affords macrocycles with a fully π-conjugated planar or pseudoplanar backbone. It obviously influences not only the electronic properties of single molecules but also their supramolecular behavior. $\pi-\pi$ Stacking plays an important role among the intermolecular interactions that affect also macroscopic properties of possible materials. The highly rigid backbone that frames an internal cavity on the nanometer scale is often grafted by flexible tentacles, which increase the solubility and are of importance in the further tailoring of the molecular and supramolecular properties.

We were interested in effects, which may arise from incorporation of rigid, bulky, and nonconjugated σ-bonded building blocks into the backbone of SPMs. It will undoubtedly change the electronic properties as well as the

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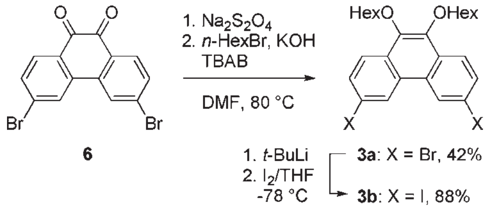
(1) For recent reviews on shape-persistent macrocycles, see: Höger, S. *Pure Appl. Chem.* **2010**, *82*, 821. Diederich, F.; Kivala, M. *Adv. Mater.* **2010**, *22*, 803. Hua, Y.; Flood, A. H. *Chem. Soc. Rev.* **2010**, *39*, 1262. Gong, B. *Acc. Chem. Res.* **2008**, *41*, 1376. Zang, L.; Che, Y.; Moore, J. S. *Acc. Chem. Res.* **2008**, *41*, 1596. Bazzicalupi, C.; Bencini, A; Bianchi, A.; Danesi, A.; Faggi, E.; Giorgi, C.; Santarelli, S.; Valtancoli, B. *Coord. Chem. Rev.* **2008**, *252*, 1052. Tykwinski, R. R.; Gholami, M.; Eisler, S.; Zhao, Y.; Melin, F.; Echegoyen, L. *Pure Appl. Chem.* **2008**, *80*, 621. Höger, S. In *Functional Organic Materials*; Müller, T. J. J., Bunz, U. H. F., Eds.; Wiley-VCH, Weinheim, Germany, 2007; p 225. Zhang, W.; Moore, J. S. *Angew. Chem., Int. Ed.* **2006**, *45*, 4416. Li, Z.-T.; Hou, J.-L.; Li, C.; Yi, H.-P. *Chem.—Asian J.* **2006**, *1*, 766. MacLachlan, M. J. *Pure Appl. Chem.* **2006**, *78*, 873. Höger, S. *Chem.—Eur. J.* **2004**, *10*, 1320.

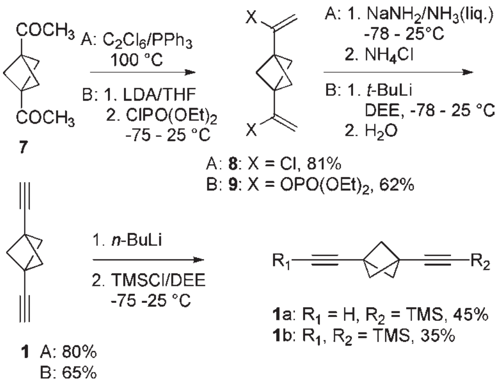
(2) For a review on syntheses strategies, see: Sadowy, A. L.; Tykwinski, R. R. In *Modern Supramolecular Chemistry. Strategies for Macrocyclic Synthesis*; Diederich, F., Stang, P. J., Tykwinski, R. R., Eds.; Wiley-VCH: Weinheim, Germany, 2008; p 185.

10.1021/ol1031816

Scheme 1. Synthesis of the Phenanthrene Vertex Connectors **3**

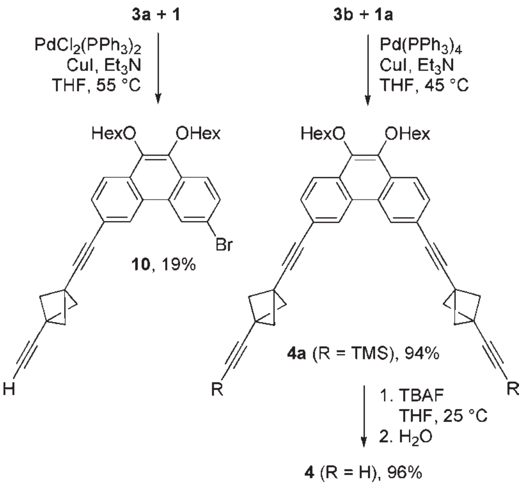


Scheme 2. Synthesis of Rod-like Building Blocks **1**[a]



[a] Method A or B was applied respectively.

Scheme 3. Synthesis of the V-Shaped Precursor **4**



packing ability of the resulting macrocycles. Understanding the effects might be of importance in tailoring the properties of new compounds and materials of specific purposes. The bulky σ-bonded building block of our choice was 1,3-diethynylbicyclo[1.1.1]pentane (**1**) because its rigid linear rod-like shape resembles the 1,4-diethynylbenzene that had proven its usefulness in acetylene–arylene chemistry. We assumed that its terminal triple bonds would allow taking full advantage of alkyne chemistry also in this case. To prove it, we designed a triangular SPM **2** that combines the bulky σ-bonded units in its sides with planar aromatic ones in the vertices.

As the planar building blocks, the 3,6-dihalophenanthrene connectors **3** were chosen because the bonds in their reactive sites 3 and 6 form an 60° angle suitable for the equilateral triangle. The alkoxy substituents in the positions 9 and 10 presumably increase the solubility of the target molecule. We designed the synthesis of the triangular molecule **2** as a convergent process in which the simple building blocks **1** and **3** were used for the construction of two larger precursors whose assembly would give the final macrocycle. A V-shaped precursor **4** results from the combination **1**–**3**–**1** and a rod-like precursor **5** combines the blocks in the order **3**–**1**–**3**. We expected that the assembly of the V-shaped angle with its rod-like base would guarantee a satisfactory yield of the final triangle **2**.

The building block **3** was prepared by a modified procedure[3] starting from 3,6-dibromo-9,10-phenathroquinone (**6**)[4] (Scheme 1). Since the primarily obtained dibromoderivative **3a** did not prove satisfactory reactivity in subsequent reactions, it had to be transferred into the diiodo **3b** by a lithium halogen exchange.

The building block **1** was prepared by a known procedure,[5] in which the diketone **7** was transferred to the chloroolefine **8** that provided **1** by elimination in liquid ammonia (Scheme 2, Method A). A different approach to **1**, the elimination of an enol phosphate[6] **9** (Method B), had been successful in a similar case, recently,[7] but gave lower yields this time. The diyne **1** was protected at one terminus to prevent oligomerization during subsequent syntheses. Its partial silylation afforded the monosilylated **1a** in a satisfactory yield. The disilylated byproduct **1b** was easily separated for further recycling (Scheme 2).

The V-shaped **4** could not be prepared by reaction of the dibromo **3a** with an excess of **1** as originally proposed. After 14 h when all the starting **1** had already been consumed, the reaction (Scheme 3) afforded only the monocoupled product **10** in 19% yield. The cross-coupling reaction was obviously too slow so **1** was lost in a competing oxidative homocoupling reaction further favored by presence of two free alkyne termini in **1**. When the monoprotected diyne **1a** had been used together with the more reactive diiododerivative **3b**, the extent of homocoupling and oligomerization was reduced and the desired **4** was obtained in an excellent yield (Scheme 3).

The preparation of the rod-like side precursor **5** also benefited from the higher reactivity of **3b**. The reactions of the diyne **1** with **3a** or **3b** gave rather the same yields of **5a**

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(3) Boden, B. N.; Hui, J., K.-H.; MacLachlan, M. J. *J. Org. Chem.* **2008**, *73*, 8069.

(4) Bhatt, M. *Tetrahedron* **1964**, *20*, 83.

(5) Schwab, P.; Noll, B. C.; Michl, J. *J. Org. Chem.* **2002**, *67*, 5476. Bunz, U.; Szeimies, G. *Tetrahedron Lett.* **1990**, *31*, 651.

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(7) Kaleta, J.; Michl, J.; Mazal, C. *J. Org. Chem.* **2010**, *75*, 2350.

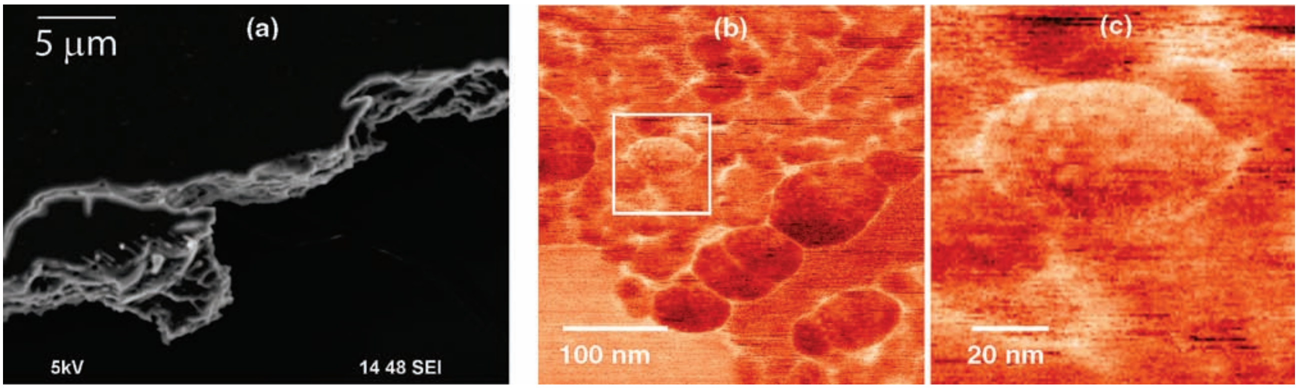
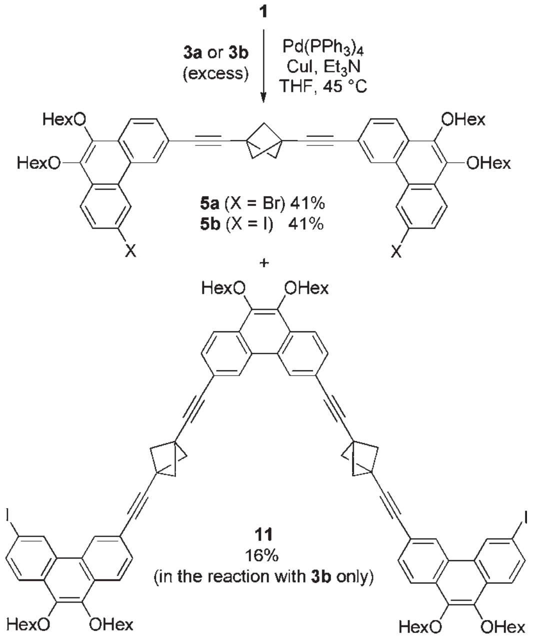
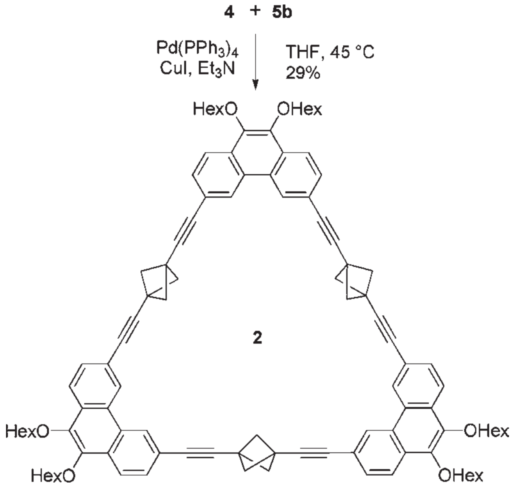


Figure 1. (a) SEM picture of a multilayered film of **2**. (b) AFM picture of a film of **2** on a mica surface. (c) A detail of the framed area of the picture (b) showing the fine structure of one "bubble" with remarkable objects of approximately 6 nm size. The larger versions of the pictures can be found in the Supporting Information.

Scheme 4. Synthesis of the Side Precursor **5**



Scheme 5. Final Assembly of the Triangular Macrocycle **2**



or **5b**, respectively, but a separation of **5b** from the crude reaction mixture was much easier; moreover, a prospectively useful byproduct **11** was isolated too (Scheme 4). In addition, the next step further gained from the higher reactivity of **5b**.

The final macrocycle **2** was prepared by coupling of the V-shaped precursor **4** with the rod-like side precursor **5b** (Scheme 5). NMR analysis of the reaction mixture showed that the coupling reaction afforded more than 60% of **2**, but its unwillingness to crystallize together with further difficulties in separation decreased the isolated amount of the pure **2** to only 29%.

We did not find any conditions for crystallization of the compound **2**. A satisfactory pure material which was obtained by precipitation of **2** from DCM solution showed only irreproducible thermal behavior with observable decomposition over 200 °C. When a solution of **2** was accidentally spilt into the water bath, it formed a cohesive film on the surface that could have been readily separated and recovered. During the concentration of the solutions in vacuum, similar films spread out over the inner walls of the distillation flasks. One could remove the film from the flask with tweezers almost in one piece relatively easily.

SEM investigations of the film obtained by evaporation of a DCM solution of **2** on water surface showed its multilayered structure (Figure 1a). A more detailed picture was obtained by AFM measurements of a similar film that had been prepared by evaporation of a diluted DCM solution of **2** on a mica surface. The results were not very clear but showed a thin film with a wavy, bubble-like surface (Figure 1b). Some of the "bubbles" markedly showed a fine structure with segments of approximately 6 nm size (Figure 1c).

Such behavior inspired our suggestion that the molecules of **2** prefer some kind of 2-D arrangement as a result of the specific combination of planar and bulky segments in their structure. The bulkiness of the bicyclopentane cages, which space the phenanthrene vertices of the triangle **2**, does not allow a "full-face" $\pi-\pi$ stacking of the molecules.[8] This prevents a columnar organization often observed in the case of the SPMs with a fully conjugated planar backbone.[9]

To harness $\pi-\pi$ stacking, probably the most effective intermolecular interaction that the molecules of **2** have at disposal, they overlap at least in part so the phenanthrene rings in the vertices of one molecule interact with those in different molecules of **2**. The mutual head-to-tail orientation of the overlapping phenanthrene units is thus similar like that found in crystals of 9,10-phenanthrenequinhydrone.[10] Penetration of exterior hexyl chains into the interior cavities of the neighboring macrocycles interlocks the partially overlapped triangles. Some examples of a similar arrangement of SPMs in crystals have already been given in the literature.[11] In an ideal case, the molecules might arrange in a regular hexagonal grid with a mesh size of around 6 nm, which is depicted in Figure 2. Of course, the real structure of the film will be much less regular than the varnished example, but a sporadic occurrence of such regular domains could explain the 6 nm "spots" observed by AFM.

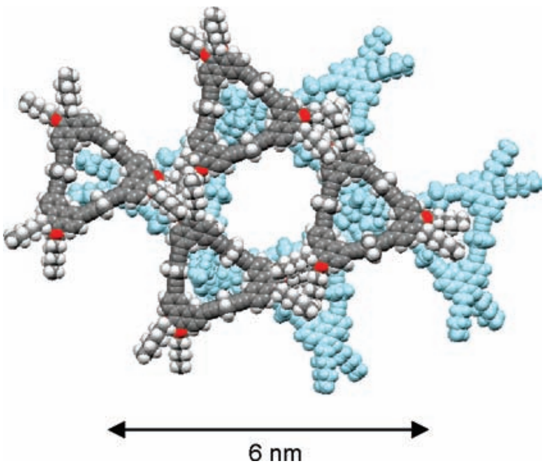


Figure 2. An idealized, MM2 minimization model of 2D organization of the triangular molecules of **2** by $\pi-\pi$ stacking of their vertices (red ball = oxygen atom; the lower molecules are colorized light blue for clarity).

The intermolecular attractions are however too weak to be revealed in solution (concentration dependence of ^{1}H NMR shifts or UV$-$vis spectra), but some evidence of them comes from MALDI-MS spectra where peaks of a dimer (M_2+H^+; 2949.6) and even a trimer (M_3+H^+; 4424.2) were observed. A high conformational flexibility of bicyclo[1.1.1]pentane cages of **2**, which can almost freely rotate around their longitudinal axes within the yet geometrically well-defined SPM, can lie behind a certain spontaneity of the film formation that results, e.g. in its outspreading over glassware walls. The rotation could ease a sliding of the triangular molecules over each other until they interlock.

In conclusion, we have synthesized the shape-persistent macrocyclic compound **2**, which combines planar phenanthrene units and bulky bicyclopentane cages in its molecular backbone. A convergent synthetic pathway used two building blocks, 1,3-diethynylbicyclo[1.1.1]pentane (**1**) and 3,6-diiodophenanthrene **3b**, for syntheses of two larger precursors that were finally coupled affording the target macrocycle **2** in good yield. The reported synthesis is the very first example of an application of the bicyclopentane motif in the construction of SPMs. Its incorporation into the SPM's backbone brings some new features such as bulkiness, σ-bonding that breaks the full-cycle conjugation, and some conformational flexibility due to its easy longitudinal rotation. We have used some of them to rationalize an observed tendency of **2** to form films on various surfaces. Our results in this area are very preliminary, and further study of these phenomena, which will certainly cover balancing the size of exterior tentacles and interior cavities, construction of SPMs of different geometry, and the use of different planar building blocks, is expected.

Acknowledgment. The authors thank to Profs. J. Havel and P. Skládal (MU Brno) and S. Bakardieva (IIC Prague) for MALDI-MS, AFM, and SEM measurements, respectively. The work was supported by the Ministry of Education, Youth and Sports of the Czech Republic (Grant Nos. MSM0021622410 and KONTAKT ME 09114). J.K. has greatly acknowledged the financial support from Synthon s.r.o., CZ.

Supporting Information Available. Experimental procedures, NMR spectra of new compounds, MALDI-MS and UV$-$vis spectra of **2**, and SEM and AFM pictures of the obtained films are given. This material is available free of charge via the Internet at http://pubs.acs.org.

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(11) For examples of overlapping and interlocking SPMs, see: Shabelina, N.; Klyatskaya, S.; Enkelmann, V.; Höger, S. *C. R. Chimie* **2009**, *12*, 430. Höger, S.; Weber, J.; Leppert, A.; Enkelmann, V. *Beil. J. Org. Chem.* **2008**, *4*, 1. Grave, C.; Lentz, D.; Schäfer, A.; Samorì, P.; Rabe, J. P.; Franke, P.; Schlüter, A. D. *J. Am. Chem. Soc.* **2003**, *125*, 6907.