Molecular Devices

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# Molecular Switches Flipped by Oxygen**

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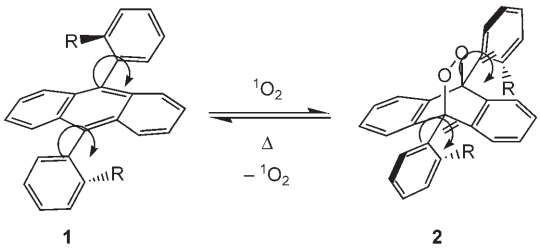
Molecular machines are of current interest in biology and chemistry.[1] Nature provides the archetype—elegant motor proteins driven by adenosine triphosphate (ATP).[2] Artificial motors[3] and switches,[4] which represent central devices of molecular machines, have been synthesized by various strategies during the past few years, with special emphasis on the question of energy supply.[5] Many systems are powered by light, electrons, protons, or heat; more recently, a chemically driven unidirectional motor has been described.[6] However, singlet oxygen has not been used to fuel synthetic motors or to flip molecular switches until now.

The sensitized photoreaction of oxygen with visible light generates singlet oxygen ($^1O_2$), which conveniently oxidizes organic compounds under mild conditions.[7] During our investigations on stereoselective reactions[8] and photolithography[9] with this reagent, we became interested in the photooxygenation of anthracenes. Herein we describe our results on the construction of a molecular rotary switch, flipped by singlet oxygen and thermal isomerization. The stator and rotor are connected in only one step from commercially available starting materials, the switching process proceeds with good to high yields, and oxygen is formed as the only waste product.

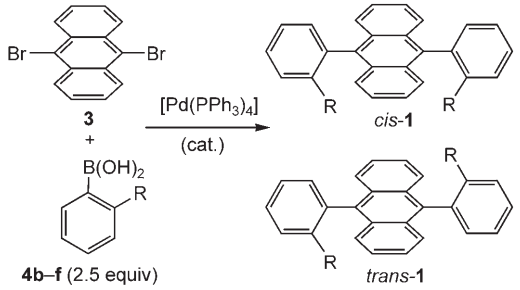
Our system is based on the photooxygenation of 9,10-bisarylanthracenes **1** to give the corresponding 9,10-endoperoxides **2** (Scheme 1). For the phenyl-substituted compound **1a** (R = H), this reaction is known to proceed reversibly with high yields, and many repetitive cycles of cycloaddition and cycloreversion are possible.[10] If *ortho* substituents on the aryl ring are present (R ≠ H), the rotation around the C–C single bond should be sterically hindered, affording *cis* and *trans* isomers. At higher temperatures random thermal (Brownian) isomerizations might take place, but after oxidation the endoperoxide structure **2** should block the axial rotation (Scheme 1). Furthermore, the two stations of the switch could be distinguished by simple optical readout.




1 2

***Scheme 1.*** Concept of the reversible reaction of 9,10-bisarylanthracenes **1** with singlet oxygen ($^1O_2$) to give the 9,10-endoperoxides **2** with rotation around a C–C single bond.

Interestingly, only few examples for the preparation of 9,10-bisarylanthracenes **1** from anthraquinone have been reported.[11] Therefore, we applied the Suzuki coupling[12] to obtain the 9,10-bisarylanthracenes **1b–f** from 9,10-dibromoanthracene (**3**) and the boronic acids **4** in good yields (Scheme 2). With the sterically more demanding derivatives




R

| | | | |
|---|---|---|---|
| **b:** | Me | *cis*-**1b** (30%) | *trans*-**1b** (48%) |
| **c:** | Et | *cis*-**1c** (31%) | *trans*-**1c** (32%) |
| **d:** | *i*Pr | *cis*-**1d** (31%) | *trans*-**1d** (31%) |
| **e:** | OMe | *cis*-**1e** (36%) | *trans*-**1e** (44%) |
| **f:** | F | 74% (*trans*/*cis*-**1f** 60:40) | |

***Scheme 2.*** Synthesis of **1** by Suzuki coupling.

**4c** and **4d**, monocoupling occurred as a side reaction. Each *cis*/*trans* isomer **1b–e** could be separated by column chromatography or crystallization; only the fluoro derivative **1f** was isolated as a mixture. The structures of the products and their configurations were proven by distinct NMR signals and X-ray analysis.[13] In summary, we connected the rotor (*ortho*-substituted benzene) with the stator (anthracene) of the newly designed molecular switch in only one step from commercially available starting materials, which makes the synthesis much simpler than those of other known systems.

Possible rotations around the C–C single bonds were investigated by heating anthracenes **1** to various temperatures. The fluoro derivative **1f** undergoes thermal (Brownian) *cis*/*trans* isomerization in solution at 70 °C within 100 min, which was easily followed by $^{19}$F NMR spectroscopy.[13] However, all other anthracenes **1b–e** are configurationally

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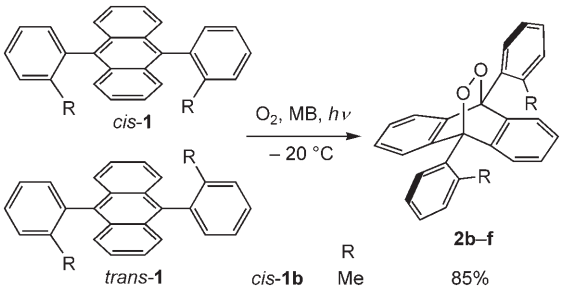
stable up to 250 °C. This observation can be rationalized by the steric demand of the substituents R and unfavorable interactions with the adjacent hydrogen atom of the anthracene system. This is in good accordance with the rotational barrier of 104 kJ mol$^{-1}$ determined for the methyl derivative **1b** by gas chromatography.[11c] Finally, we forced a thermal axial rotation of the methyl- and methoxy-substituted anthracenes **1b** and **1e** neat at 320 °C without decomposition. In all cases, the thermodynamically more stable *trans* isomers are formed in excess; only the sterically most hindered derivatives **1c** and **1d** cannot rotate at all. Thus, we set up the prerequisites for a molecular switch with Brownian 180° rotations of an aryl rotor around an anthracene stator for distinct temperatures and substituents R.

The crucial experiments were the reactions of the anthracenes **1** with $^1O_2$, which was conveniently generated at −20 °C from molecular oxygen by irradiation with two sodium lamps in the presence of catalytic amounts of methylene blue (MB) as the sensitizer. We oxidized the *cis* and *trans* isomers **1** independently to investigate possible rotations (Scheme 3). The photooxygenations proceeded smoothly to give the 9,10-endoperoxides **2** by [4+2] cyclo-

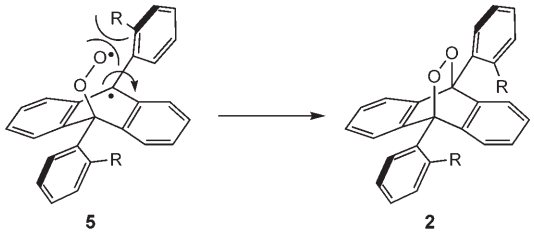



| | R | |
|---|---|---|
| *cis*-**1b** | Me | 85% |
| *trans*-**1b** | Me | 49% |
| *cis*-**1c** | Et | 54% |
| *trans*-**1c** | Et | 27% |
| *cis*-**1d** | *i*Pr | 24% |
| *trans*-**1d** | *i*Pr | 10% |
| *cis*-**1e** | OMe | 80% |
| *trans*-**1e** | OMe | 61% |
| *trans/cis*-**1f** | F | 93% |

***Scheme 3.*** Photooxygenations of **1**.

addition; only the sterically more demanding anthracenes **1c** and **1d** afforded oxidation by-products.[13] Additionally, the reactions could be followed easily by optical readout, since the products are nonfluorescent in contrast to the anthracenes **1**. Finally, the endoperoxides **2b**, **2e**, and **2f** were isolated in good to high yields and in analytically pure form by column chromatography.[13]

Interestingly, the peroxides **2** are formed exclusively as *cis* isomers, irrespective of the *cis* or *trans* configuration of the starting materials **1**, which is confirmed by NMR studies and X-ray analysis.[13] Thus, the *trans* isomers undergo a selective 180° rotation around the C–C single bonds during oxidation at −20 °C, whereas anthracenes **1b–e** are thermally stable up to 250 °C. The mechanism of the photooxygenation of acenes is still a matter of debate, but very recent theoretical studies indicate a radical pathway.[14] This would explain the observed rotation resulting from steric (R = Me, Et, *i*Pr, **1b–d**) and electrostatic (R = OMe, F, **1e**,**f**) repulsions between the incoming oxygen and the substituents R in the reactive radical intermediate **5** (Scheme 4). The activation energies on




***Scheme 4.*** Radical intermediates **5** and rotation to endoperoxides **2**.

the pathway to such radicals exceed 120 kJ mol$^{-1}$, [14] energies higher than the rotation barriers of anthracenes **1**. Thus, singlet oxygen functions not only as the fuel for the 180° rotation but also as the brake for the molecular switch,[15] since the products **2** cannot rotate back to the *trans* isomers.

To exclude a rotation by a photochemical process in the excited state of the anthracenes, $^1O_2$ was generated from sodium molybdate and hydrogen peroxide in the dark. Again, the endoperoxides **2** are formed exclusively as *cis* isomers, and thus the hindered axial rotation is powered by a chemical oxidation and not by light. Therefore, the anthracenes **1** are fueled by $^1O_2$, and our system is well adapted for a simple molecular switch flipped by oxygen.

The next station of the rotor was easily attained by thermolysis of the endoperoxides **2** at 110 °C (Figure 1). This reaction afforded the anthracenes **1** in quantitative yield, and the products were isolated in analytically pure form without further purification.[13] We distinguished the two stations of

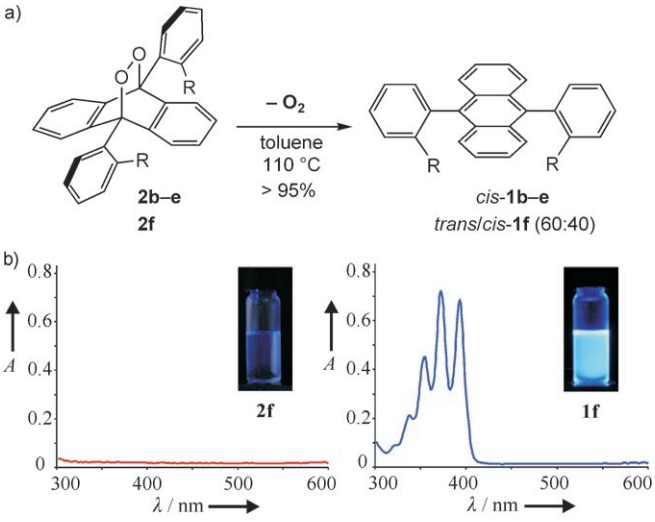


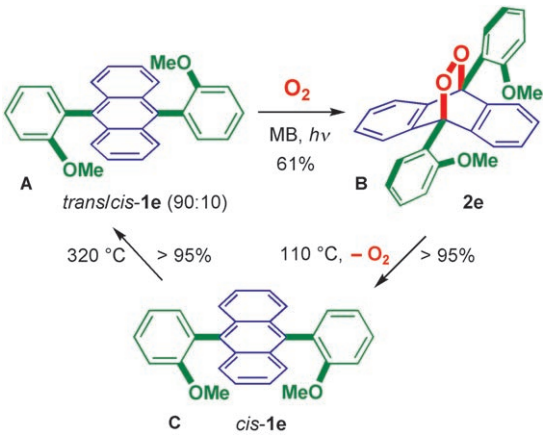

***Figure 1.*** a) Thermolysis of the 9,10-endoperoxides **2** and b) UV/Vis spectra of **2f** and **1f** in solution ($CHCl_3$) along with photographs (insets).

the rotor easily by optical readout, owing to the characteristic fluorescence of the anthracenes **1** in contrast to the non-fluorescent endoperoxides **2** (Figure 1). Furthermore, molecular oxygen is the only waste product, and thus the thermolysis represents the back reaction of the photooxygenation.

To complete the switching process and to set up the final molecular device for repetitive cycles, we chose the methoxy derivative *trans*-**1e**, since of the relevant *trans* isomers it provides the best yield in the reaction with $^1O_2$. Indeed, heating anthracene *cis*-**1e** to 320 °C forces the rotation around the C–C single bond resulting in the thermodynamically more stable *trans* isomer because of steric and electrostatic repulsions. After 10 min the *trans*/*cis* ratio was 90:10, and the anthracene **1e** was re-isolated quantitatively without decomposition.

The complete cycle of the molecular switch is characterized by three stations (Scheme 5). Starting from the anthracene *trans*-**1e** (station A), reaction with $^1O_2$ in the key step yields the endoperoxide **2e** (station B). Cycloreversion by thermolysis affords selectively the *cis* isomer **1e** in quantitative yield (station C). During the first two steps, the rotor (green) undergoes a selective 180° rotation around the stator (blue), with oxygen as the only waste product. Finally, heating to 320 °C returns the molecular switch to its initial state with high yield and high *trans* selectivity (station A), and thus repetitive switching is possible.




***Scheme 5.*** Three stations of the molecular switch **1e** with stator (blue) and rotor (green).

In summary, we set up molecular rotary switches, which can be flipped by molecular oxygen in its singlet state and by thermal energy. The stator and rotor are easily connected in only one step from commercially available starting materials. High energetic barriers for the rotations of the aryl substituents around the C–C single bonds of the anthracenes were found, which were overcome during the oxidation with singlet oxygen. The rotation of the switch proceeds with good yields, and the different stations can be conveniently observed by UV spectroscopy. Finally, a full switching process requires only three succinct reaction steps, and oxygen is formed as the sole waste product, making our molecular switch environmentally friendly.

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