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An Electrochemically Controllable Nanomechanical Molecular System Utilizing Edge-to-Face and Face-to-Face Aromatic Interactions

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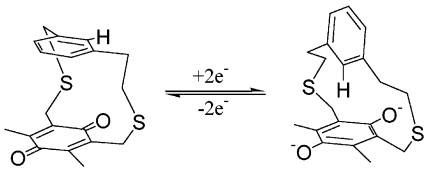
ABSTRACT



A new molecular system, 2,11-dithio[4,4]metametaquinocyclophane containing a quinone moiety, was designed and synthesized. As the quinone moiety can readily be converted into an aromatic π-system (hydroquinone) upon reduction, the nanomechanical molecular cyclophane system exhibits a large flapping motion like a molecular flipper from the electrochemical redox process. The conformational changes upon reduction and oxidation are caused by changes of nonbonding interaction forces (devoid of bond formation/breaking) from the edge-to-face to face-to-face aromatic interactions and vice versa, respectively.

A great deal of interest has recently been evinced in the development of molecular scale analogues of mechanical devices (molecular machines) such as rotors, shuttles, turnstiles, ratchets, tweezers, switches, and memory devices, in anticipation of their potential applications as mechanical and electronic nanodevices.[1] In particular, various switching modes changing molecular shapes have been investigated.[2] It would be particularly useful if the switching mode could be controlled. Thus, we have investigated a novel nanomechanical molecular flipper-like system wherein the conformational change can be triggered electrochemically.

In the recent past, the design and development of novel molecular entities (ionophores, nanodevices) using π-electron containing systems has been an active research topic.[3−6] One of the interesting insights obtained therein was that subtle changes in the π-electron densities could significantly influence both the nature and the magnitude of the resulting intermolecular interactions. Therefore, a way to control the π-electron density would yield novel molecular systems with

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unusual characteristics. In this connection, derivatives of the quinones, whose electronic characteristics can be electrochemically or photochemically controlled, have recently been used to fabricate nanostructures.[7]

Given the current interest in fabricating novel nanomechanical systems, we have designed a new molecular system, 2,11-dithio[4,4]metametaquinocyclophane **1** containing a quinone moiety (Figure 1). The lower part of the

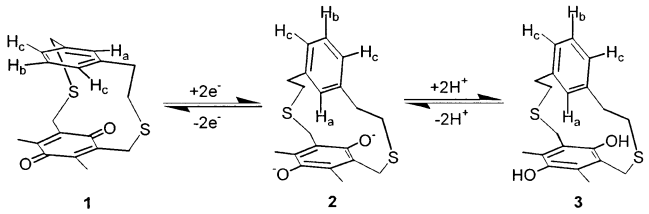

Figure 1. Schematic view of the conformational change of the upper benzene ring in the normal state **1**, the dianionic state **2**, and the reduced state **3**. The reaction between **1** and **2** that is composed of two single electron redox steps (through $\mathbf{1}^{-\bullet}$) by electrochemical process is fast, whereas that between **2** and **3** is very slow.

quinocyclophane **1** has a *p*-benzoquinone moiety, which is an electrochemically active species and has large electron affinity (~40 kcal/mol) from highly enhanced aromatic π-conjugation upon accepting two electrons. Thus, **1** can readily change to the dianionic state **2** as an extremely fast process involving electron transfer. In the presence of solvents containing H^+ sources, the dianionic species changes into hydroquinone, and thus **2** can be converted into 2,11-dithio[4,4]metametahydroquinocyclophane **3**, as a slow process involving proton exchange. All these reactions are reversible or pseudoreversible.

An interesting point of this system is that the structural changes of edge-to-face (T-shaped) and face-to-face (stacked) orientations can be electrochemically controlled, and hence the reversible process of conformational characteristics of the quinocyclophane system can yield a controllable nanomechanical device.

In an effort to investigate the possible utility of conformational characteristics, we have studied the interaction energies between *p*-benzoquinone and benzene using ab initio calculations.[8] In the neutral state of the benzoquinone−benzene pair (simulating **1**), the stacked conformer is 5 kcal/mol more stable than the T-shaped one. On the other hand, in the dianionic state of the *p*-benzoquinone−benzene pair (simulating **2**), the T-shaped conformer is 6 kcal/mol more stable than the stacked one, because of (i) the enhanced charge−charge electrostatic interaction between the positively charged H atom of the benzene and the negatively charged quinone dianion moiety in the T-shaped conformer and (ii) the strong π-H interaction between the large π-electron density of the dianionic quinone moiety and the edge H atom of the benzene. These interaction energies are indeed reflected in the conformational energy study of cyclophanes **1** and **2**. The stacked conformer of **1** is 7 kcal/mol more stable than the T-shaped one, whereas the T-shaped conformer of **2** is 9 kcal/mol more stable than the stacked one, indicating that the conformational energy change caused by the side linkers between benzene and quinone/hydroquinone in the cyclophane system is not large. The predicted structures of **1** and **2** (Figure 2) are shown in comparison

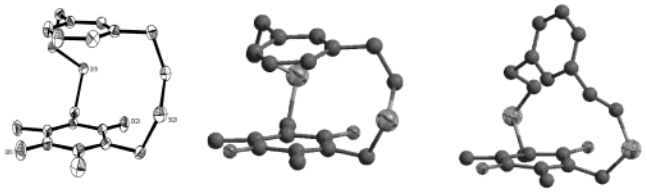

Figure 2. X-ray crystal structure of **1** (left) and ab initio (MP2/6-31G*) structures of **1** (middle) and **2** (right).

with the X-ray structure of **1** (to be discussed below). After a time, in the case of the interaction energy between *p*-hydroquinone and benzene (simulating **3**), both T-shaped and stacked conformations are similar in energy. However, the T-shaped conformation is slightly more favored (by ~1 kcal/mol) at a more accurate ab initio level.[9] Therefore, the

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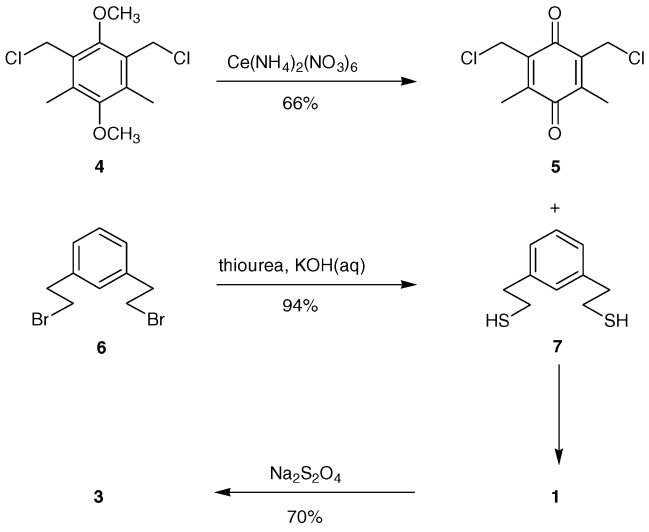
(8) MP2/6-31+G* calculations for the *p*-benzoquinone−benzene and the *p*-benzoquinone dianion−benzene pairs, and MP2/6-31G* calculations for the cyclophane systems using the Gaussian 98 suite of programs (Frisch. M. J.; Trucks, G. W.; Schlegel, H. B.; Scuseria, G. E.; Robb, M. A.; Cheeseman, J. R.; Zarkzewski, V. G.; Montgomery, J. A., Jr.; Stratmann, R. E.; Burant, J. C.; Dapprich, S.; Millam, J. M.; Daniels, A. D.; Kudin, K. N.; Strain, M. C.; Farkas, O.; Tomasi, J.; Barone, V.; Cossi, M.; Cammi, R.; Mennucci, B.; Pomelli, C.; Adamo, C.; Clifford, S.; Ochterski, J.; Petersson, G. A.; Ayala, P. Y.; Cui, Q.; Morokuma, K.; Malick, D. K.; Rabuck, A. D.; Raghavachari, K.; Foresman, J. B.; Cioslowski, J.; Ortiz, J. V.; Stefanov, B. B.; Liu, G.; Liashenko, A.; Piskorz, P.; Komaromi, I.; Gomperts, R.; Martin, R. L.; Fox, D. J.; Keith, T.; Al-Laham, M. A.; Peng, C. Y.; Nanayakkara, A.; Gonzalez, C.; Challacombe, M.; Gill, P. M. W.; Johnson, B. G.; Chen, W.; Wong, M. W.; Andres, J. L.; Head-Gordon, M.; Replogle, E. S.; Pople, J. A. *Gaussian 98*; Gaussian Inc.: Pittsburgh, PA, 1998).

stacked conformer of **1** and the T-shaped conformer of **2** are highly stable, while in the case of **3**, the T-shaped conformer is slightly favored.

To verify these predictions, we have synthesized **1** and **3** (Scheme 1). The X-ray crystal structure of **1** confirms the

Scheme 1



enhanced stability for the stacked conformer in agreement with the calculated structure (Figure 2).[10] In the case of **3**, it is slowly transformed into **1** in a day, and so it was not possible to obtain single crystals of **3** (even in the absence of oxygen gas to hinder oxidation).[11] However, since Gelmann and co-workers[4] showed that the X-ray structure of the 2,11-dithio[4,4]metametacyclophane is the T-shaped conformer, **3** is likely to have the T-shaped conformation in consideration of the similarity in aromaticity between benzene and hydroquinone.[12,13]

Corroborative evidence of such conformational change between **1** and **3** is further provided by NMR spectra (Figure 3). The chemical shifts for H_a of **1** and **3** are 7.09 and 6.57 ppm, respectively. The high upfield shift for H_a of **3** reveals that **3** has the T-shaped conformation, in which H_a is shielded

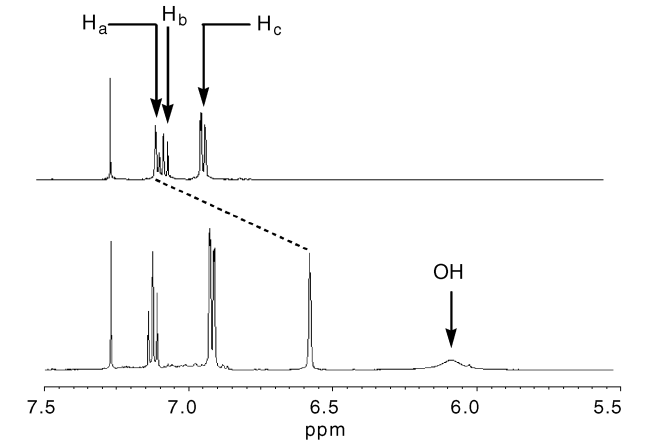


Figure 3. ^{1}H NMR spectra of **1** (top) and **3** (bottom) in $CDCl_3$.

by the anisotropic ring current of the hydroquinone ring. This is in agreement with ab initio calculations for which the T-shaped conformation for the benzene−*p*-hydroquinone pair is slightly favored over the stacked one as previously mentioned. It was not possible to study the conformation of **2** by direct experimental measurement,[14] because **2** is a very short-lived transient species. However, it is unambiguous that **2** should have the T-shaped structure not only because **3** favors the T-shaped conformation but also because the T-shaped conformer of **2** shows very high stability in ab initio calculations.[15]

The cyclic voltammogram of **1** shows two clear reversible redox reactions between **1** and **2** (Figure 4). It has been known that two reduction peaks for the quinone represent two single-electron reductions, resulting in the formation of quinone dianion. Typically, in aprotic media, quinones show two reduced states separated by about 0.7 V, which correspond to the formation of a radical anion species and a dianion species of quinones, respectively.[16] This is in agreement with the reduction charcteristics of **1**. Two well-separated reduced states of **1** (**1**$^{-\bullet}$ and **2**) are formed in the aprotic solvent of acetonitrile upon reduction.[17] Therefore, the electronic states of **1** and **2** (through **1**$^{-\bullet}$) can be easily transformed into each other by simple electrochemical control of the redox reaction, which results in large conformational flapping motions due to a preference for the stable conformation caused by the change in the electronic state of the quinone moiety.

(9) MP2/6-311++G** calculations with MP2/6-31G* zero-point energy correction for the benzene−hydroquinone pair.

(10) Crystal data for the structure of **1** have been deposited in the Cambridge Crystallographic Data Center as supplementary publication no. CCDC-177472. Crystal data of **1**: monoclinic, space group $P2_1/c$ with a = 16.7998(8) Å, b = 7.3924(4) Å, c = 14.2021(7) Å, and $\alpha = \gamma = 90°$, β = 91.3370(10)° for empirical formula $C_{20}H_{22}O_2S_2$; V = 1763.29(15) Å^3, Z = 4, T = 223(2) K. ρ_{calcd} = 1.350 g cm^{-3}, $2\theta_{max}$ = 48.34°. Final full-matrix least-squares refinement of F^2 with all 2796 independent reflections and 217 variables converged to $R1$ ($I > 2\sigma(I)$) = 0.0389, $wR2$ (all data) = 0.1041, and GOF = 1.604.

(11) The transformation of **3** into **1** with the lapse of time was confirmed by the UV spectra as well as the NMR spectra (see Supporting Information).

(12) The aromatic−aromatic interactions between the stacked benzene−benzene pair and the stacked benzene−hydroquinone pair are almost the same (~2 kcal/mol) according to ab initio calculations as well as chemistry insights.

(13) To confirm the conformation of **3**, we synthesized 2,11-dithio[4,4]-metametahydroquinocylophane dimethyl ether **8**. The X-ray structure of compound **8** showed that it has a T-shaped conformation (see the Supporting Information).

(14) We tried to analyze the conformation of **2** in basic condition containing an aqueous NaOD solution by using the NMR spectroscopy, but it was not possible due to the instability of **2** in this condition.

(15) In comparison with **3**, **2** has additional electrostatic energy between the quinone dianion and the positively charged H atom in the benzene in favor of the T-shaped conformer. In addition, the T-shaped energy is 9 kcal/mol lower than the stacked one in ab initio calculations (the difference of 9 kcal/mol is much larger than the possible error tolerance of a few kcal/mol).

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(17) We tried to obtain a protonated species, **3**, in the presence of the acidic additive, upon electrochemical reduction of **1**. However, it resulted in the breakage of thioether linkages.

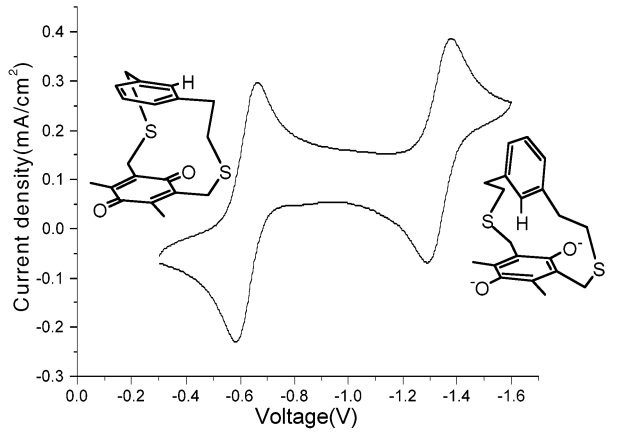

Figure 4. Cyclic voltammogram of **1** (1 mM) and TBAP (0.1 M) in CH_3CN at 25 °C (scan rate 100 mV/s).

In summary, we have designed a novel nanomechanical molecular cyclophane system composed of quinone and benzene rings that exhibits a flapping motion from the electrochemical redox process. It shows the potential availability of utilizing the differences in nonbonding interaction forces (devoid of bond formation/breaking) to yield a nanomechanical device. The large flapping/flipping motion from the T-shaped and stacked conformation and vice versa could be applied to design molecular hinges, molecular switches, and memory devices as well as mobile nanomechanical devices as a first step toward a propelling molecular vessel or a molecular flipper[18] that can be controlled by an electrochemical process.

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Supporting Information Available: Experimental procedures and characterizations of compound **1**, **3**−**5**, and **7**; X-ray structural information on **1**; UV spectra of **1** and **3**; X-ray crystal structure of **8**. This material is available free of charge via the Internet at http://pubs.acs.org.

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(18) According to the molecular motional analysis based on our calculations, the present quinocyclophane system can play the role of molecular flipper in solvents by the high-frequency alternating current applied to the cyclic voltammogram. That is, the system can be utilized as a nanomechanical device in solvents. In the case of **1**, no solvent molecules exist in a reasonably large space between benzene and quinone rings because of the presence of rich electron clouds which repel the electron clouds of solvent molecules. On the other hand, in the case of **2**, solvent molecules surround the benzene ring moiety. Upon reduction, **1** changes to **2**. During this conformational change, the benzene ring moves closer to the quinone ring without much disturbing solvent molecules. On the other hand, upon oxidation, **2** changes to **1**. For this conformational change, the solvent molecules surrounding the benzene ring are squeezed out from the space between the benzene and quinone rings as these rings stack to each other. This results in a strong thrusting force toward the backward direction. This would let the molecular system move backward by the external alternating electric current. Though the moving distance would be limited to a short distance for the present system, the system could be considered as a preliminary version for the precursor of molecular flipper/vessel.