Photoswitches

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Modulating the Lewis Acidity of Boron Using a Photoswitch**

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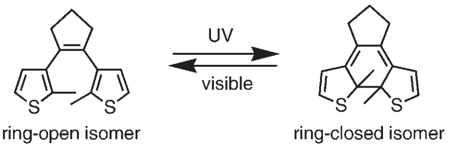
Tricoordinate organoboron compounds are versatile Lewis acids used as catalysts or reagents for important organic transformations,[1] and commercially as co-catalysts in metallocene-mediated olefin polymerization[2] and as catalytic curing agents for epoxy resins.[3] The Lewis acidity of boron also imparts unique properties to new π-electronic materials for use in sensing, electron-transport and other materials science applications.[4] Integrating an external stimulus to regulate the Lewis acidity in boron-containing compounds offers a means to control chemical processes that are catalyzed by these versatile chemical species and modulate the behavior of functional materials containing them. This integration is the focus of the studies described herein.

Light is a particularly effective stimulus to spatially and temporally trigger changes in structure and function of molecules and materials. This can be achieved reversibly by inducing the reactions of photochromic compounds between their two isomers, each of which have unique steric and electronic properties.[5] Photoresponsive dithienylcyclopentenes (DTCPs) are especially appealing systems because they tend to undergo thermally irreversible ring-closing and ring-opening reactions when irradiated with UV and visible light, respectively, often with a high degree of fatigue resistance (Scheme 1).[6] There are a few examples describing how the electronic and geometric changes that accompany the photoreactions of DTCP can be used to regulate chemical reactivity and catalysis.[7] However, these compounds exhibit only small observable effects on the rate of catalysis,[7d–e] and in some cases, the presence of the reactive substrate significantly reduces the photoactivity of DTCP.[7a–c] We have demonstrated that more dramatic changes in how each of the photoisomers behave in chemical reactions can be achieved by taking advantage of the photoinduced rearrangement of the "pi" bond in the central 5-membered ring of the DTCP.[8] In a well-designed system, the electronic changes localized within the central cyclopentene ring are more significant than the often too subtle electronic and steric differences between the thiophene heterocycles in the ring-open and ring-closed DTCP isomers. This report describes one such example.



Scheme 1. Reversible photocyclization reaction of a DTCP.

The central 5-membered ring in compound **1a** is a 1,3,2-dioxaborole system in which the Lewis acidity of the boron atom can be significantly and reversibly modulated using two different wavelengths of light.[9] The 1,3,2-dioxaborole in this ring-open isomer is a planar, conjugated system of overlapping p orbitals containing $4n+2$ π electrons. It is therefore expected to have significant aromatic character[10] and a low Lewis acidity due to the p orbital of the boron atom being partially occupied by the delocalized π electrons. Irradiation with UV light triggers the cyclization of isomer **1a** to generate **1b**. Now the borate group is cross-conjugated with the linearly conjugated π backbone of the rest of the molecule. This rearrangement of π electrons should reduce the amount of electron density at the boron center and turn the Lewis acid "on". The system can be turned "off" again using visible light to reverse the cyclization reaction and regenerate the aromatic ring system.

Computational investigations performed on simplified versions of isomers **1a** and **1b** (the three phenyl rings have been removed in **1a′** and **1b′**) estimate that the ring-open form is considerably lower in energy than its ring-closed counterpart, with an energetic preference of 19.0 kcal mol^{-1}, calculated at the M06-2X/DZ(2d,p) level of theory. As anticipated, the molecular orbitals of **1a′** are part of a conjugated π-orbital system that includes delocalization within the dioxaborole ring. A comparison of the lowest unoccupied molecular orbitals shows there is orbital density on the boron atom only in isomer **1b′** (Figure 1), an initial indication that there should be a difference in the Lewis acid nature between the two isomers. Other calculated values support the prediction, including the ionization potentials for **1a′** and **1b′** (calculated to be 6.90 and 6.03 eV, respectively), the difference in charge distribution on the boron established with a variety of different analyses,[11] and calculations on the reduced forms of the two isomers, which show the energetic preference for the ring-open isomer over the ring-closed isomer drops to only a few kcal mol^{-1}.

Computational structures and properties of the ring-open and ring-closed isomers, **1a** and **1b**, are very similar to those

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Supporting information for this article is available on the WWW under http://www.angewandte.org or from the author.

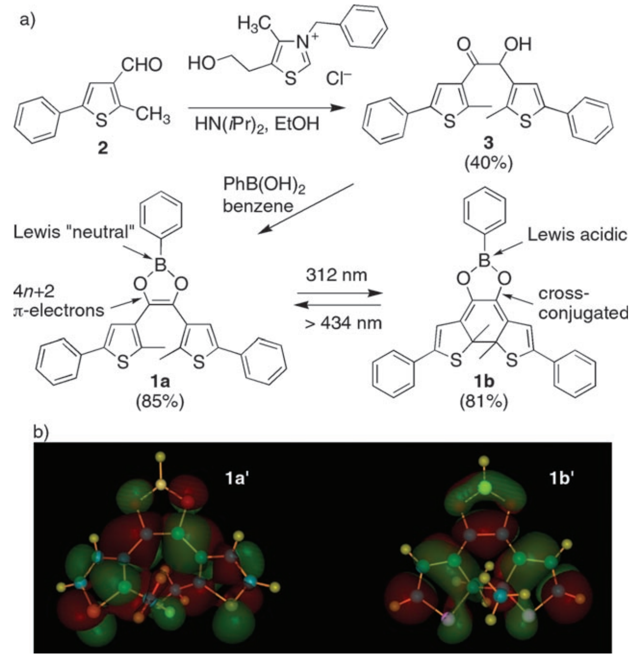

Figure 1. a) Synthesis and reversible ring closing of dithienylethene **1a**. The dioxaborole ring in the ring-open isomer, **1a**, is expected to have greater aromatic character than the ring in the ring-closed counterpart, **1b**. b) The calculated lowest unoccupied molecular orbitals of a simplified version of each isomer show that only **1b'** has orbital density on the boron atom.

already described for the simplified versions, with the former isomer being preferred over the latter by 18.0 kcal mol^{-1} at the M06-2X/DZ(2d,p) level of theory. The molecular orbitals and the charge distribution maps of **1a** and **1b** also show similar features to those of the simplified versions. The ionization potentials in **1a** and **1b** are slightly lower, at 5.95 and 4.72 eV, respectively. The reduced forms of compounds **1a** and **1b** bring the ring-closed isomer lower in energy than the ring-open form by approximately 5 kcal mol^{-1}.

Compound **1a** is prepared by condensing hydroxyketone **3** and phenylboronic acid as illustrated in Figure 1. A compound similar to **3** has been reported previously,[12] however, a new method was developed to improve the synthesis. When the known aldehyde **2**[13] is treated with 3-benzyl-5-(2-hydroxyethyl)-4-methylthiazolium chloride, the hydroxyketone **3** is produced. Although the product is only generated in relatively small amounts, the major compound isolated is the starting aldehyde, which can be resubjected to the reaction conditions. The result is a convenient way to prepare large amounts of compound **3**.

As is common with dioxaborole derivatives, solutions of **1a** are easily oxidized in air to yield the diketone version of **3** as the deborylation product.[10] In comparison, anhydrous and degassed solutions are highly stable. ^{11}B NMR spectroscopy of **1a** in [D$_6$]benzene shows a chemical shift of 31.4 ppm relative to BF_3OEt_2, a result that is in agreement with a planar tricoordinated boron center with a vacant p_z orbital.[14]

Irradiating a benzene solution (anhydrous and degassed) of compound **1a** with 312 nm light[15] triggers the photocyclization reaction and generates the ring-closed isomer **1b**.[16] The visual demonstration of this photoreaction is the change in color of the solution from colorless to purple due to the formation of the extended π-conjugated backbone created in the ring-closed isomer. The corresponding UV/Vis absorption spectra show trends typically observed for ring-closing reactions of dithienylethene derivatives (Figure 2a). The high-energy bands in the spectra become less intense as a broad band centered at 535 nm appears. At a concentration of 3.3×10^{-5} M (in [D$_6$]benzene), a photostationary state is reached within 12 seconds, containing 81 % of the ring-closed isomer as measured by ^{1}H NMR spectroscopy. The ring-closed isomer is stable at room temperature and the ring-opening reaction is only induced by irradiating the solution of **1b** with visible light (greater than 434 nm),[15] which regenerates the original UV/Vis spectrum corresponding to **1a**.

The first experimental evidence supporting the hypothesis set forth in the introduction of this report is provided by

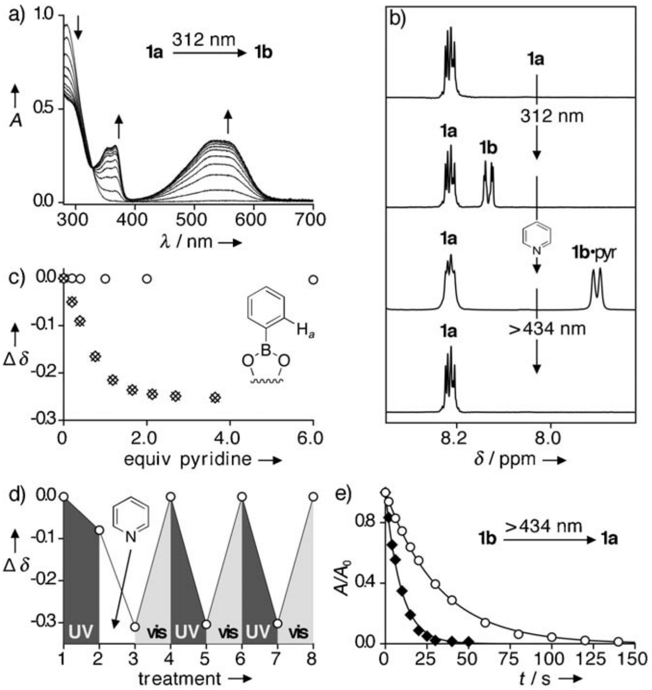

Figure 2. a) Changes in the UV/Vis absorption spectra of a benzene solution (3.3×10^{-5} M) of **1a** as it is irradiated with 312 nm light until the photostationary state is reached. b) ^{1}H NMR chemical shift corresponding to proton H_a before and after a [D$_6$]benzene solution (1.0×10^{-3} M) of **1a** is irradiated with 312 nm light (until a 1:1 mixture of **1a** and **1b** is reached), after pyridine (pyr) is added and after irradiation with > 434 nm light to regenerate **1a**. c) Change in the chemical shift of proton H_a in **1a** (○) and **1b** (◇) as [D$_6$]benzene solutions (1.0×10^{-3} M) are treated with pyridine. The calculated chemical shifts are also shown (×) for **1b**. d) Chemical shift when a similar solution of **1a** is irradiated with UV light, treated with pyridine and irradiated with alternating visible and UV light. UV (312 nm) irradiation periods are 10 min generating 40–45 % of **1b**. Visible (> 434 nm) irradiation periods are 5–7 min to regenerate 100 % of the ring-open isomer. e) Typical changes in the UV/Vis absorption spectra of a benzene solution (3.2×10^{-5} M) of **1b** as it is irradiated with > 434 nm light in the presence (○) and absence (◆) of pyridine, and their corresponding first order decay fit (solid lines) with $k = 0.031$ and 0.11 s^{-1}, respectively.[11]

comparing the peaks observed in the ^{1}H NMR spectra corresponding to the phenyl-ring protons directly adjacent to the boron atom (H_a in Figure 2) in isomers **1a** and **1b**. The upfield shift (≈0.1 ppm) observed for these peaks as ring-closing is induced (Figure 2b) is in agreement with the loss in aromatic character of the dioxaborole unit as **1a** is converted to **1b**. This shift can be expected for protons that were originally lying within the combined deshielding regions of two ring systems having aromatic character (the benzene and the dioxaborole in **1a**) but now feel the effect of only one (the benzene in **1b**).

The relative Lewis acidity of the ring-open and ring-closed photoisomers **1a** and **1b** can be evaluated by measuring their respective binding affinities to a Lewis base such as pyridine. Figure 2b and c show the changes in the peaks in the ^{1}H NMR spectra corresponding to protons H_a as [D$_6$]benzene solutions of each photoisomer are treated with pyridine.[17] There are minimal recordable spectral changes in the case of ring-open **1a** even after 10 equivalents of pyridine are added to the solution. On the other hand, the peaks for the ring-closed isomer are significantly affected by the presence of pyridine and shift by more than 0.2 ppm upfield from their original positions. The changes in chemical shift for **1b** can be fit to a 1:1 binding model giving an association constant of $(7.0 \pm 0.4) \times 10^{3}\,\text{M}^{-1}$.[11] Because of the small changes in chemical shift in the case of **1a**, an association constant could not be reliably estimated for this isomer. It can be assumed to be very small. Computational predictions for the addition of pyridine to the ring-open and ring-closed isomers support these results, with $\Delta E_{\text{rxn}} = 0.6$ and $6.32\ \text{kcal mol}^{-1}$ for **1a** and **1b**, respectively.

Compound **1** retains its photochromic activity in presence of pyridine and shows selective, light-induced Lewis acid–base reactivity. When a mixture of **1a**, **1b** and approximately 1.1 molar equivalents of pyridine (relative to **1b**) in [D$_6$]benzene is irradiated with visible light (greater than 434 nm) to induce complete ring-opening, the peaks in the ^{1}H NMR spectrum corresponding to hydrogen H_a in the complex **1b**·pyridine shift from 7.91 back to 8.22 ppm, which corresponds to the ring-open isomer, illustrating the release of the pyridine from the complex. As shown in Figure 2d, alternatively irradiating the same solution with UV and visible light toggles the system between **1b**·pyridine and **1a** + pyridine.

Although compound **1** retains its photochromic activity in the presence of pyridine, the absorption maximum of the ring-closed isomer **1b** in benzene is blue-shifted by 10 nm by the addition of 5 equivalents of pyridine.[11] Moreover, the rate constant for the ring-opening reaction in the presence and absence of pyridine was evaluated to be $(0.029 \pm 0.006)\ \text{s}^{-1}$ and $(0.13 \pm 0.02)\ \text{s}^{-1}$, respectively (Figure 2e), showing that the photochemical reaction is approximately 4 times slower in the presence of the Lewis base. We attribute this rate difference to the fact that regenerating the aromatic character in the dioxaborole contributes to the driving force for the ring-opening reaction. When isomer **1b** is bound to pyridine, the boron center adopts a tetrahedral geometry minimizing the extent to which regenerating the aromatic stabilization can contribute (the dioxaborole group must become planar to enhance aromaticity). In the absence of pyridine, **1b** can adopt a planar geometry. Similar kinetics and hypsochromic shifts are observed when pyridine is used as the solvent, supporting the conclusion that the photochemistry is not significantly hindered in the **1b**·pyridine complex.

In summary, we have demonstrated that the Lewis acidity of a boron atom integrated into a photochromic backbone can be modulated using light of the appropriate wavelength. This ability to regulate the Lewis acidity could enable the control of chemical processes requiring a Lewis acid as an activator, reagent, or catalyst, a possibility that we are currently investigating.

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[1] K. Ishihara, H. Yamamoto, *Eur. J. Org. Chem.* **1999**, 527–538.
[2] E. Y.-X. Chen, T. J. Marks, *Chem. Rev.* **2000**, *100*, 1391–1434.
[3] G. L. Jialanella, T. Ristoski, US Patent 7,247,596, July 24, **2007**, and references therein.
[4] S. Yamaguchi, A. Wakamiya, *Pure Appl. Chem.* **2006**, *78*, 1413–1424.
[5] a) *Molecular Switches* (Ed.: B. L. Feringa), Wiley-VCH, Weinheim, **2001**; b) *Photochromism Molecules and Systems* (Eds.: H. Dürr, H. Bouas-Laurent), Elsevier, Amsterdam, **2003**; c) *Organic Photochromic and Thermochromic Compounds* (Eds.: J. C. Crano, R. J. Guglielmetti), Plenum, New York, **1999**.
[6] a) Special issue on photochromism: M. Irie, *Chem. Rev.* **2000**, *100*, 1685–1716; b) M. Irie in *Molecular Switches* (Ed.: B. L. Feringa), Wiley-VCH, Weinheim, **2001**, pp. 37–62; c) M. Irie in *Photochromic and Thermochromic Compounds, Vol. 1* (Eds.: J. C. Crano, R. J. Guglielmetti), Plenum, New York, **1999**, pp. 207–222; d) H. Tian, S. Yang, *Chem. Soc. Rev.* **2004**, *33*, 85–97; e) H. Tian, S. Wang, *Chem. Commun.* **2007**, 781–792.
[7] a) S. H. Kawai, S. L. Gilat, J.-M. Lehn, *Eur. J. Org. Chem.* **1999**, 2359–2366; b) Y. Odo, K. Matsuda, M. Irie, *Chem. Eur. J.* **2006**, *12*, 4283–4288; c) D. Sud, T. B. Norsten, N. R. Branda, *Angew. Chem.* **2005**, *117*, 2055–2057; *Angew. Chem. Int. Ed.* **2005**, *44*, 2019–2021; d) H. D. Samachetty, N. R. Branda, *Chem. Commun.* **2005**, 2840–2842; e) H. D. Samachetty, N. R. Branda, *Pure Appl. Chem.* **2006**, *78*, 2351–2359.
[8] a) V. Lemieux, N. R. Branda, *Org. Lett.* **2005**, *7*, 2969–2972; b) V. Lemieux, S. Gauthier, N. R. Branda, *Angew. Chem.* **2006**, *118*, 6974–6978; *Angew. Chem. Int. Ed.* **2006**, *45*, 6820–6824; c) D. Sud, T. J. Wigglesworth, N. R. Branda, *Angew. Chem.* **2007**, *119*, 8163–8165; *Angew. Chem. Int. Ed.* **2007**, *46*, 8017–8019.
[9] Although the photoswitching of the Lewis acidity of a catecholborane by an azobenzene that reversibly varied the number of coordinating ligands was recently demonstrated (N. Kano, J. Yoshino, T. Kawashima, *Org. Lett.* **2005**, *7*, 3909–3911), it is plagued by severe limitations such as slow photoisomerization (2 h to reach the photostationary state) and low conversion (only 51% of the photoisomeric product is formed). These limitations, as well as the thermal instability often observed for azobenzene derivatives, are not usually suffered by dithienylethene derivatives. Another limitation is based on the fact that the operation of the azobenzene system relies on changing the coordination number at the boron center using a photoresponsive ligand. This implies that if a Lewis base stronger than the azobenzene is present, it will displace the photoswitch.

[10] a) R. L. Letsinger, S. B. Hamilton, *J. Org. Chem.* **1960**, *25*, 592–595; b) G. Smolinsky, *J. Org. Chem.* **1961**, *26*, 4915–4917.

[11] See Supporting Information for details.

[12] S. N. Ivanov, B. V. Lichitskii, A. A. Dudinov, A. Y. Martynkin, M. M. Krayushkin, *Chem. Heterocycl. Compd.* **2001**, *37*, 85–90.

[13] J. P. Girault, P. Scribe, G. Dana, *Tetrahedron* **1973**, *29*, 413–418.

[14] R. G. Kidd in *NMR of Newly Accessible Nuclei*, *Vol. 2* (Ed.: P. Laszlo), Academic Press, New York, **1983**.

[15] All ring-closing reactions were carried out using the light source from a lamp used for visualizing TLC plates at 312 nm (Spectroline E series, 470 W cm^{-2}). The ring-opening reactions were carried out using the light of a 300 W halogen photo-optic source passed through a 434 nm cutoff filter to eliminate higher energy light.

[16] It was immediately observed that the ring-closed photoisomer **1b** is significantly more sensitive to oxidation than its ring-open counterpart. All irradiation studies were performed in anhydrous and oxygen-free atmosphere.

[17] A 1:1 mixture of **1a** and **1b** was used to monitor the changes in chemical shift for the ring-closed isomer. This mixture was obtained by irradiating a solution of **1a** with 312 nm light for 10 min.