



Synthesis and photochromic properties of a dithiazolyindole

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ABSTRACT

A novel photochromic 2,3-dithiazolyindole has been synthesized and its photochromic properties was elucidated. This compound showed reversible photochromism both in solution and in a crystal with no spontaneous bleaching under dark conditions. The photocyclization quantum yield of the dithiazolyindole was as high as 83% in hexane, suggesting the photoreactive conformation was stabilized through intramolecular interactions. X-ray crystal structure analysis revealed that the dithiazolyindole adopted the photoreactive conformation with quasi- C_2 symmetry around the hexatriene moiety in the crystalline state. This conformation was assisted by presumed intramolecular CH/N hydrogen bonding between the central *N*-methylindole and the side-chain thiazolyl units in combination with steric interactions between methyl groups at the reactive center carbons. The suggestion of intramolecular hydrogen bonding in solution was also supported by a ^1H NMR variable temperature study.

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1. Introduction

Photochromic molecules undergo a reversible color change, which originates from their structural change upon light irradiation [1–6]. Photochromic molecules can be employed to modulate various physicochemical properties upon light irradiation and they have received remarkable attention for their potential applications to various photoswitches and optical memory systems. Among the classes of photochromic compounds diarylethenes with heterocyclic aryl groups are the most interesting because of their specific properties such as high thermal stability of the colored state, fatigue resistance, and high photochromic reactivity even in solid state [7]. Diarylethenes are known to have several conformations because of the rotational isomerization around single bonds between the side aryl groups and the central ethene unit. Since the photocyclization reaction to the cyclohexadiene form proceeds only from the C_2 symmetrical conformation of hexatriene form, the photocyclization quantum yields of most diarylethenes have been reported to be about 50% or less [7a,b]. Therefore, the control of ground state geometry has been a subject of considerable interest in this field [8]. Recently, photochromic triangular terarylenes have been reported to show similar photochromic reactions to those of diarylethenes [9,10]. Unlike the diarylethenes, terarylenes and related molecules can be designed to have various types of

intramolecular interactions between the central and both of the side aryl units and some of these systems exhibited considerably high photocyclization quantum yields [11]. In the present study, we report on a highly reactive photochromic terarylene molecule exhibiting a photocyclization quantum yield as high as 83%, and its ground state conformation is efficiently stabilized in the photoreactive quasi- C_2 symmetric conformation around the hexatriene moiety by intramolecular H-bonding and steric interactions.

2. Material and methods

2.1. Methods

^1H NMR spectra were recorded on a JEOL AL-300 spectrometer (300 MHz). Separative HPLC was performed on a HITACHI LaChrom ELITE HPLC system and a JASCO LC-2000 Plus system. Mass spectra were measured with a mass spectrometer JEOL JMS-T100LC AccuTOF. Absorption spectra in solution were studied with JASCO V-550 and V-670 spectrophotometers with a temperature control unit. Photoirradiation was carried out using an USHIO 500 W ultra-high-pressure mercury lamp. Monochromatic light was obtained by passing the light through a monochromator (Shimadzu SPG-120S, 120 mm, $f = 3.5$). Absorption spectra in the single-crystalline phase were measured using an Olympus BX-51 polarizing microscope connected with a Hamamatsu PMA-11 photodetector with an optical fiber. Polarizer and analyzer were set in parallel to each other. X-ray crystallographic analyses were carried out with a Rigaku R-Axis RAPID/s Imaging Plate diffractometer with Mo $K\alpha$ radiation at 296 K.

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2.2. Experimental

2,3-Dithiazolyindole **1a** was synthesized according to Scheme 1.

2.2.1. Synthesis of 3-bromo-2-iodo-1-methyl-1H-indole (**3**)

To a solution of 3-bromo-2-iodo-1-(phenylsulfonyl)-1H-indole [12] (**2**, 1.0 g, 2.2 mmol) in DMF (8 mL) was added NaH (2.0 g, 50.0 mmol) at 0 °C under argon, and the reaction mixture was stirred at room temperature for 0.5 h. Methyl iodide (0.4 mL, 6.3 mmol) was then added to the stirred reaction mixture, and the mixture was stirred at room temperature for 15 h. Water was added to the resulting reaction mixture, and the water phase was extracted with Et₂O. The combined organic phase was dried with anhydrous magnesium sulfate, filtered, and concentrated. Silica gel column chromatography (hexane/ethyl acetate 10:1) afforded compound **3** (0.53 g, 1.6 mmol, 73%) as an off-white solid.

¹H NMR (300 MHz, CDCl₃): δ 7.53–7.50 (dd, 1H), 7.33–7.30 (d, 1H), 7.23–7.10 (m, 2H), 3.82 (s, 3H); mp 56–58 °C.

2.2.2. Synthesis of 2,3-bis(5-methyl-2-phenylthiazol-4-yl)-1-methyl-1H-indole (**1a**)

A mixture of **3** (0.14 g, 0.4 mmol), 5-methyl-2-phenyl-4-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl) thiazole (**4**, 0.29 g, 1.0 mmol), Pd(OAc)₂ (9 mg, 0.04 mmol), tri(o-tolyl)phosphine (24 mg, 0.08 mmol), and K₂CO₃ (0.67 g, 4.8 mmol) in a 100-mL four-necked flask was flushed with nitrogen for 10 min. A solution of DMF (25 mL) was added using a syringe and the mixture was heated at 100 °C for 15 h under nitrogen. The cooled reaction mixture was extracted with ether and the organic layer was dried with anhydrous magnesium sulfate, filtered, and concentrated. Silica gel column chromatography (hexane/ethyl acetate 9:1) and normal phase HPLC (hexane/ethyl acetate 49:1) afforded compound **1a** (6 mg, 0.013 mmol, 3%) as a white solid.

¹H NMR (300 MHz, CD₂Cl₂): δ 8.00–7.97 (d, *J* = 7.5 Hz, 2H), 7.96–7.93 (d, *J* = 7.5 Hz, 2H), 7.79–7.76 (d, *J* = 7.8 Hz, 1H), 7.49–7.41 (m, 7H), 7.36–7.31 (t, *J* = 7.8 Hz, 1H), 7.21–7.15 (t, *J* = 7.8 Hz, 1H), 3.85 (s, 3H), 2.02 (s, 3H), 1.98 (s, 3H). ¹³C NMR (75 MHz, CDCl₃/TMS): δ 164.92, 164.11, 147.87, 144.30, 138.08, 135.01, 134.61, 134.15, 132.34, 130.31, 129.83, 129.52, 129.35, 129.22, 127.73, 126.62, 126.47, 124.14, 122.98, 121.13, 121.05, 120.34, 119.79, 110.91, 110.59, 109.91, 31.50, 12.216; dp 120 °C.

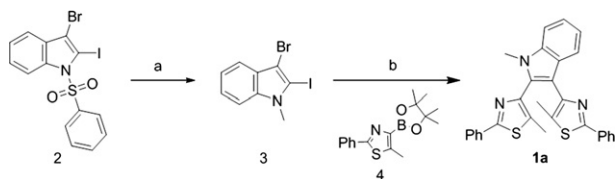
EI HRMS (*m/z*) [*M*]⁺ calcd. for C₂₉H₂₃N₃S₂ (*M*⁺): 477.1333; Found (*M*⁺): 477.1332.

1b: ¹H NMR (300 MHz, CD₂Cl₂): δ 7.97 (m, 4H), 7.62 (d, 1H), 7.45 (m, 6H), 7.23 (t, 1H), 7.12 (t, 1H), 3.88 (s, 3H), 2.61 (s, 6H).

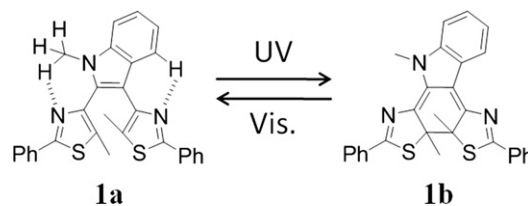
3. Results and discussion

3.1. Molecular design of new photochromic terarylene

2,3-Bis(2-phenyl-5-methylthiazol-3-yl)-1-methylindole, **1a** was designed as illustrated in Scheme 2, in which the photoreactive conformation is potentially stabilized by intramolecular hydrogen bonding between the central and the side aryl groups. In addition, the CH-π interactions between the methyl groups at the reactive carbon atoms and the aryl groups also seem to stabilize the



Scheme 1. Synthetic route for compound **1**.



Scheme 2. Photochromic reactions of terarylene **1**.

photoreactive conformation of C₂ symmetry around the hexatriene moiety. Similar conformational control with the intramolecular hydrogen bonding has been employed in foldamer chemistry [13]. Steric repulsion between methyl groups in the thiazole units and the 1-methylindole unit is also expected to contribute partly to the relative stabilization of the reactive conformation.

3.2. Photochromism

As shown in Fig. 1, **1a** exhibited an absorption band between 250 and 400 nm before irradiation, while a new absorption band appeared between 550 and 800 nm after the irradiation with UV light ($\lambda = 313$ nm).

Since isosbestic points were observed, this spectral change is attributed to the two-component photochromic reaction comparable to those observed in diarylethene and terarylene derivatives. A proposed reaction scheme is also presented in Scheme 2. The colored solution was bleached completely after visible light irradiation with light of a wavelength longer than 500 nm.

The colored ring-closed compound, **1b**, formed after the UV-light irradiation was isolated by normal-phase HPLC, which showed the same mass-number of **1a**. The chemical structure of **1b** was confirmed by ¹H NMR spectroscopy. The values of λ_{max} and ϵ of **1a** and **1b** are summarized in Table 1. After UV light irradiation for a long period (ca. 2 h), small amount of unknown by-products were observed in the HPLC chart and the isosbestic point in Fig. 1 showed slight shift indicating side-reactions. The conversion ratio from **1a** to **1b** at their quasi-stationary states achieved under the continuous irradiation with UV light ($\lambda = 313$ nm) was about 97%, which may include about 2–3% of a probable error. The cyclization quantum yield of **1a** in hexane was determined to be $\Phi_{\text{oc}} = 0.83$ using 4,5-bis(5-methyl-2-phenylthiazol-4-yl)-2-phenylthiazole as a reference compound [11a]. This value seems to be significantly high in comparison with previously reported values for diarylethenes and is similar to that of a compound recently reported by Yokoyama and coworkers [11c].

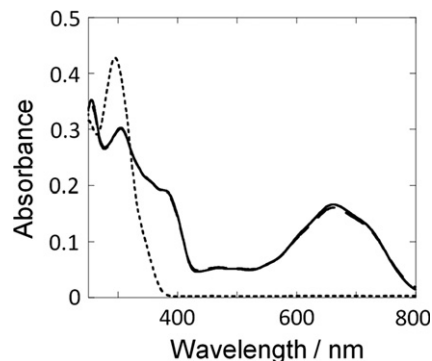


Fig. 1. Absorption spectral changes of **1** in hexane: open-form **a** (dotted line), closed-form **b** (solid line) and photostationary state under irradiation with 313 nm light (dashed line). The concentration of **1** was 1.3×10^{-5} M.

Table 1

Absorption maxima and coefficients of the open- and closed ring isomer of **1**, together with the quantum yield and the conversion ratios at photostationary states in hexane.

	1a	1b
λ_{max} [nm] (ϵ [$10^4 \text{ M}^{-1}\text{cm}^{-1}$])	295 (3.2)	661 (1.2)
Φ_{oc}	0.83	
Conversion[%]	97	

3.3. Crystal structure

A single crystal of **1a** was obtained by recrystallization from a solution in hexane and was characterized by X-ray crystallographic analysis. An ORTEP drawing of **1a** is presented in Fig. 2a [14]. Compound **1a** displays a conformation with the C_2 symmetry around the hexatriene moiety, which is favorable for the photocyclization reaction [7]. Compound **1a** also showed photochromic coloration in the crystalline state as shown in Fig. 2b. The distance between the reacting carbon atoms in **1a** was evaluated to be 0.350 nm, which is short enough for the photocyclization reaction regarding the characteristic structure–reactivity relationship reported by Kobatake et al. [15]. Meanwhile, the distances between N2–H7 and N3–H1 were estimated to be 0.257 and 0.265 nm, respectively. These values are substantially smaller than the sum of the *van der Waals* radii of (C–)H (0.12 nm) and N (0.155 nm) atoms [16]. These atomic contacts suggest a weak CH–N hydrogen bonding interaction between N2–H7 and N3–H1, which may be assumed to tether the photoreactive conformation of **1a** in the

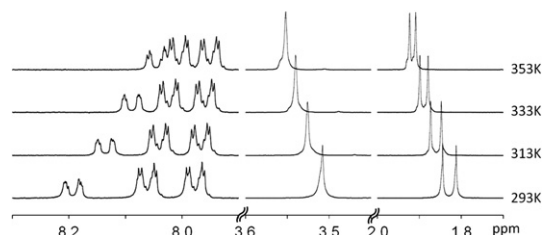


Fig. 3. Temperature dependence of ^1H NMR spectra of **1a** in $\text{C}_6\text{D}_5\text{CD}_3$.

crystalline phase and also in solution phase to some degree. The bond angle of H7–N2–C11 was approximated to be 122° and that of H1–N3–C21 was 133° , which also seem to be reasonable for the hydrogen bonding interactions.

3.4. Temperature dependent ^1H NMR

In order to evaluate conformation of **1a** in solution variable temperature ^1H NMR spectroscopy was employed and signals were assigned by comparing with those of a reference compound, 1-methylindole. In compound **1a**, as shown in Fig. 3, the signal for H1 (in Fig. 2a) of the central *N*-methylindole unit was observed at 8.21 ppm at 293 K. This chemical shift is far downfield compared to that of 1-methylindole (at 7.65 ppm). A similar notable downfield shift has been reported as a characteristic feature of the intramolecular CH–N hydrogen bonding for similar terarylenes [11d,17]. The chemical shift of the H1 of **1a** in the D_8 -toluene solution showed systematic high-field shift to 8.06 ppm upon heating to 353 K. At the higher temperature, the distance between (C–)H and N atoms and the twisting angle between the *N*-methylindole and the thiazole rings should become larger. The signals of the methyl protons at the thiazole units at 1.80–1.85 ppm also showed characteristic downfield shift by increasing temperature. This downfield shift also supported the change of conformation upon heating. These methyl groups, at 293 K, seems to be close to the thiazole ring of the opposite side because of the specific CH– π interaction, and the reverse ring-current effect is likely to promote the methyl signals at the higher field at 293 K. The CH– π interaction and the reverse ring-current effect seem to be weakened at the elevated temperature.

3.5. DFT calculation

A density functional theory (DFT) study at the B3LYP/6-31G* [18] level was also performed for evaluating a stable structure of **1a**. The optimized structure illustrated in Fig. 4 has C_2 -symmetric geometry around the central hexatriene moiety and the distance

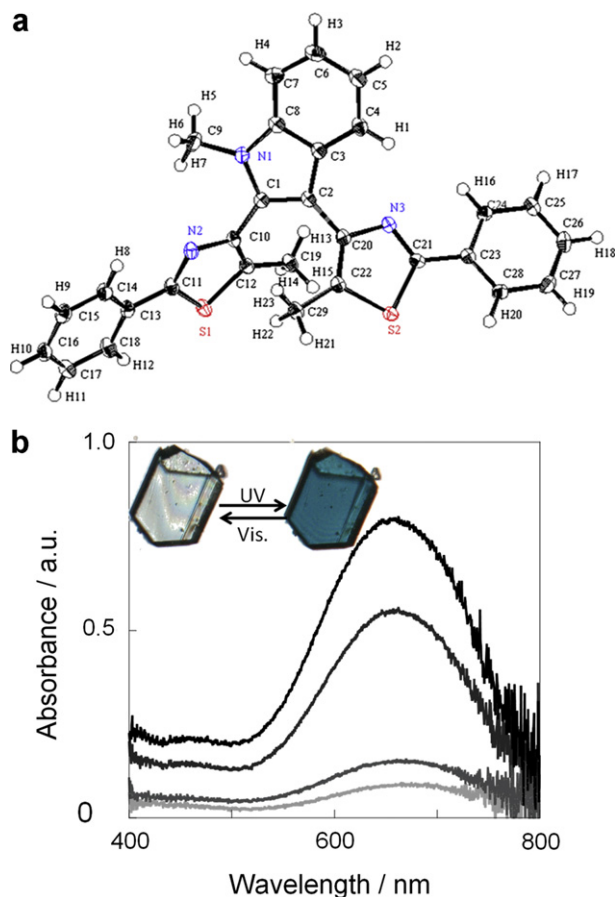


Fig. 2. (a) ORTEP drawing of open-ring isomer in crystal **1a**, showing 50% probability displacement ellipsoids. (b) Absorption spectral change of a single crystalline of **1a** under UV light irradiation on a microscope.

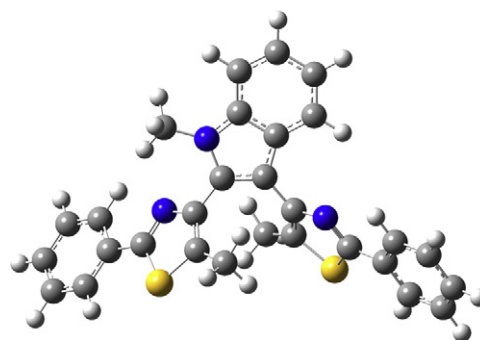


Fig. 4. Optimized structure of compound **1a** obtained by the DFT calculation at the B3LYP/6-31G* level.

between reactive carbon atoms was as close as 0.368 nm. This optimized structure approximately agrees with the X-ray analysis result and appears suitable for the photocyclization reaction. The close atomic contacts between N2–H7 (2.36 nm) and N3–H1 (2.83 nm) atoms were also reproduced in this DFT calculation, which suggests specific stabilization of the reactive conformation with these non-covalent interactions.

4. Conclusions

A new triangular terarylenes has been designed and synthesized that contains specific intramolecular interactions between the central and side units that facilitate the photochromic response. The photocyclization quantum yield of compound **1a** in hexane was as high as 0.83, which is close to that of one of the most sensitive photochromic compound so far reported. X-ray crystal structure analysis revealed that compound **1a** is in the photoreactive conformation with quasi- C_2 symmetry. Variable temperature ^1H NMR spectroscopy, crystal structure and DFT calculations suggest the possibility of weak intramolecular hydrogen bonding interactions in the new triangular terarylene.

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- [14] Crystallographic data for **1a**: $\text{C}_{28}\text{H}_{22}\text{N}_4\text{S}_2$, $a = 8.5818(9)$, $b = 15.2526(16)$, $c = 17.9298(18)$ Å, orthorhombic, space group $\text{P}2_12_12_1$, $Z = 4$, $V = 2346.9(4)$ Å³, $\rho_{\text{calcd.}} = 1.354$ g cm⁻³. Of 19188 reflections up to $2\theta = 50.7^\circ$, 4281 were independent ($R_{\text{int}} = 0.078$) and 3465 were with $I > 2\sigma(I)$. The structure was solved by direct methods and refined with a full matrix against all F^2 data. Hydrogen atoms were calculated in riding positions. $wR = 0.1061$, $R = 0.0469$. CCDC-796947 contains the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.
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