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# Structure-fluorescence relationship of push-pull 2-phenylbenzothiazole derivatives designed based on the firefly light-emitter

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#### ABSTRACT

6-Dimethylamino-2-phenylbenzothiazole (1a) mimicking the firefly oxyluciferin structure and the derivatives with an electron-withdrawing substituent on the phenyl group were prepared, and their fluorescence properties were investigated in various solvents. 1a showed solvatochromic fluorescence with good fluorescence quantum yields ( $\Phi_f > 0.8$ ). The introduction of an electronwithdrawing group led to a red-shift of the emission maximum. In particular, the derivatives with the 2,2-dicyanoethenyl and (1,3-dihydro-1,3-dioxo-2*H*-inden-2-ylidene)methyl groups showed near-infrared fluorescence in chloroform. In addition, it was found that the derivative with the phenylimine moiety showed efficient solid-state fluorescence, resulted from a molecular arrangement inhibiting intermolecular interactions for quenching the fluorescence state in crystals.

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Fireflies efficiently produce bioluminescent light with various colors from green to red.<sup>1</sup> The bioluminescence is caused by the enzymatic reaction of firefly luciferin with ATP and O2 to produce oxyluciferin (OLH) and light. The light emitting center of the reaction is the keto-phenolate anion of OLH (OL<sup>-</sup>) in the excited singlet  $(S_1)$  state (Scheme 1).<sup>2</sup> To confirm the reaction mechanism, the spectroscopic property of OL<sup>-</sup> were clarified based on that of the phenolate anion of 5,5-dimethyl OLH (Me<sub>2</sub>OLH, Scheme 1).<sup>3</sup> Because  $OL^{-}$  is a solvatochromic fluorophore with relatively high quantum yields, OL is an attractive prototype for designing new fluorophores. The characteristic fluorescence property of OL<sup>-</sup> is originated from the molecular structure consisted of the electron-donating and withdrawing moieties (Scheme 1). The significance of the electronically push-pull structure in OL<sup>-</sup> was supported by the property of 6'-dimethylamino spectroscopic analogue Me<sub>2</sub>NMe<sub>2</sub>OL (Scheme 1).<sup>4</sup> We, thus, planned to design benzothiazoles mimicking the push-pull structures of OL and Me<sub>2</sub>NMe<sub>2</sub>OL, while the benzothiazole ring has been widely used for various fluorophore designs including solvatochromic fluorophores.<sup>5</sup> To tune spectroscopic properties of benzothiazole fluorophores for various usages, it is needed to reveal relationship between structure and fluorescence property of the derivatives. For this purpose, we investigated here the spectroscopic properties of 2-phenylbenzothiazoles 1 (Scheme 1) with push-pull structures. In the course of the study, it was found that one of the derivatives showed a moderate solid-state fluorescence.

We adopted 6-dimethylamino-2-phenylbenzothiazole 1a as a

basic structure with an electron-donating moiety similar to Me<sub>2</sub>NMe<sub>2</sub>OL. To introduce various electron-withdrawing substituents to the 2-phenyl group in **1a**, aldehyde **1b** was synthesized as a push-pull derivative. Then, push-pull derivatives **1c-e** were prepared by condensation reactions with **1b**.



Scheme 1. Structures of firefly oxyluciferin phenolate anion  $(OL^{-})$ , 5,5-dimethyloxyluciferin analogues (Me<sub>2</sub>OLH and Me<sub>2</sub>NMe<sub>2</sub>OL), and push-pull 2-phenylbenzothiazole derivatives **1a-f**.

Spectroscopic properties of **1a-f** were investigated in solutions of cyclohexane, chloroform, acetonitrile and methanol. Figure 1 shows the fluorescence spectra while the absorption spectra are

#### Tetrahedron

deposited in Supplementary data (SD). The numerical data are listed in Tables 1 for the fluorescence and in Table S1 in SD for the absorption. Phenyl derivative **1a** showed a solvent-dependent shift of fluorescence emission maxima ( $\lambda_f$ ) with good quantum yields ( $\Phi_{\rm f}$ ) over 0.8, while electronic absorption maxima ( $\lambda_{\rm ab}$ ) of **1a** showed a small solvent-dependency. The  $\lambda_f$  values were redshifted with an increase in the solvent polarity to show a variation in the range of 393 to 483 nm, indicating that the  $S_1$ state of 1a has electronically polarized character more than the ground  $(S_0)$  state.<sup>6</sup> Introduction of only the pushing dimethylamino group on the benzothiazole moiety caused pushpull property in the  $\pi$ -electronic structure although **1a** has no pulling substituent on the 2-phenyl group. The  $\lambda_{ab}$  and  $\lambda_{f}$  values of **1b-f** in cyclohexane are red-shifted compared to those of **1a**. Similar to **1a**, **1b-f** showed solvent-dependent variations of the  $\lambda_{\rm f}$ values in contrast to a small solvent-dependency of the  $\lambda_{ab}$  values. The substituents on the 2-phenyl group of **1b-f** were expected to affect the spectroscopic properties by their electron withdrawing properties together with expansion of the  $\pi$ -conjugated system. In fact, the electron withdrawing strengths were quantified by using the Hammett  $\sigma_{\rm p}$  values for the formyl (0.42) in 1b, 2,2dicyanoethenyl (0.84) in 1c and (phenylimino)methyl (0.42) in 1e.<sup>7</sup> At the same  $\sigma_p$  value for the formyl and (phenylimino)methyl groups, the  $\lambda_{\rm f}$  values of **1b** and **1e** in cyclohexane, chloroform, and acetonitrile were similar to each other, while the  $\Phi_{\rm f}$  values of 1b were greater than those of 1e. Aldehyde 1b showed a blueshifted fluorescence spectrum in methanol, suggesting that the formyl group of 1b gave a hemiacetal. Interestingly, 1e showed a good  $\Phi_{\rm f}$  value (0.72) only in acetonitrile. Derivatives 1c and 1d showed red-shifted  $\lambda_f$  values upon changing cyclohexane to chloroform, while they showed no fluorescence in acetonitrile and methanol. In particular, the  $\lambda_f$  values in chloroform reached the near-infrared region. The 2,2-dicyanoethenyl in 1c and (1,3dihydro-1,3-dioxo-2H-inden-2-ylidene)methyl groups in 1d induce a strongly polarized character of the S<sub>1</sub> states lead to a preferential nonradiative decay in polar solvents. Hydrazone 1f showed lower  $\Phi_{\rm f}$  values than imine 1e, and a fluorescence spectral change of 1f depending on the solvents was smaller than that of **1e**.



**Figure 1.** Fluorescence spectra of **1a** (A), **1b** (B), **1c** (C), **1d** (D), **1e** (E), and **1f** (F) in cyclohexane (black), chloroform (blue), acetonitrile (green), and methanol (red) at 298 K.

**Table 1.** Fluorescence properties of **1a-f** in various solvents at298 K.

Compd.	$\lambda_{\rm f}$ / nm $(\Phi_{\rm f})^{\rm a}$					
	C <sub>6</sub> H <sub>12</sub>	CHCl <sub>3</sub>	CH <sub>3</sub> CN	CH <sub>3</sub> OH		
1a	393, 413 (0.84)	443 (0.84)	475 (0.83)	483 (0.94)		
1b	444, 469 (0.80)	550 (0.85)	626 (0.66)	494 (0.10)		
1c	526, 562 (0.85)	683 (0.64)	$N/A^b$	N/A <sup>b</sup>		
1d	535, 572 (0.13)	727 (0.35)	$N/A^b$	N/A <sup>b</sup>		
1e	445, 469 (0.057)	534 (0.12)	610 (0.72)	639 (0.067)		
1f	444, 469 (0.023)	517 (0.057)	541 (0.067)	545 (0.026)		

<sup>a</sup> Emission maximum ( $\lambda_f$ ) and quantum yield ( $\Phi_f$ ) in parenthesis. <sup>b</sup>Not observed.

To understand the photophysical properties of the S<sub>1</sub> states of **1a-f**, fluorescence lifetimes ( $\tau_f$ ) of **1a-f** in cyclohexane were measured (Table 2). The decay profiles of the fluorescence are deposited in Figure S2 in SD. The estimated rate constants ( $k_f$ ) of the fluorescence emission processes for **1a-d** were similar among them. Introduction of the (1,3-dihydro-1,3-dioxo-2*H*-inden-2-ylidene)methyl group causes an increase in the rate constant ( $k_{nr}$ ) of nonradiative decay, resulting in a small  $\Phi_f$  value of **1d**. The S<sub>1</sub> states of **1e** and **1f** showed the  $k_f$  values smaller than those of **1a-d**, resulting in the less fluorescent property of **1e** and **1f**.

**Table 2.** Photophysical properties of **1a-f** in cyclohexane at295 K.

Compd.	$\tau_{\rm f}^{\rm a}/{\rm ns}$	$arPhi_{ m f}^{ m b}$	$k_{\rm f}^{\rm c}/10^8 \rm \ s^{-1}$	${\varPhi_{\mathrm{nr}}}^{\mathrm{d}}$	$k_{\rm nr}^{\rm e} / 10^8  {\rm s}^{-1}$
1a	2.1	0.84	4.0	0.16	0.77
1b	2.5	0.80	3.2	0.20	0.80
1c	3.1	0.85	2.7	0.15	0.48
1d	0.41	0.12	2.9	0.88	22
1e	2.2	0.057	0.26	0.94	4.3
1f	2.0	0.023	0.12	0.98	4.9

<sup>a</sup>Fluorescence lifetime. <sup>b</sup>Fluorescence quantum yield. <sup>c</sup>Rate constant of the fluorescence emission process determined by  $k_f = \Phi_f \tau_f^{-1}$ . <sup>d</sup>Quantum yield of nonradiative decay processes determined by  $\Phi_{nr} = 1 - \Phi_f$ . <sup>e</sup>Rate constant of nonradiative decay processes determined by  $k_{nr} = \Phi_{nr} \tau_f^{-1}$ .

To evaluate the correlation between the spectroscopic and  $\pi$ electronic properties of 1a-f, DFT and TD-DFT calculations of **1a-f** were carried out with the B3LYP/6-31G(d) method<sup>8</sup> (Table 3). The  $S_0 \rightarrow S_1$  transitions of **1a-f** correspond to  $\pi, \pi^*$  transitions with main contribution of the HOMO-JLUMO configuration. The  $\lambda_{ab}$  values of **1a-f** in cyclohexane and the wavelengths estimated from the energies of the  $S_0 \rightarrow S_1$  transitions  $(\lambda_{tr})$ increased with a decreased of the energy differences between HOMO and LUMO ( $\Delta E_{H-L}$ ). The HOMO and LUMO levels of **1b-e** were lower than those of **1a**, supporting that the substituents on the 2-phenyl group effectively act as the electron withdrawing groups. Electronic distributions of the HOMOs and LUMOs of 1a-e localized in the benzothiazole and 2-phenyl moieties, respectively (Figure S3 in SD), resulting in enhanced polarized character of the  $S_1$  states generated by the  $S_0 \rightarrow S_1$  transitions. The HOMO energy level of 1f was higher than that of 1a, and electrons in the HOMO of 1f were distributed throughout the  $\pi$ electronic system. Thus, the phenylhydrazone moiety mainly works for expanding the  $\pi$ -conjugated system. The oscillator strength (f) for the  $S_0 \rightarrow S_1$  transition of **1f** was larger than those of 1a-e. This result supports the observation that the molar absorptivities of **1f** are larger than those of the other derivatives

(Table S1 in SD).<sup>9</sup> In contrast to this result, the  $k_{\rm f}$  value of **1f** together with that of **1e** were less than those of **1a-d**, suggesting that a structural change in the C=N bonds of **1e** and **1f** in the S<sub>1</sub> states decelerates the radiative process. In fact, the LUMOs of e **1e** and **1f** have nodal planes at the C=N bonds (Figure S3 in SD).

**Table 3.** Calculation data of **1** in vacuum with DFT and TD-DFT using B3LYP/6-31G(d).

Compd.	HOMO	LUMO	$\Delta E_{\rm H-L}^{a}$	$\lambda_{\rm tr}/{\rm nm}$ (f) <sup>b</sup>	configuration <sup>c</sup>
-	/eV	/eV	/eV		-
1a	-4.99	-1.25	3.74	359 (0.61)	$\mathrm{H} \rightarrow \mathrm{L} \; (0.70)$
1b	-5.22	-2.10	3.12	428 (0.59)	$\mathrm{H} \rightarrow \mathrm{L} \; (0.70)$
1c	-5.40	-2.92	2.48	537 (0.66)	$\mathrm{H} \rightarrow \mathrm{L} \; (0.71)$
1d	-5.16	-2.62	2.54	531 (0.76)	$\mathrm{H} \rightarrow \mathrm{L} \; (0.71)$
1e	-5.06	-1.93	3.13	433 (0.97)	$\mathrm{H} \rightarrow \mathrm{L} \; (0.70)$
1f	-4.82	-1.64	3.18	423 (1.45)	$\mathrm{H} \rightarrow \mathrm{L} \; (0.70)$

<sup>a</sup> Energy difference between HOMO and LUMO. <sup>b</sup> Wavelength estimated from the energy of the  $S_0 \rightarrow S_1$  transition. Oscillator strengths are in the parentheses. <sup>c</sup> Configuration of excitation. Coefficients are in the parentheses. H and L denote HOMO and LUMO, respectively.

It was found that only imine **1e** showed solid state fluorescence with the  $\lambda_{\rm f}$  value at 600 nm (Fig. 3) with a moderate  $\Phi_{\rm f}$  value (0.49). The crystal structure of **1e** indicated that dimeric units (A/A' pairs) with a head-to-tail orientation make stair-like stacked structures (Fig. 4). Imine **1e** has an elongated shape, and the long axes of the two molecules in the unit are nearly parallel. Because the phenyl ring of the imine moiety is twisted at 30° in the molecular structure of **1e**, electronic interactions for quenching the fluorescence state may be inhibited in the dimers.<sup>10</sup> Concerning to **1e**, the packing in the crystals would inhibit a structural change in the C=N bond in the S<sub>1</sub> state, resulting in efficient solid-state fluorescence.



Figure 3. Fluorescence spectra of 1e in the solid state at 298 K.



**Figure 4.** The crystal structures of **1e**; the side views (a) and (b), and the top view (c) of the stair-like stacked structure. A and A' designate molecules making the A/A' dimeric units.

prepared In conclusion. the push-pull 2we phenylbenzothiazoles 1a-f, and clarified the spectroscopic properties. Phenyl derivative 1a shows solvatochromic fluorescence with good  $\Phi_{\rm f}$  values in various solvents. The introduced electron withdrawing groups in 1b-f lead to red-shifts of the  $\lambda_{\rm f}$  values compared to **1a**. In particular, **1c** and **1d** show near-infrared fluorescence in chloroform, and have ON/OFF fluorescence functionality by switching polar and less polar solvents. The  $\Phi_{\rm f}$  values of imine **1e** and hydrazone **1f** are less than those of aldehyde 1b. Imine 1e shows efficient fluorescence in the solid state, because the crystal packing inhibits a structural change of 1e in the S1 state and the twisted phenyl group of the imine moiety interferes intermolecular interactions for quenching. Further fine tuning of the push-pull structure is in progress for designing luminescent materials of soft crystals.

#### Acknowledgments

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#### **Supplementary Material**

Supplementary data (organic synthesis, UV-vis absorption and fluorescence life time measurements, X-ray crystallographic data for CCDC 1820886, and DFT calculation results with tables of atom coordinates for the optimized geometries for compounds Acception 1a-f) associated with this article can be found, in the online version, at https://doi.org/###

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### Highlights

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• 2-Phenylbenzothiazoles were prepared by mimicking the firefly oxyluciferin structure.

• Dimethylamino derivative shows solvatochromic fluorescence with good quantum yields.

• Derivatives with a strong electron-withdrawing group show near-infrared fluorescence.

• Phenylimine derivative shows efficient solid-state fluorescence. A CCK

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### **Graphical Abstract**

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