A Thermodynamic Study on Phthalide-Type dyes in Aqueous Alcohol Solutions

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Phthalide-type dyes in aqueous variable alcohol solution were studied by UV–vis absorption spectroscopy. In this study, 7-[4-(diethylamino)-2-ethoxyphenyl]-7-(1-ethyl-2-methyl-1H-indol-3-yl)furo[3,4-b]pyridin-5 (7H)-one ("Blue-63") was used. Generally, a blue shift is observed from dyes in higher-carbon-number-alcohol solvents. The results indicated the dye equilibrium constant in aqueous alcohol solutions. The equilibrium constant (*K*), Gibbs energy change (ΔG), enthalpy change (ΔH), and entropy change (ΔS) of the dye, depending on temperature change, were also calculated using UV absorbance.

Keywords: Thermochromism, Phthalide-type color, Thermodynamic property, Leuco dye, Equilibrium constant

Introduction

Thermochromism is a reversible color change resulting from variation in temperature. Thermochromism has been observed in many substances: inorganic, organic, metal-organic, and macromolecular compounds. It can appear both in solution and solid state.¹

Phthalide-type dyes, also known as leuco dyes, are thermochromic dyes. These dyes, being intermolecular donoracceptor systems, are capable of changing their spectral and luminescent properties considerably under electronic excitation. For this reason, these dyes are widely used in various fields of science and engineering^{2–4} with applications that include biological stains and water-tracing agents,⁵ laser dyes,⁶ pH indicators,⁷ photosensitizers,⁸ quantum counters,⁹ and anticancer agents.¹⁰

Reaction of the electron-donating colorless phthalide (color former of the dye precursor) with an electron-accepting color developer results in reversible opening of the lactone ring, yielding the resonance-stabilized cationic dye. Thus, it is obvious that the properties of the color former are also dependent on those of the developer, but this is a complex problem and beyond the scope of this article. However, where important differences arise, the developer dependence will be referred to; it is necessary to briefly mention the various types of developers used in present-day carbonless copying papers.¹¹

Thermochromic color change provides an excellent opportunity to study thermodynamic properties because the color changes involved allow one to follow the progress of the transformation with temperature. Earlier reports have described thermochromic systems.^{12–15} An experiment to derive thermodynamic values from a thermochromic equilibrium has also been reported.¹⁶ In the present report, an experiment that uses a phthalide-type dye (Blue-63) and a simple, double-beam spectrophotometer is described; it is suitable

for both physical chemistry and introductory chemistry laboratories.

Leuco dye Blue-63 exhibits several interesting equilibria. In solution, the spectrum of the dye depends on temperature, solvent, and concentration.¹⁷ In alcohol solvents, Blue-63 exists as an equilibrium mixture of a colorless lactone [L] and a colored zwitterion [Z] (Scheme 1).

The formation of the equilibrium depends on both solvent hydrogen bond donating ability and solvent dielectric/polarizability characteristics.^{18,19}

In this study, structural changes in the lactone/zwitterion form in variable alcohol solutions were investigated to clarify the lactone/zwitterion reaction of phthalide dyes. The synthesis of 7-[4-(diethylamino)-2-ethoxyphynyl]-7-(1ethyl-2-methyl-1H-indol-3-yl)furo[3,4-b]pyridin-5(7H)-one (Blue-63) is reported as the condensation of quinolinic anhydride, N-ethyl-2-methylindoline, N,N-diethyl-3-phenetidine, acetic anhydride, acetic acid, ammonium hydroxide, and zinc chloride as a Friedel-Crafts catalyst. Blue-63 was studied by means of UV-vis spectroscopy methods, and the equilibrium constant (K), enthalpy change (ΔH), entropy change (ΔS) , and Gibbs energy change (ΔG) were determined in variable alcohol solutions (concentration range 10^{-3} to 10^{-5} M) at 20.0-60.0 °C. The effects of the dye molecular structure on (K), (ΔG) , (ΔH) , and (ΔS) are discussed.

Experimental

Synthesis of 7-[4-(diethylamino)-2-ethoxyphynyl]-7-(1-ethyl-2-methyl-1H-indol-3-yl)furo[3,4-b]pyridin-5(7H)-

one (Blue-63). There are several reports on the synthesis of Blue-63.²⁰ As described in scheme 2, quinolinic anhydride 1.02 g (149.10 g/mol, 7.5 mM, 1.1 eqiv), *N*-ethyl-2-methylindoline 1 g (161.24 g/mol, 6.20 mM), and zinc chloride 0.14 g (136.29 g/mol, 1.03 mM) in 5 mL acetic acid were mixed at room temperature for 3 h. *N*,*N*-Diethyl-3-phenetidine



Scheme 1. Reverse thermochromic behavior of phthalide-type dye in aqueous alcohol solutions.



Scheme 2. Preparation of phthalide-type dye (Blue-63).

1.32 g (193.29 g/mol, 6.83 mM) in acetic anhydride was added and heated at 65 $^{\circ}$ C for 2 h. The reaction mixture was poured into 20 mL isopropyl alcohol, 7 mL ammonium hydroxide was added, and the mixture was neutralized. The precipitate was collected by filtration and washed with isopropyl alcohol. The solid intermediate was then added to isopropyl alcohol and heated to 85 $^{\circ}$ C for 5 h. Filtration of the solution afforded a white crystalline product.

Blue-63: Yield 72%. mp 358.3 °C. FT-IR (KBr, cm⁻¹) 2973, 2932, 2894 (aromatic-C-H), 1752 (carbonyl-C=O), 1610, 1560 (aromatic-C=C). ¹H-NMR (500 MHz DMSO) δ 8.78 (d, 1H), 8.26 (d, 1H), 7.67 (d, 1H), 7.55 (d, 1H), 7.40 (d, 1H), 7.05 (d, 1H), 6.88 (m, 2H), 6.09 (m, 2H), 4.18 (m, 2H), 3.72 (d, 1H), 3.69 (d, 1H), 3.33 (m, 4H), 2.44 (m, 3H), 1.22 (m, 3H), 1.06 (m, 6H), 0.61 (m, 3H). ¹³C-NMR (DMSO) δ 173.701, 168.951, 158.661, 154.670, 150.137, 135.557, 134.924, 134.094, 132.246, 126.420, 123.860, 121.904, 120.812, 119.996, 119.392, 111.728, 109.615, 109.102, 102.939, 95.943, 92.022, 62.911, 44.132, 40.458, 40.292, 40.125, 39.958, 39.791, 39.624, 39.458, 37.572, 15.433, 14.214, 13.137, 12.929.

Sample Preparation. The various alcohols (methyl-, ethyl-, propyl-, butyl-) used were of spectrometric grade from Sigma-Aldrich. Stock solutions $(1.0 \times 10^{-3} \text{ M})$ were prepared by dissolving these solid dyes in alcohol solutions. The concentration of the reagent was measured at $1.0 \times 10^{-3} \text{ M}$ in order to observe the absorbance of the lactone form. Acid was added in the case of zwitterion form and the concentration was controlled at $1.0 \times 10^{-5} \text{ M} \sim 5.0 \times 10^{-5} \text{ M}$, and the concentration of the test piece was measured. About 1 mL of 1 N HCl acid was added to 100 mL solution to make the acid solution.

Instrumentation. FT-IR (Fourier transform infrared spectroscopy) were obtained using a Thermo Fisher Nicolet 850 spectrophotometer (Waltham, MA, USA). 1H and 13C nuclear magnetic resonance (NMR) was recorded on an Avance 500 (Bruker 500 MHz) instrument. Absorption spectra were recorded on a UV-1601PC UV–vis spectrophotometer (Shimadzu Corp, Kyoto, Japan) in which the specimen chamber temperature was controlled by a CPS-240A (Shimadzu Corp, Kyoto, Japan).

Results and Discussion

Characterization. The chemical structures and composition of the resulting compound were characterized by ¹H-NMR, ¹³C-NMR, and FT-IR.

UV–Vis Spectrum Properties. Figure 1 shows the absorption spectra of the lactone and zwitterion forms of Blue-63 in butyl alcohol solution at room temperature. The Blue-63 lactone and zwitterion spectrum confirms the two λ_{max} at 584 nm and 270 nm. The lactone form concentration in the sample was measured at 1.0×10^{-3} M and the zwitterion concentration was measured at 1.0×10^{-5} M. The concentration difference between the lactone form was stable. It was not possible to measure the zwitterion at the same concentration.

Figure 2 shows the different absorption spectra of Blue-63 showing the same concentration at different temperatures. The results show that Blue-63 may exist in equilibrium with the zwitterion in methyl alcohol solution between 20.0 and $60.0 \,^{\circ}$ C. In all cases, the visible absorption peak decreased with increasing temperature. The absorption spectrum was changed according to temperature, and thus it could be

confirmed that the equilibrium between the lactone and zwitterion was tilted to one side by the temperature change. This slope can be confirmed by the change in absorption spectra.

Spectral results for Blue-63 in various alcohols are shown in Figure 3. A steady decrease in the intensity of the visible absorption of Blue-63 was observed with progressively longer carbon chain lengths of the alcohol. The maximum absorption was obtained at different wavelengths with different alcohols (methyl = 577.6 nm, ethyl = 579.1 nm, propyl = 581.9 nm, butyl = 583.8 nm). A red shift was observed in the dye with higher-carbon-number-alcohol solvents. In contrast to Blue-63 results, the zwitterion absorption spectrum was relatively insensitive to solvent changes. The phenyl ring containing the = $^+N(Et)_2$ and benzene ring containing -COO⁻ are maintained by steric hindrance from each other. The zwitterion will maintain a strong conjugation by substitution of -COO⁻. Using zwitterions as the solvent results in an interaction



Figure 1. Absorption spectra of the lactone and zwitterion forms of Blue 63 in butyl alcohol solution at room temperature.



Figure 2. Absorption spectra of the zwitterion form of 1.0×10^{-5} M Blue-63 with HCl in methyl alcohol solution.

between the zwitterion and -COO⁻ of the solvent. Thus, the solvent zwitterion and -COO⁻ conjugation of the dye are interfered with by a greater interaction of the two positive charges of carbon between -COO⁻, causing the red shift. Figure 3 shows the red shift based on the difference of polarity of the solvent, by which it can be confirmed that as the polarity of the solvent reduces, the absorbance also reduces.

Figure 4 shows the absorption spectra of lactone of Blue-63 in butyl alcohol at various concentrations. Peaks were obtained at 278 nm. The absorption intensity of the lactone form relative to Blue-63 was enhanced with increasing dye concentration. It is possible to calculate the molar extinction coefficient (ε) based on the change in absorbance due to concentration change. This is shown in Table 1.

The plot of ln A versus 1/T is a straight line, as shown in Figure 5. From the slope, the enthalpy change was calculated to be 21.77 kJ/mol for Blue-63 at 20.0–60.0 °C in methyl alcohol solution.



Figure 3. Absorption spectra of the zwitterion form of 1.0×10^{-5} M Blue-63 with HCl in different solvents at 30 °C.



Figure 4. Absorption spectra of the lactone form of Blue-63 in butyl alcohol solution at various concentrations.

A Thermodynamic Study on Phthalide-Type Dyes

Table 1. Thermodynamic parameters of Blue-63.							
	Blue-63						
	T (Kelvin)						
	T_1	T_2	$\epsilon (1/M \cdot cm)$	Κ	ΔH (KJ/mol)	ΔG (KJ/mol)	$\Delta S (KJ/mol·K)$
MeOH	293.15	333.15	17125	2.72	21.77	-2.44	-82.57
EtOH	293.15	333.15	23600	1.46	21.26	-0.92	-75.67
PrOH	293.15	333.15	25750	1.28	21.74	-0.61	-76.23
BuOH	293.15	333.15	30750	0.68	21.36	0.94	-69.67



Figure 5. Plot of ln A versus 1/T for the open form of Blue-63 in methyl alcohol solution ($\lambda_{max} = 577.6$ nm).

Thermodynamics of Phthalide-Type Dyes. The strong visible absorption of the zwitterion provides a convenient handle to follow the L \Leftrightarrow Z equilibrium. To determine the concentration of zwitterion, it is necessary to have a reference standard. From this, it is possible to calculate the equilibrium constant (*K*) for the L \Leftrightarrow Z equilibrium,

$$K = \frac{[Z]}{[L]} \tag{1}$$

From the variation of K with temperature, the enthalpy change (ΔH) is calculated using the van't Hoff equation as:

$$\ln\left(\frac{K_{\rm eq}(T_2)}{K_{\rm eq}(T_1)}\right) = -\frac{\Delta H}{R}\left(\frac{1}{T_2} - \frac{1}{T_1}\right) \tag{2}$$

The equilibrium constant is proportional to absorption as:

$$\ln\left(\frac{A_z(T_2)}{A_z(T_1)}\right) = -\frac{\Delta H}{R}\left(\frac{1}{T_2} - \frac{1}{T_1}\right)$$
(3)

where *R* is the gas constant (8.314 J/mol·K) and *T* is the Kelvin temperature. The Gibbs energy change (ΔG) of the L \Leftrightarrow Z equilibrium can be determined at each temperature by

$$\Delta G = -RTlnK \tag{4}$$

Also, the entropy (ΔS) can be obtained by using a calculated Gibbs energy change and enthalpy change.

$$\Delta G = \Delta H - T\Delta S \tag{5}$$

Values obtained for , *K*, enthalpy change, entropy change, and Gibbs energy change are shown in Table 1. Variation of the difference between the enthalpy of the polar solvents and the interaction between solvent and sample were confirmed.

Conclusions

We have demonstrated the synthesis of phthalide-type Blue-63 mediated by a Friedel-Crafts catalyst and investigated its structure. Absorption spectra with a blue shift were observed for Blue-63 with higher-carbon-number-alcohol solvents. The spectrometric determination of the thermodynamic parameters of Blue-63 dye in various alcohol solutions is reported. The enthalpy change (ΔH), entropy change (ΔS), Gibbs energy change (ΔG), and equilibrium constant (K) were obtained.

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