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Spectroscopic investigations of vinyl-substituted 10*H*-phenothiazine

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ABSTRACT

Different 10*H*-phenothiazine derivatives modified at their 3- and 3,7-positions with conjugated electron-deficient pyridine or pyridinium groups using ethenyl linkers are described. Spectral variations of 3-((*E*)-2-(Methylpyridium-4-yl)vinyl)-10*H*-phenothiazine iodide and 3,7-bis((*E*)-2-(Methylpyridium-4-yl)vinyl)-10*H*-phenothiazine diiodide, which are attributed to intramolecular charge transfer, electronic rearrangement and contact ion-pair mechanisms, were observed to be either base or ion dependent. Depending on the extent of deprotonation of the nitrogen atom in the 10-position of the phenothiazine core, donor–acceptor or push–pull systems provide fluorophore-switching and potential near infrared sensor application.

1. Introduction

Near infrared (NIR) absorbing dyes and pigments are molecules of much current interest because of their potential applications in optoelectronic devices [1,2]. In particular, NIR dyes play prominent roles in medicinal chemistry and biotechnology [3–5]. Typically, functional dyes with significant bathochromic shifts are obtained by taking advantage of the strong donor-acceptor interactions in these molecules [6,7] or by extending the π-system of the chromophores [8,9]. However, most of these dyes exhibit complex architectures that require multi-step synthetic procedures resulting in poor yields.

The phenothiazine (PTZ) core has been an important moiety in heterocyclic chemistry since it was first reported in 1883 [10]. Many important pharmacological applications of PTZ are attributed to its stable radical cation heterocyclic form [11–13]. The well-defined electron-donating properties of PTZs [14–16] can be partially associated with electrophores to produce dyads and triads [17–20] that influence the oxidation potentials of PTZs, especially electronic substitutions in the 3- or 3, 7- positions. Thus, because of its ground-state intramolecular charge transfer (ICT) and excited-state photo-induced electron transfer (PET) properties, the phenothiazine is widely used as organic light-emitting diodes (OLEDs) [21,22], acid–base dyes and pigments [23,24], semiconductors [14,25,26], chemical sensors [27] or near-IR dyes [28–31].

However, most of these applications use the protected PTZ structure with covalent substitutions on the nitrogen atom at the 10-position (10N–H). In the present study, we describe the convenient preparation of divinyl substituted 10*H*-phenothiazines at the 3- or 3, 7- positions (Scheme 1). The deprotonation of these PTZ derivatives at 10N–H is critically important and based on our results, fluorophores and NIR chromophores can be switched on by the loss of protons at 10N–H. We conclude that these alkaline NIR dyes, especially PTZ3 and PTZ4, are potentially useful for ionic sensor applications.

2. Experimental

2.1. Material

General chemicals were of the best grade available, supplied by Acros Organic Co., Merck Ltd., or Aldrich Chemical Co. and were used without further purification. Cell culture medium and organelle markers were from Invitrogen. All the solvents employed were of spectrometric grade.

2.2. Apparatus

Absorption spectra were taken on a *Thermo Genesys 6* UV–visible spectrophotometer, and fluorescence spectra were recorded

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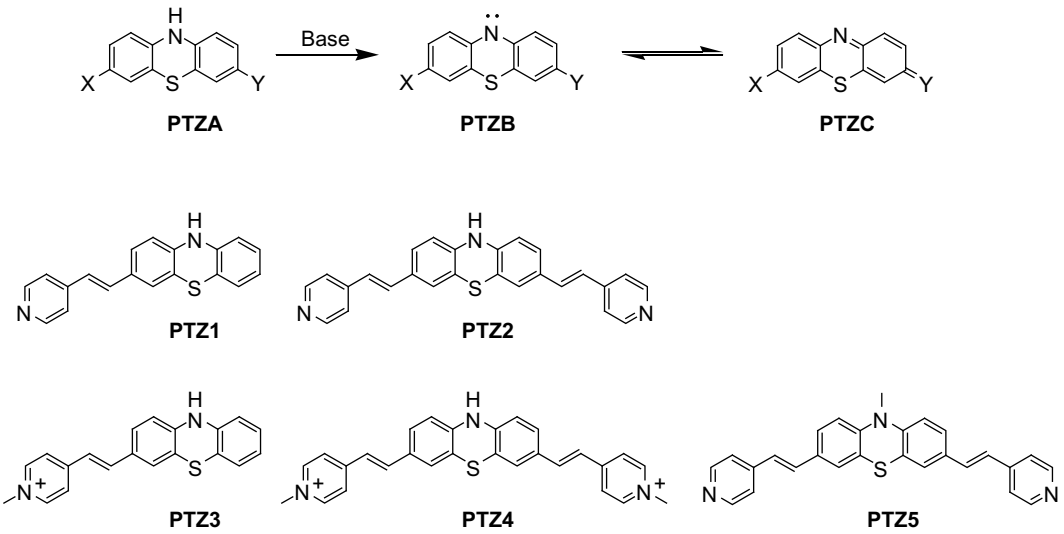


Scheme 1. The 3- or 3,7-divinyl substituted PTZ derivatives.

on a *HORIBA JOBIN-YVON Fluoromas-4* spectrofluorometer with a 1 nm band-pass in a 1 cm cell length at room temperature.

2.3. Determination of quantum yields

The quantum yields of PTZ derivatives were determined according to the literature [32].

$$\Phi_u = \Phi_s \times (A_{fu} \times A_s \times \lambda_{exs} \times \eta_u)/(A_{fs} \times A_u \times \lambda_{exu} \times \eta_s)$$

Where Φ_u is quantum yield of unknown; A_f is integrated area under the corrected emission spectra; A is absorbance area at the excitation wavelength; λ_{ex} is the excitation wavelength; η is the refractive index of the solution; the subscripts u and s refer to the unknown and the standard, respectively. For the same λ_{ex}, we chose BMVC as the standard, which has the quantum yield of 0.25 in glycerol and 0.02 in DMSO [33].

2.4. General procedure for the synthesis of phenothiazine derivatives (Scheme 2)

Synthesis of these phenothiazines derivatives are shown in Scheme 1. 10*H*-phenothiazine containing solution was brominated with *N*-bromosuccinimide (NBS)/THF in additional funnel and then, followed by Heck coupling reaction [34] with 4-vinylpyridine or 4-methoxyly styrene under catalyst Pd $(OAc)_2$. Methyl-pyridinium derivatives can be easily prepared by mean of addition of methyl iodine in acetone system.

2.4.1. Synthesis of 3-bromo-10H-phenothiazine (2)

A double-necked round bottomed flask was charged with phenothiazine (PTZ) 10 mmol in THF solution (20 mL). Then NBS (10 mmol) was dissolved in 20 mL THF and was added dropwise over 1 h with an addition-funnel. The reaction was stirred at ice bath until the complete consumption by TLC monitoring. The solvent was evaporated in vacuum and the residue purified via column chromatography (silica, ethyl acetate/hexane. 1:8, v/v, Rf = 0.38) to remove the dibromo-substituted side product. The final light green products were crystallized from acetone/EA. (yield: 55%). Data for **2** : ^{1}H NMR (400 Hz, DMSO-d_6): δ = 8.706(s, 1H), 7.122(dd, J = 8.4, 2.4 Hz, 1H), 7.095 (d, J = 2.4 Hz, 1H), 6.984 (ddd, J = 8.0, 7.6, 1.2 Hz, 1H), 6.896(dd, J = 7.6, 1.2 Hz, 1H), 6.750(ddd, J = 7.6, 7.6, 0.8 Hz, 1H), 6.650(dd, J = 8.0, 0.8 Hz, 1H), 6.590(d, J = 8.4 Hz, 1H) ppm.

2.4.2. 3,7-Dibromo-10H-phenothiazine (3)

A double-necked round bottomed flask was charged with phenothiazine (PTZ) 10 mmol in THF solution (20 mL). Then NBS (22 mmol) was dissolved in 45 mL THF and was added dropwise over 1 h with an addition-funnel. The reaction was stirred in ice bath until the complete consumption by TLC monitoring. The solvent was evaporated in vacuum and the residue purified via column chromatography (silica, ethyl acetate/hexane. 1/8, v/v, Rf = 0.34). The final light green products were crystallized from acetone/EA. (yield: 70%). Data for **3**: ^{1}H NMR (400 Hz, DMSO-d_6) :δ = 8.848 (s, 1H), 7.140 (dd, J = 8.0, 2 Hz, 2H), 7.113 (d, J = 2.0 Hz, 2H), 6.571 (d, J = 8.0 Hz, 2H) ppm.

2.4.3. 3,7-Dibromo-10-methyl-10H-phenothiazine (4)

Compound **3** (2 mmol) and NaH (3.5 mmol) were placed in a double-necked round bottomed flask with THF solution and stirred at room temperature. CH_3I (5 mmol) was added to the system after 30 min and refluxed for 2 h under N_2 condition. After the reaction finished, system quenched with trace of methanol and extracted with CH_2Cl_2/H_2O. The organic layer was dried by anhydrous $MgSO_4$ and filtered. The product was isolated by silica gel column chromatography using ethyl acetate/hexane (1/8, Rf = 0.4) solvent pairs as the eluent to afford white solid (yield: 75%). Data for **4**: ^{1}H NMR (400 Hz, DMSO-d_6): δ = 7.300 (dd, J = 8.4, 2.0 Hz, 2H), 7.248 (d, J = 2.0 Hz, 2H), 6.810 (d, J = 8.4 Hz, 2H), 3.225 (s, 3H) ppm.

2.5. 3-((E)-2-(Pyridin-4-yl)vinyl)-10H-phenothiazine (PTZ1)

The compound **2** (5 mmol) was added into a high pressure bottle containing the mixture of palladium (II) acetate (8 mg, strem) and tri-*o*-tolyl phosphine (80 mg, Aldrich), then to which was added the solvent pair (triethylamine 5 mL/acetonitrile 15 mL) and 4-vinylpyridine (10 mmol, Merck). The bottle was sealed after bubbling 10 min with nitrogen. After keeping the system under ~105 °C for three days, the system was cooled to room temperature and then extracted with CH_2Cl_2/H_2O twice. The solvent was dried by $MgSO_4$ and evaporated in vacuum. The residue was chromatographed on silica gel by Hexane/Acetone (1/1). The orange solid compound was obtained by recrystallizing with acetone/EA (yield: 72%). Data for

PTZ1 : ^{1}H NMR (400 Hz, DMSO-d_6): δ = 8.807 (s, 1H), 8.480 (d, J = 5.4 Hz, 2H), 7.46 (d, J = 5.4 Hz, 2H), 7.33(d, J = 16.0 Hz,1H), 7.250 (dd, J = 8.4, 2.0 Hz, 1H), 7.228(d, J = 2.0 Hz, 1H), 7.018 (d, J = 16.0 Hz,1H), 6.971 (dd, J = 7.6, 1.6 Hz, 1H), 6.910 (dd, J = 7.6, 1.2 Hz, 1H), 6.752 (ddd, J = 7.6, 7.6, 1.2 Hz, 1H), 6.660(m, 2H). Anal. Calcd. %. For $C_{19}H_{14}N_2S$: C, 75.47; H, 4.67; N, 9.26. $C_{19}H_{14}N_2S\cdot H_2O$: C, 71.22; H, 5.03; N, 9.14. Observation: C, 71.24; H, 5.03; N, 9.14.

2.5.1. 3,7-Bis((E)-2-(Pyridin-4-yl)vinyl)-10H-phenothiazine (PTZ2)

The compound **3** (5 mmol) was added into a high pressure bottle containing the mixture of palladium (II) acetate (16 mg, strem) and tri-*o*-tolyl phosphine (ed. Note; *Irritating to eyes, respiratory system and skin)* (160 mg, Aldrich), then to which was added the solvent pair (triethylamine 5 mL/acetonitrile 15 mL) and 4-vinylpyridine (20 mmol, Merck). The bottle was sealed after bubbling 10 min with nitrogen. After keeping the system under ~105 °C for three days, the system was cooled to room temperature and then extracted with CH_2Cl_2/H_2O twice. The solvent was dried by $MgSO_4$ and evaporated in vacuum. The residue was chromatographed on silica gel by Hexane/Acetone (1/2). The dark-red solid compound was obtained with recrystallizing under acetone/EA (yield: 68%). Data for PTZ2: ^{1}H NMR (400 Hz, DMSO-d_6): δ = 9.032 (s, 1H), 8.487 (d, J = 4.8 Hz, 4H), 7.458 (d, J = 4.8 Hz, 4H), 7.332 (d, J = 16.4 Hz, 2H), 7.251 (m, 4H), 7.032(d, J = 16.4 Hz, 2H), 6.655 (d, J = 8.4 Hz, 2H). Anal. Calcd. %. For $C_{26}H_{19}N_3S$: C, 77.01; H, 4.72; N, 10.36. $C_{26}H_{19}N_3S\cdot 3H_2O$: C, 67.95; H, 5.48; N, 9.14. Observation: C, 67.98; H, 5.50; N, 9.11.

2.5.2. 3-((E)-2-(Methylpyridium-4-yl)vinyl)-10H-phenothiazine iodide (PTZ3)

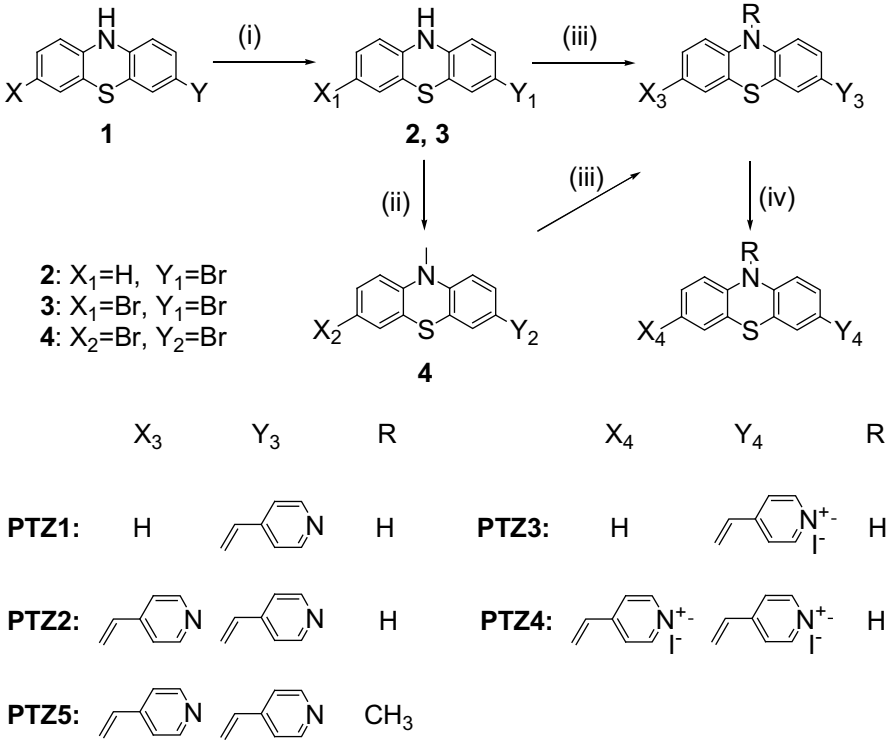
After refluxing the compound PTZ1 with excess CH_3I in acetone more than 6 h, the compound was collected (yield: 90%) as a dark-red powder and recrystallized from methanol twice. Data for PTZ3: ^{1}H NMR (400 Hz, DMSO-d_6): δ = 9.045 (s, 1H), 8.747 (d, J = 6.4 Hz, 2H), 8.060 (d, J = 6.4 Hz, 2H), 7.788 (d, J = 16.0 Hz, 1H), 7.332 (d, J = 8.0 Hz, 1H), 7.321 (s, 1H), 7.253 (d, J = 16.0 Hz,1H), 6.995 (dd, J = 8.0, 7.6 Hz, 1H), 6.915 (d, J = 7.6 Hz, 1H), 6.776 (dd, J = 8.0, 7.6 Hz, 1H), 6.696 (d, J = 8.0 Hz, 1H), 6.679 (d, J = 8.0 Hz, 1H), 4.195 (s, 3H). Anal. Calcd. %. For $C_{20}H_{17}IN_2S$: C, 54.06; H, 3.86; N, 6.30. $C_{20}H_{17}IN_2S\cdot 3/2H_2O$: C, 50.96; H, 4.28; N, 5.94. Observation: C, 51.08; H, 4.25; N, 5.98.

2.5.3. 3,7-Bis((E)-2-(Methylpyridium-4-yl)vinyl)-10H-phenothiazine diiodide (PTZ4)

Similar procedure as PTZ3 (yield: 90%), PTZ2 as reactant and a dark-red powder that was recrystallized from methanol twice. Data: ^{1}H NMR (400 Hz, DMSO-d_6): δ = 9.46(s, 1H), 8.76(d, J = 6.0 Hz, 4H), 8.071 (d, J = 6.0 Hz, 4H), 7.793 (d, J = 16.0 Hz, 2H), 7.345 (s, 2H), 7.736 (d, J = 8.4 Hz, 2H), 7.287 (d, J = 16.0 Hz, 2H), 6.717 (d, J = 8.4 Hz, 2H), 4.207 (s, 6H). Anal. Calcd. %. For $C_{28}H_{25}I_2N_3S$: C, 48.78; H, 3.66; N, 6.10. $C_{28}H_{25}I_2N_3S\cdot 3H_2O$: C, 45.24; H, 4.20; N, 5.65. Observation: C, 45.31; H, 4.22; N, 5.57.

2.5.4. 10-Methyl-3,7-bis((E)-2-(pyridin-4-yl)vinyl)-10H-phenothiazine (PTZ5)

The compound 4 (5 mmol) was added into a high pressure bottle containing the mixture of palladium (II) acetate (16 mg, strem) and tri-o-tolyl phosphine (160 mg, Aldrich), then to which was added the solvent pair (triethylamine 5 mL/acetonitrile 15 mL) and 4-vinylpyridine (20 mmol, Merck). The bottle was sealed after bubbling 10 min with nitrogen. After keeping the system under ~105 °C for three days, the system was cooled to room temperature and then extracted with CH_2Cl_2/H_2O twice. The solvent was dried by $MgSO_4$ and evaporated in vacuum. The residue was chromatographed on silica gel by by Hexane/Acetone 1/2. The orange-red solid compound was obtained by recry- stallization with Acetone/Hexane (yield: 72%). Data: ^{1}H NMR (400 Hz, DMSO-d_6): δ = 8.510 (d, J = 4.8 Hz, 4H), 7.508 (s, 2H), 7.504 (d, J = 4.8 Hz,



Scheme 2. Synthesis of PTZ1–PTZ5. Reaction reagents and conditions: (i) NBS/THF, rt. (ii) NaH/THF, CH_3I, rt, then reflux under nitrogen. (iii) Mixture of $Pd(OAc)_2$/(o-tol)$_3$P complex and 4-vinylpyridine or 4-methoxyly styrene with Et_3N/MeCN as solvent pair. (iv) CH_3I/acetone, reflux.

4H), 7.483 (d, J = 8.0 Hz, 2H), 7.450 (d, J = 16.0 Hz, 2H), 7.16 (d, J = 16.0 Hz, 2H), 7.002 (d, J = 8 Hz, 2H), 3.304 (s, 3H). Anal. Calcd. %. For $C_{27}H_{21}N_3S$: C, 77.30; H, 5.05; N, 10.02. $C_{27}H_{21}N_3S \cdot 1.5H_2O$: C, 72.62; H, 5.42; N, 9.41. Observation: C, 72.65; H, 5.40; N, 9.44.

3. Results and discussion

Heck reaction synthesis of 3- or 3,7-divinyl substituted PTZ derivatives was achieved by reacting 3-bromo or 3,7-dibromo-phenothiazine, respectively, with 4-vinylpyridine in palladium (II) acetate/tri-*o*-tolyl phosphine complex, exploiting the organic coupling rearrangement (as Scheme 2). All reaction products were in the *trans*- configuration as confirmed by the *J* coupling constants of their spectra using nuclear magnetic resonance (NMR) and an Elemental Analyzer. The PTZ derivatives substituted with 3- or 3, 7-conjugated 4-vinylpyridine presented well-defined extinction coefficients and quantum yields in the visible region of the electromagnetic spectrum. (Fig. 1, PTZ1, PTZ2, and PTZ5) While the bathochromic shifts were observed in the ionic compounds PTZ3 and PTZ4 that accompanied the dramatic decrease of their quantum yields (Table 1). In order to elucidate the absorption red shift and fluorescence quench of PTZ3 and PTZ4, we checked the spectral variations of PTZ1 and PTZ2 from protonation under 1 mM hydrogen chloride contained DMSO solution (spectra not shown). The absorption maxima (λ_{max}) of protonated PTZ1 (477 nm) and PTZ2 (518 nm) were closed to PTZ3 and PTZ4 respectively, in the meantime the emission quantum yields were decreasing. It hinted that partial positive charge of pyridinium in protonated PTZ1 and PTZ2 may mimic stronger push–pull effects of PTZ3 and PTZ4 which were caused by electron transfer from the phenothiazine donor to the 4-methyl-pyridinium acceptor. Further, the typical solvatochromic effects in PTZ were shown in inset of Fig. 1. The PTZ3 and PTZ4, exhibiting apparently negative solvatochromism, had stronger ICT (intramolecular charge transfer) effects than PTZ1 and PTZ2. We interrupted that 4-methyl-4′-vinylpyridinium moieties of PTZ3 and PTZ4 may exhibit similar TICT (twisted intramolecular charge transfer) mechanism as stilbazolium (stilbazole = styrylpyridine) salts [35–37] and cause the absorption red shift and fluorescence quench with respect to PTZ1 and PTZ2. On the other hand, the reference compound PTZ5 was synthesized as a control for deprotonation of 10N–H PTZ derivatives and to examine the planarity of the PTZ core. PTZ5 absorbed at a higher energy (blue shift, $\Delta\lambda = 31$ nm) than PTZ2 is likely attributable to the presence of butterfly conformations caused by the steric effects of the substituents on the nitrogen atom at the 10-position as indicated by the folding angle [38].

Table 1
Basic spectral parameters of PTZ derivatives, NMR chemical shifts of *10*N–H, extinction coefficients of absorption, and quantum yield of emission.

N	N–H[a]	λ_{abs} (ε)[b]	$\lambda_{em.}$[c]	Φ[d]
PTZ1	8.807	407(1.83)	575	0.293
PTZ2	9.012	440(2.29)	575	0.301
PTZ3	9.095	485(2.43)	605, 813(s)	<0.001
PTZ4	9.460	532(4.10)	751, 817(s)	<0.001
PTZ5	–	409(2.17)	563	0.350

[a] Chemical shifts: δ (ppm).
[b] Absorption coefficients: M^{-1} cm^{-1}.
[c] Emission wavelength maximum excited at the absorption maximum.
[d] Fluorescence quantum yields.

Fig. 2a–d exhibits the influence of deprotonation on the spectral shapes and λ_{max} of PTZ1, PTZ2, PTZ3, and PTZ4, respectively. The λ_{max} values of the molecular absorptions showed marked bathochromic shifts when a large excess of base (~140 equivalents (eq.)) was added to each of the dye solutions in DMSO. Uniform spectral shifts from 407 to 602 nm for PTZ1 and 440–670 nm for PTZ2 were observed. Similar results were observed for the dye solutions to which NaOH, KOH, tBuOK, Na_3PO_4, K_2CO_3, and TBAF was added; however, no uniform spectral shifts presented when weaker organic bases such as $TBAHSO_4$ and $TBAClO_4$ were used. Thus, the strength of the conjugated base (PTZB form in Scheme 1 and 3) of PTZ1 or PTZ2 was estimated to be roughly comparable to that of K_2CO_3. Owing to this, in the presence of K_2CO_3, PTZ1 (Fig. 2a) and PTZ2 (Fig. 2b) suffered ~20% and ~80% proton losses, respectively, as indicated by the increased intensity of the peaks at 602 and 670 nm at steady state. The enhancement of dissociation for the proton on the nitrogen (*10*N) of PTZ was due to the extending of π-system at the 3-, or 3, 7- positions of the PTZ derivatives. This inference became more convincing when we checked the ^{1}H NMR spectra in DMSO-d_6 solutions (Table 1). Protons of *10*N–H on PTZ1 and PTZ2 were deshielding and further downfield to higher ppm values than phenothiazine (8.564 ppm). Furthermore, because *10*N–H was further downfield on PTZ2 than PTZ1, the acidity of *10*N–H on PTZ2 was stronger than that of PTZ1 and consequently, K_2CO_3 can reveal the ~20% and ~80% deprotonations for PTZ1 (Fig. 2a) and PTZ2 (Fig. 2b), respectively.

More apparent deprotonations and red shifts were observed for PTZ3 and PTZ4 systems which conjugated with stronger electron-

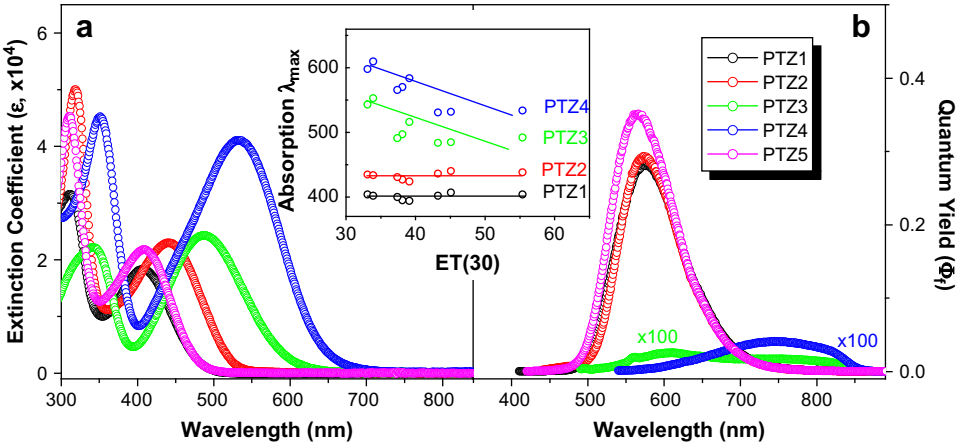


Fig. 1. (a) Absorption and (b) emission spectra of five PTZ derivatives in DMSO solutions; represented by extinction coefficient and quantum yield, respectively. Excited wavelengths were depicted as absorption maxima as shown in Table 1. Inset showed the plot of absorptions maxima versus ET(30) (polarity parameters of Methanol, Dimethyl sulfoxide, N,N-dimethylformide, Chloroform, Ethyl acetate, Tetrahydrofuran, Toluene, Xylene) of four PTZ derivatives.

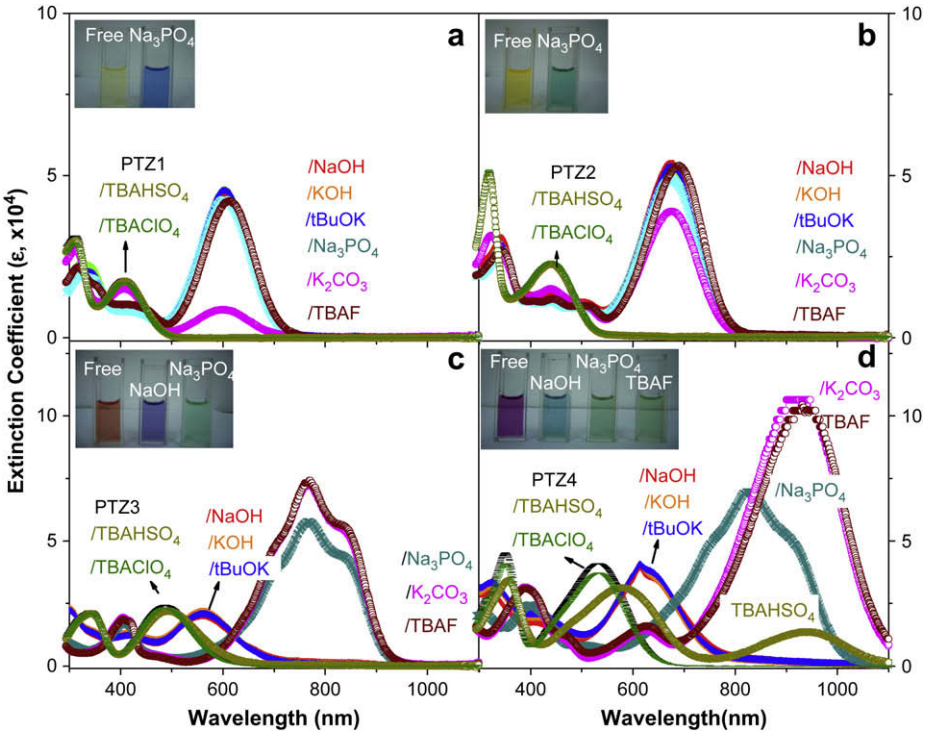
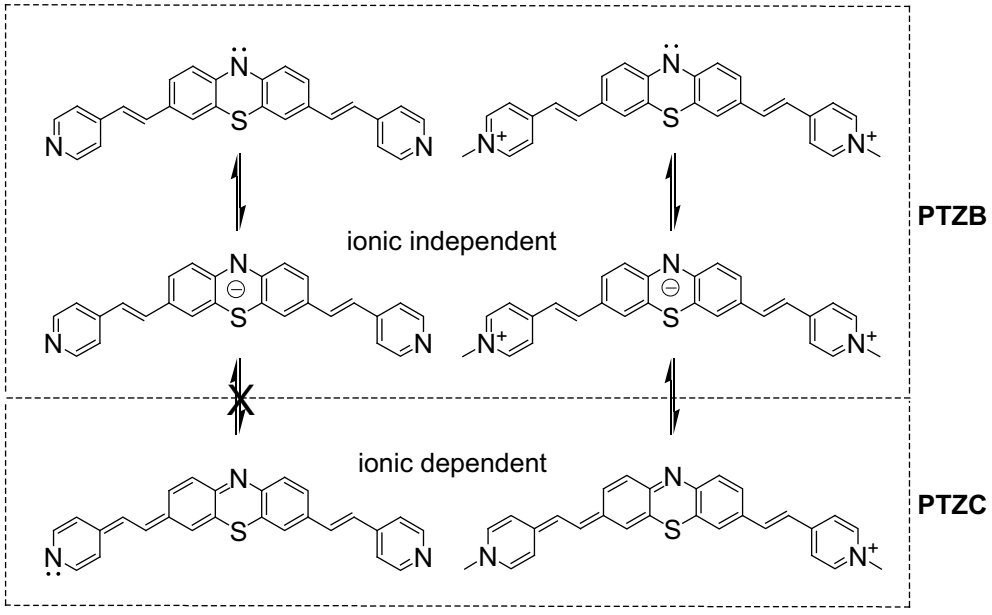


Fig. 2. Spectral variations of 25 μM (a) PTZ1, (b) PTZ2, (c) PTZ3, and (d) PTZ4 in DMSO in the presence of NaOH, KOH, tBuOK, Na_3PO_4, K_2CO_3, TBAF, $TBAHSO_4$, and $TBACIO_4$. The total concentrations of bases were 3.5 mM. Insets show visible emission images that are easily observed with the naked eye.

withdrawing pyridinium groups. The λ_{max} for PTZ3 was approximately 770 nm in TBAF, Na_3PO_4, and K_2CO_3 but merely a slight red shift at 565 nm was observed in NaOH, KOH, and tBuOK. No spectral change was observed when $TBAHSO_4$ and $TBACIO_4$ were used (Fig. 2c). The λ_{max} of PTZ4 further red shifted to 920 nm in TBAF, $TBAHSO_4$, and K_2CO_3; 830 nm in Na_3PO_4 and 625 nm in NaOH, KOH, and tBuOK (Fig. 2d). Compared to PTZ1 and PTZ2, both PTZ3 and PTZ4 exhibited totally deprotonated absorption bands in the presence of K_2CO_3. This meant that the acidities of *10*N–H for PTZ3 and PTZ4 should be stronger than those for PTZ1 and PTZ2. Similarly, by comparing the NMR deshielding of the *10*N–H of these PTZ derivatives, we concluded that the downfield shifts of the *10*N–H protons in DMSO-d_6 with respect to the acidities were in the order: PTZ4 > PTZ3 > PTZ2 > PTZ1 and supposedly, the basicities of their relative conjugated bases would be in the order PTZB4 < PTZB3 < (K_2CO_3) < PTZB2 < PTZB1 (Table 1). Therefore, we proposed that the conjugate basicity of PTZ3 should be lower than that of K_2CO_3 but higher than that of PTZ4 whose conjugate basicity



Scheme 3. Possible electronic delocalization under alkaline conditions.

is similar to that of $TBAHSO_4$ (15% peak growth at steady state; Fig. 2d). Alternatively, both the absorption and emission spectral patterns of the control compound PTZ5 remained unchanged under these experimental conditions (data not shown). These results verified spectral diversity with respect to the deprotonation occurring at *10*N–H for these PTZ derivatives.

The trends in the spectral variations of deprotonated PTZ1 (PTZB1) and PTZ2 (PTZB2) were consistent and independent of the type of base employed. However, the degrees of bathochromic shift ($\Delta\lambda$) of PTZ3B and PTZ4B were divided into two groups; smaller $\Delta\lambda$ ($<$90 nm) in NaOH, KOH, and tBuOK and larger $\Delta\lambda$ ($>$250 nm) in K_2CO_3, Na_3PO_4, and TBAF. Follow the discussion and references [35,36] of Fig. 1, there were two possibilities of electron delocalization between these deprotonation forms once the PTZ derivatives were deprotonated (Scheme 2). For PTZ1 and PTZ2, the electrons of PTZB cannot further rearrange to PTZC, whatever hybridized with the sulfur atom or not which resulted in the localization of electrons to the inner PTZ ring and therefore, became salt or ion independent (Scheme 2, left). However, electron rearrangement was feasible for PTZB3 and PTZB4, each of which in turn, could reversibly rearrange to form PTZC. Hence, ion-exchange or contact ion-pair (CIP) effects [39–41] should be taken into consideration mechanistically. This was probably why both deprotonated PTZ3 and PTZ4 were ionic dependent, and the above mentioned rearrangement was regulated by anions with an increasing ICT effect in the presence of TBAF, K_2CO_3, and Na_3PO_4 but with a decreasing ICT effect in the presence of NaOH, KOH, and tBuOK (Scheme 2, right), relative to PTZ1 and PTZ2. These phenomena were more apparent in the case of PTZ4 because of its di-substituted pyridinium cations. Consequently, we not only estimated the acidities at 10N–H in our PTZ derivatives but also fabricated anionic sensors (salts of organic acids) in the NIR spectral region.

4. Conclusions

To summarize, in the present study, we described a convenient method for the preparation of novel phenothiazine derivatives that could be used as basic or anion sensors. Due to the significant wavelength shifts and large extinction coefficients, the changes were easily perceived with the naked eye. Spectral dualities that switch between NIR absorptions and visible region fluorophores could be achieved in phenothiazine by a mechanism of either losing or retaining *10*N–H protons. We investigated our observations further using donor–acceptor ICT effects and contacted or separated ion-pair effects.

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References

[1] Fabian J, Nakazumi H, Matsuoka M. Near-infrared absorbing dyes. Chem Rev 1992;92:1197–226.
[2] Law KY. Organic photoconductive materials: recent trends and developments. Chem Rev 1993;93:449–86.
[3] Mahmood U, Weissleder R. Near-infrared optical imaging of proteases in cancer. Mol Cancer Ther 2003;2:489–96.
[4] Cheng Z, Levi J, Xiong Z, Gheysens O, Keren S, Chen X, et al. Near-infrared fluorescent deoxyglucose analogue for tumor optical imaging in cell culture and living mice. Bioconjug Chem 2006;17:662–9.
[5] Sasaki E, Kojima H, Nishimatsu H, Urano Y, Kikuchi K, Hirata Y, et al. Highly sensitive near-infrared fluorescent probes for nitric oxide and their application to isolated organs. J Am Chem Soc 2005;127:3684–5.
[6] Kohl C, Becker S, Müllen K. Bis(rylenedicarboximide)-*a*,*d*-1,5-cgdiaminoanthraquinones as unique infrared absorbing dyes. Chem Commun 2002: 2778–9.
[7] Langhals H. An unexpectedly simple NIR dye for 1.1μm with a central mesoionic structure. Angew Chem Int Ed 2003;42:4286–8.
[8] Tsuda A, Osuka A. Fully conjugated porphyrin tapes with electronic absorption bands that reach into infrared. Science 2001;293:79–82.
[9] Avlasevich Y, Müllen K. Dibenzopentarylenebis(dicarboximide)s: novel near-infrared absorbing dyes. Chem Commun 2006;42:4440–2.
[10] Bernthsen A, Dent B. Chem Ges 1883;16:2996.
[11] Albery WJ, Foulds AW, Hall KJ, Hillman AR, Edgell RG, Orchard AF. Thionine coated electrode for photogalvanic cells. Nature 1979;282:793–7.
[12] Mattana A, Biancu G, Alberty L, Accardo A, Delogu G, Fiori PL, et al. In vitro evaluation of the effectiveness of the macrolide rokitamycin and chlorpromazine against *Acanthamoeba castellanii*. Antimicrob Agents Chemother 2004;48:4520–7.
[13] Wagner C, Wagenknecht HA. Phenothiazine as a redox-active DNA base substitute: comparison with phenothiazine-modified uridine. Org Biomol Chem 2008;6:48–50.
[14] Achar BN, Ashok MA. Electrical measurements and thermal kinetics study of phenothiazine and a few of its derivatives. Mat Chem Phys 2008;108:8–15.
[15] Cho DW, Fujitsuka M, Sugimoto A, Yoon UC, Mariano PS, Majima T. Photoinduced electron transfer processes in 1,8-naphthalimide linker phenothiazine dyads. J Phys Chem B 2006;110:11062–8.
[16] Stockmann A, Kurzawa J, Fritz N, Acar N, Schneider S, Daub J, et al. Conformational control of photoinduced charge separation within phenothiazine–pyrene dyads. J Phys Chem A 2002;106:7958–70.
[17] Krämer CS, Zeitler K, Müller TJJ. First synthesis and electronic properties of (hetero) aryl bridged and directly linked redox active phenothiazinyl dyads and triads. Tetrahedron Lett 2001;42:8619–24.
[18] Krämer CS, Zeitler K, Müller TJJ. Synthesis and electronic properties of alkynylated phenothiazines. Eur J Org Chem 2003:3534–48.
[19] Sailer M, Nonnenmacher M, Oeser T, Müller TJJ. Synthesis and electronic properties of 3-acceptor-substituted and 3, 7-bisacceptor-substituted phenothiazines. Eur J Org Chem 2006;2:423–35.
[20] Sailer M, Franz AW, Müller TJJ. Synthesis and electronic properties of monodisperse oligophenothiazines. Chem Eur J 2008;14:2602–14.
[21] Kim GW, Cho MJ, Yu YJ, Kim ZH, Jin JI, Kim DY, et al. Red emitting phenothiazine dendrimers encapsulated 2-{2-[2-(4-dimethylaminophenyl) vinyl]-6--methylpyran-4-ylidene} malononitrile derivatives. Chem Mater 2007;19: 42–50.
[22] Cho NS, Park JH, Lee SK, Lee J, Shim HK, Park MJ, et al. Saturated and efficient red light-emitting fluorene-based alternating polymers containing phenothiazine derivatives. Macromolecules 2006;39:177–83.
[23] Okafor CO. The chemistry and application of a angular phenothiazine derivatives. Dyes Pigments 1986;7:249.
[24] Gupta RR. Phenothiazines and 1,4-benzothiazines – chemical and biomedical aspects [chapter 2]. Amsterdam: Elsevier; 1988.
[25] Aftergut S, Brown GP. Electrical properties of phenothiazine. Nature 1962;193:361–2.
[26] Knorr A, Daub J. Luminescence stimulated by electron transfer: fluorescent donor/acceptor-substituted stilbenes containing pyrenoid and heteroaromatic subunits. Angew Chem Int Ed Engl 1995;34:2664–6.
[27] Hauck M, Schonhaber J, Zucchero AJ, Hardcastle KI, Muller TJJ, Bunz UHF. Phenothiazine cruciforms: synthesis and metallochromic properties. J Org Chem 2007;72:6714–25.
[28] Cho MJ, Kim JY, Kim JH, Lee SH, Dalton LR, Choi DH. Heterocyclic nonlinear optical chromophores composed of phenothiazine or carbazole donor and 2-cyanomethylene-3-cyano-4, 5, 5-trimethyl-2,5-dihydrofuran acceptor. Bull Korean Chem Soc 2005;26:77–84.
[29] Peters AT, Wang NJ. Derivatives of 14H-Naphtho [2, 3-alPhenothiazine-8, 13-dione. Part 2: syntheses from 1, 4-dihydroxy-5-(6-, 7-, 8-) substituted anthraquinones. Dyes Pigments 1995;28:281–90.
[30] Spreitzer H, Daub J. Multi-mode switching based on dihydroazulene/vinylheptafulvene photochromism: synergism of photochromism and redox switching in heteroaryl-functionalized systems. Chem Eur J 1996;2: 1150–8.
[31] Okamoto T, Kuratsu M, Kozaki M, Hirotsu K, Ichimura A, Matsushita T, et al. Remarkable structure deformation in phenothiazine trimer radical cation. Org Lett 2004;6:3493–6.
[32] Velapoldi RA, Tønnesen HH. Corrected emission spectra and quantum yields for a series of fluorescent compounds in the visible spectral region. J Fluorescence 2004;14:465–72.
[33] Chang CC, Kuo SH, Kang CC, Chang TC. Solvent effect on photophysical properties of a fluorescence probe: bMVC. J Luminescence 2006;119-120: 84–90.
[34] Chang CC, Chen KJ, Yu LJ. Highly conjugated molecules from dibromonaphthyl derivatives and 4-vinylpyridine or 4-acetoxystyrene by the Heck reaction. J Org Chem 1999;64:5603–10.
[35] Brooker LGS, Keyes GH, Heseltine DW. Color and constitution. XI. Anhydronium bases of p-hydroxystyryl dyes as solvent polarity indicators. J Am Chem Soc 1951;73:5350–6.
[36] Ephardt H, Fromherz P. Fluorescence and photoisomerisation of an amphiphilic aminostibazolium dye as controlled by the sensitivity of radiationless deactivation to polarity and viscosity. J Phys Chem 1989;93:7717–25.

[37] Wróblewski S, Trzebiatowska K, Jedrzejewska B, Pietrzak M, Gawinecki R, Paczkowski J. Development of fluorescence probes based on stilbazolium salts for monitoring free radical polymerization processes. J Chem Soc Perkin Trans 1999;2:1909–17.
[38] Franz AW, Rominger F, Muller TJJ. Synthesis and electronic properties of sterically demanding n-arylphenothiazines and unexpected Buchwald-Hartwig aminations. J Org Chem 2008;73:1795–802.
[39] Vandereecken P, Soumillion JP, Auweraer MVD, Schryver FCD. The photophysics of alkali naphtholates: lifetimes of contact and solvent-separated ion pairs present simultaneously in weakly polar solvents. Chem Phys Lett 1987;136:441–6.
[40] Soumillion JP, Vandereecken P, Auweraer MVD, Schryver FCD, Schanck A. Photophysical analysis of ion pairing of beta-naphtholate in medium polarity solvents: mixtures of contact and solvent-separated ion pairs. J Am Chem Soc 1989;111:2217–25.
[41] Sciaini G, Marceca E, Ferna'ndez-Prini R. Development of the charge-transfer-to-solvent process with increasing solvent fluid density: the effect of ion pairing. Phys Chem Chem Phys 2006;8:4839–48.