

Thermo- and Acid/base-induced Spectral Switching of a Poly(*N*-isopropylacrylamide) Copolymer Containing Benzopyran-based D- π -A type Dye Units

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Abstract— A thermoresponsive poly(NIPAM-*co*-dye) labeled with benzopyran-based D- π -A type dye was prepared by typical radical copolymerization. It can be also constructed a acid/base-induced molecular switch by modulation of intramolecular charge transfer with protonation/deprotonation. The lower critical solution temperature behavior was investigated by means of UV-vis spectroscopy which allows the measurement of the phase transition from 25°C to 45°C in aqueous DMSO solution. The morphology of the internal microstructure of the poly(NIPAM-*co*-dye) hydrogel was observed by scanning electron microscopy. The reversible switch could be obtained by thermal and acid/base stimuli.

Keywords: *D*- π -A dye, pyran-based dye, poly(*N*-isopropylacrylamide), switch, lower critical solution temperature(LCST)

The effect of the lower critical solution temperature (LCST) in solutions of polymer gel is increasingly of interest to numerous academic and industrial applications such as drug delivery, fluorescent thermometer and separation systems¹⁻⁴. One of the most intensively studied polymers in this field is poly(*N*-isopropylacrylamide) (PNIPAM) which exhibits a LCST transition from 30 to 45°C^{5,6}. The polymer is hydrophilic and soluble in water below the LCST, but becomes hydrophobic and forms a macroscopic coacervate phase above that temperature due to the fluctuation of hydrophobic interactions and hydrogen bonding⁷. In previous papers^{8,9}, we have reported thermoresponsive behavior and photoregulated optical switching in PNIPAM copolymers with electron donor- π -conjugate-electron acceptor (D- π -A) type fluorophore. Also reported has been the acid/base-induced optical switching of the D- π -A type dyes¹⁰⁻¹⁴.

Herein we present a novel multi stimuli-responsive polymer hydrogel containing both *N*-isopropylacrylamide and acid/base-switchable D- π -A type benzopyrane-based dye units containing indole moiety as the thermosensitive and acid/base sensitive components, respectively.

The cyano-benzopyran dye is the typical D- π -A

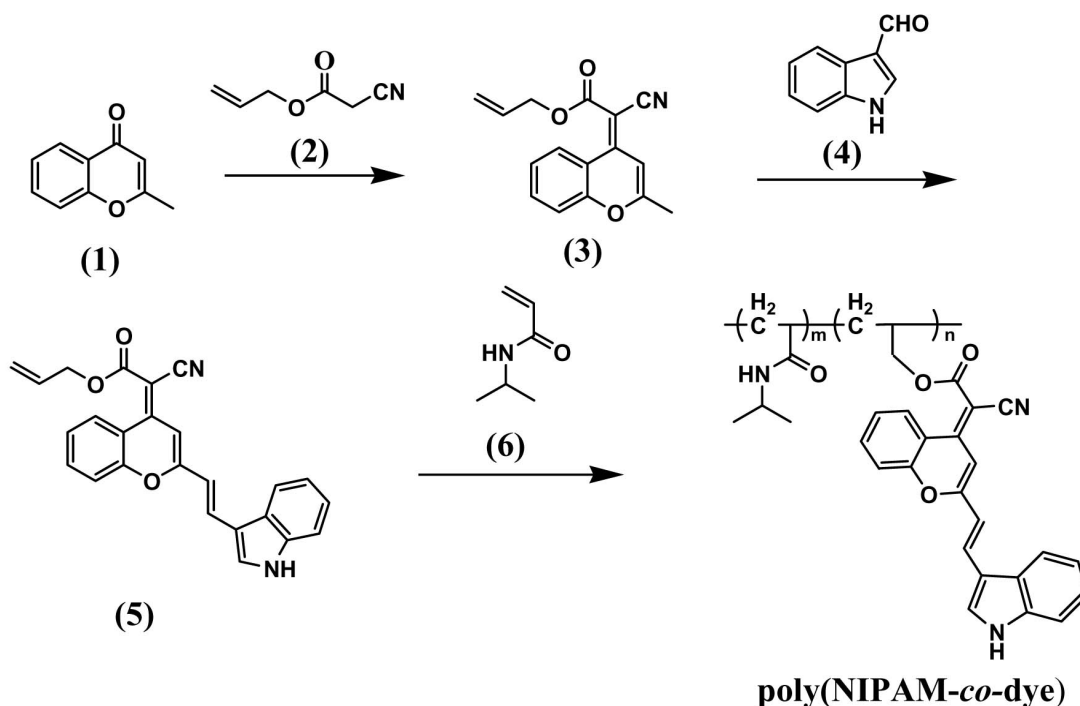
charge transfer compounds, which showed interesting photochemical and photophysical properties due to their intrinsic intramolecular charge transfer (ICT) character¹⁵. The synthetic route of a D- π -A type dye monomer **5** is depicted in Scheme 1.

In our design and synthetic strategy, we have aimed to take the following points into consideration: at first, poly(*N*-isopropylacrylamide) is thermosensitive polymer hydrogel and shows a LCST due to the presence of both hydrophilic amide groups and hydrophobic isopropyl groups in its side chains. Second, incorporation of the D- π -A type dye containing indole moiety in the polymer system could lead to a acid/base-induced spectral switching unit. 2-Methyl-chromene-4-one **1** was prepared by the literature procedure¹⁶.

The compound **3**, containing a polymerizable functional allyl group, was successfully obtained by condensing 2-methyl-chromene-4-one **1** and allyl cyanoacetate **2** in acetic anhydride solution refluxed for 24 h. D- π -A type dye monomer **5** was obtained by condensation reaction with compound **3** and indole-3-carboxaldehyde **4** using piperidine as catalyst⁹. In the next step, this dye-functionalized monomer **5** was copolymerized with *N*-isopropylacrylamide **6** by conventional radical

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Scheme 1. Synthesis of a D- π -A type dye monomer **5** and poly(NIPAM-*co*-dye)

polymerization⁸). Reaction of a monomer **5** and *N*-isopropylacrylamide **6** in THF affords a pink-coloured powder of poly(NIPAM-*co*-dye).

For the interpretation of the ICT process of dye monomer **5**, the quantum chemical DMol³ approach was used. All the theoretical calculations were performed by DMol³ program in the Materials Studio 4.4 package^{17,18} which is the quantum mechanical code using density functional theory. Perdew-Burke-Ernzerhof (PBE) function of generalized gradient approximation (GGA) level¹⁹ with double numeric polarization basis set was used to calculate the energy level of the frontier molecular orbital. Fig. 1 shows the electron distribution of the HOMO and LUMO energy level of dye monomer **5**. Comparison of the electron distribution in the frontier MOs reveals the HOMO-LUMO excitation moves the electron distribution from indole moiety to the acceptor, which showed a strong migration of ICT character of dye monomer **5**.

The interaction of the dye monomer **5** with base(NaOH)/ acid(HCl) was investigated in DMSO solution through spectrophotometric titration experiments. Fig. 2 showed the UV-vis absorption spectral

switching changes of monomer **5** in DMSO with deprotonation/protonation. Upon addition of OH⁻, the broad band at around 600 nm progressively decreases, while a new band with a peak at 640 and 825 nm appeared. The colour changed from blue to dark green. Upon addition of acid, the green colored solution became rapidly recovered to initial state. We propose that these spectral changes are due to the interaction of the OH⁻ and the NH proton of indole moiety. This would suggest that a negatively charged amino nitrogen moiety was formed, which causes a significant increase in the charge density on the amino nitrogen, with associated increasing in the push-pull effect of the ICT transition.

In Fig. 3, we show the absorption spectra of aqueous DMSO poly(NIPAM-*co*-dye) solution (H₂O/DMSO=9/1, v/v) at different temperature. As solution is heated, it becomes turbid; these temperature-responsive changes are entirely reversible. This kind of gelation behavior induced by temperature is well-known as a LCST, resulting from a balance between hydrogen-bond formation with water and intramolecular hydrophobic forces²⁰.

The values of transmittance (A₅₀₀) of aqueous

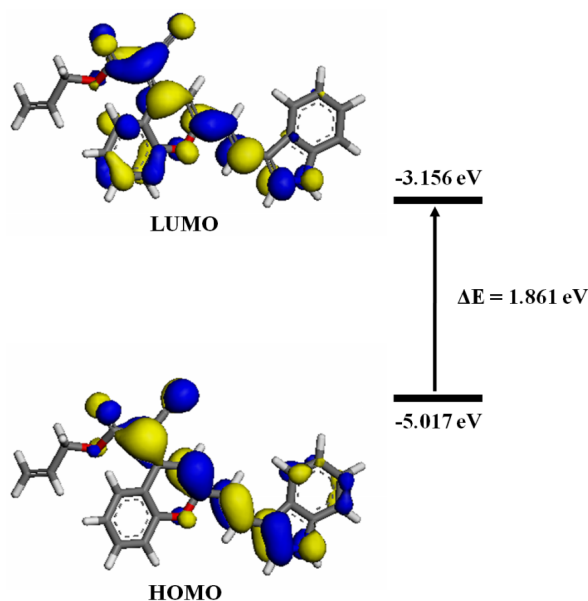


Fig. 1. Electron distribution of the HOMO and LUMO energy levels of dye monomer 3.

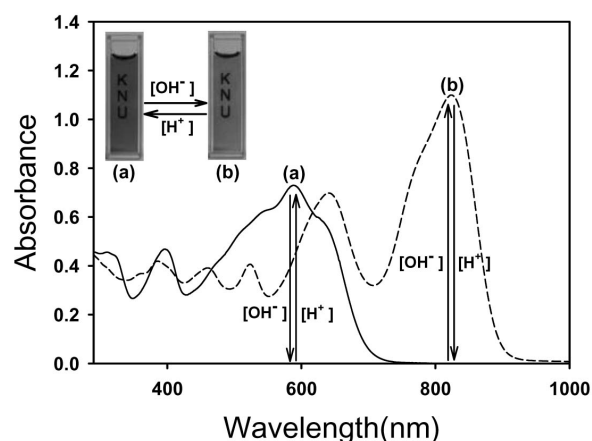


Fig. 2. The UV-vis absorption spectra switching changes of dye monomer 5 in DMSO ($5 \times 10^{-3} \text{ mol L}^{-1}$) solution with deprotonation/protonation.

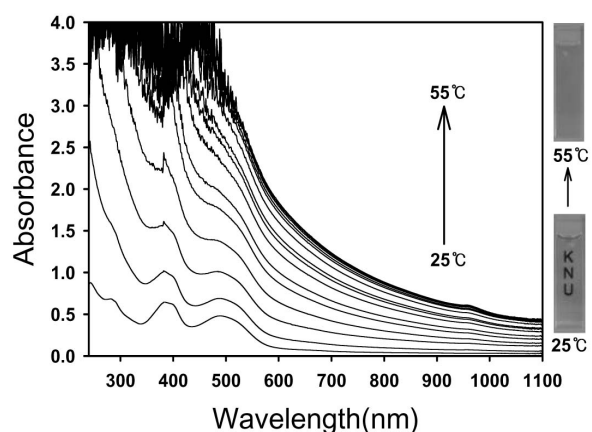


Fig. 3. Absorption spectra and images of poly(NIPAM-*co*-dye) in aqueous DMSO ($\text{H}_2\text{O}/\text{DMSO} = 9/1$, v/v) solution (0.001 g/ml) at various temperatures.

DMSO solution containing poly(NIPAM-*co*-dye) are plotted against the temperature of the solution in Fig. 5; an obvious transmittance decreases at $>25^\circ\text{C}$: LCST=25-45 $^\circ\text{C}$.

The effect of acid/base on the absorption spectra of a 0.001 g/ml solution of poly(NIPAM-*co*-dye) in 9:1 $\text{H}_2\text{O}/\text{DMSO}$ was investigated by the addition of 1 $\mu\text{l}/\text{ml}$ of 5M NaOH solution at room temperature (Fig. 5). Upon addition of OH^- , the band at 385 and 490 nm progressively decreased whilst a new band with a peak at 615 nm formed resulting in a dark green coloured solution. The addition of H^+ by using a micropipette gradually turned the original orange coloured solution.

As orange colored poly(NIPAM-*co*-dye) solution is heated to LCST, it becomes clouded to orange-

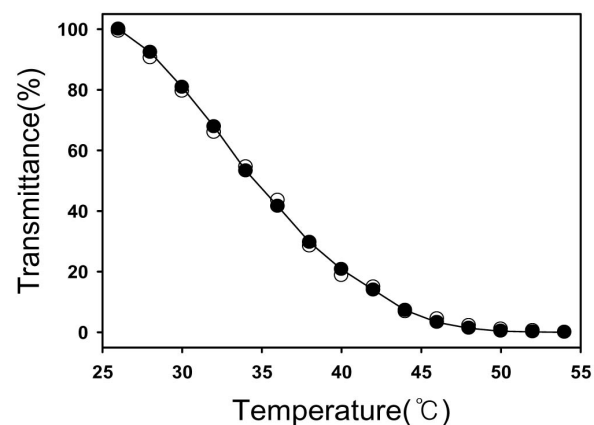


Fig. 4. Transmittance of a solution of Poly(NIPAAm-*co*-dye) in aqueous DMSO ($\text{H}_2\text{O}/\text{DMSO} = 9/1$, v/v) solution (0.001 g/ml) at various temperatures. ●, heating; ○, cooling.

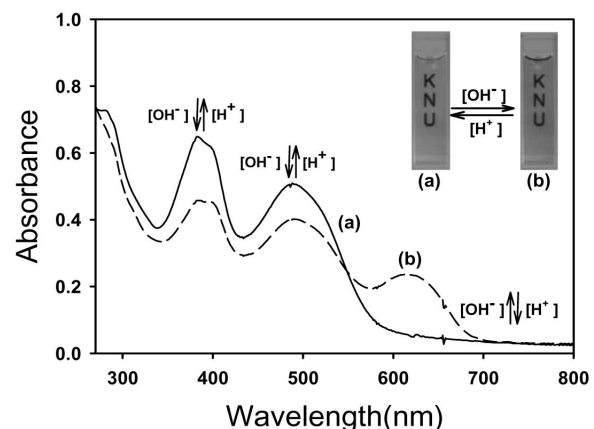


Fig. 5. Absorption spectra changing of poly(NIPAM-*co*-dye) in aqueous DMSO ($\text{H}_2\text{O}/\text{DMSO} = 9/1$, v/v) solution (0.001 g/ml) after adding 5M NaOH solution (1 $\mu\text{l}/\text{ml}$).

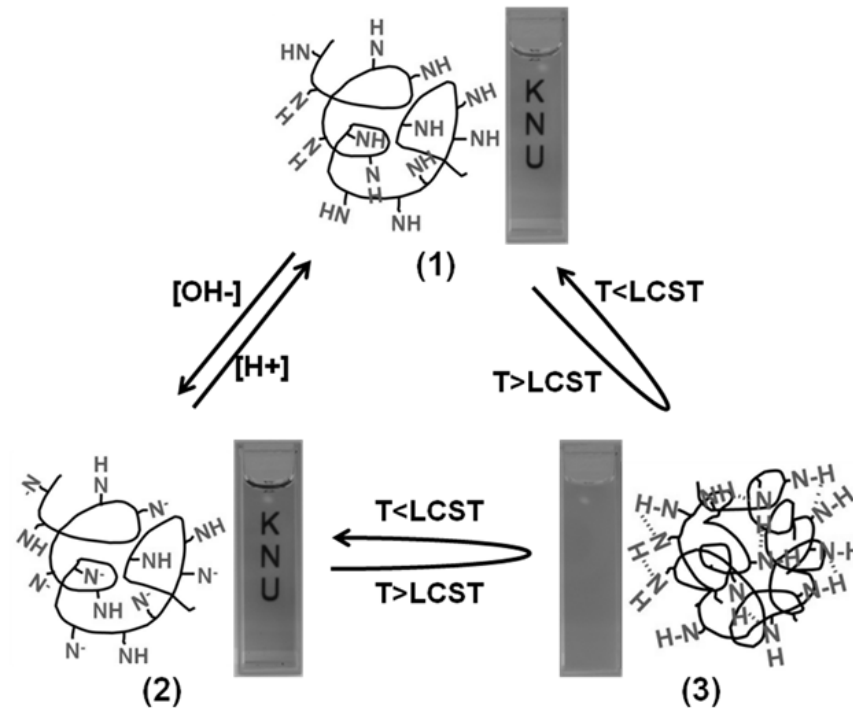


Fig. 6. Schematic representation of the multiple switching process of poly (NIPAM-co-dye) associated with the three states of (1), (2), and (3).

colored gel state, indicative of the occurrence of interpolymer aggregation with -NH fragments in indole moiety, resulting between hydrogen bond formation of -NH fragments (Fig. 6). The temperature and acid/base as the inputs may be exploited to modulate the multiple switches between the species (1), (2), and (3) in solution and hydrogel states (Fig. 6).

Fig. 7 shows a SEM image of the poly (NIPAM-co-dye) microspheres which has relatively regular size and smooth surface.

In conclusion, we synthesized a thermal, and acid/base-responsive poly(NIPAM-co-dye) composed of poly(*N*-isopropylacrylamide) partly modified with benzopyran-based D- π -A type dye. The phase transition temperature for poly(NIPAM-co-dye) was determined by UV-vis spectroscopic method. Color switching of poly(NIPAM-co-dye) was also demonstrated by modulation of deprotonation/protonation.

Therefore, the temperature and acid/base as the inputs may be exploited to modulate the multiple switches between the species (1), (2), and (3) in solution and hydrogel states (Fig. 6).

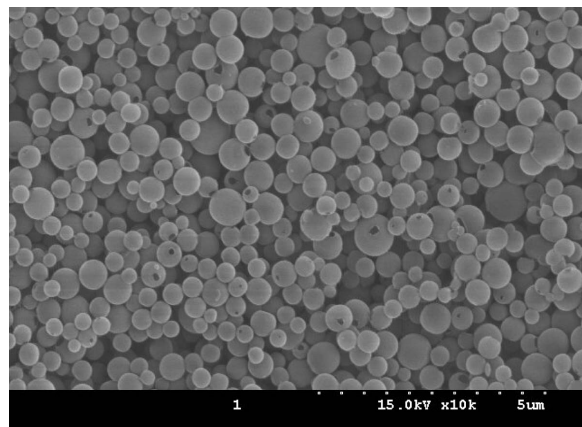


Fig. 7. SEM micrograph of poly(NIPAM-co-dye).

The concept presented here, which controls the phase separation and colour switching by inputs such as temperature and acid/base, may contribute to the development of switching molecules with multiple switching.

Acknowledgements

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