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Tetrahedron Letters
Tetrahedron Letters 46 (2005) 8427–8430

A novel all-organic chemical and electrochemical fluorescent switch

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Received 22 July 2005; revised 10 September 2005; accepted 21 September 2005
Available online 13 October 2005

Abstract—A three-component molecular system capable of switching fluorescence ON and OFF was designed and synthesized. The new redox-activator optical signal generator is an 'all-organic' system composed of 2-chloronaphthoquinone connected to 5-dimethylaminonaphthalene via a non-conjugating piperazine spacer. Both chemo- and electrophotoswitching capabilities were demonstrated.

Systems that have the ability to manipulate photochemical properties via redox states are of interest and might find use as probes for redox processes and in studies of electron and energy transfer mechanisms.[1,2] The former molecular switching systems operating via a redox couple, typically consist of a metal-centered redox couple ($M^{(n+1)+}/M^{n+}$)[3,4] or a luminescent ion core[5] (e.g., $[Ru^{II}(bpy)_3]^{2+}$) encircled by a macrocyclic receptor[6] (e.g., an azacyclam metal complex). The quinone/hydroquinone redox couple can interconvert reversibly in protic media by exchanging two protons and two electrons. Indeed, this redox couple is involved in various biological electron transport systems. Quinones have been shown to be good electron acceptors and efficient quenchers of singlet state donor fluorescence of numerous fluorophores.[7] In contrast, hydroquinones are good donors and do not quench nearby fluorophores. Direct covalent attachment of the active redox quencher (the quinone) to an efficient fluorophore would be expected to yield a reversible and dynamic donor–acceptor system, which in conjunction with fluorescence measurements might have special interest in extra- and intracellular reduction states studies.[8]

In the course of our ongoing interest in 'all-organic' switching systems, we have previously shown[9] that the introduction of a naphthoquinone substituent into *trans*-aminostilbenes, results in complete quenching of fluorescence. Upon reduction of the quinonic moiety to the hydroquinonic form, a strong fluorescence emission was observed. A profound advantage of such 'all-organic' photoswitches[10,11] is the easy manipulation of the molecular structure (quinones of different size and potential; modifiable nature and conformation of the spacer; various types of fluorophore), the relative simplicity of the formation and stability in various media.

In the present letter, we describe the synthesis and some photochemical properties of a new 'all-organic' molecular system in which 2-chloro-1,4-naphthoquinone (the redox switch) is covalently attached to 5-dimethylaminonaphthalene (the fluorophore) via a non-conjugating piperazine (the spacer). This molecular switch **1** was prepared in two simple steps. In the first step, piperazine (10 mM) was reacted with 2,3-dichloro-1,4-naphthoquinone (2 mM) in the presence of $NaHCO_3$ (4 mM) to yield 2-chloro-3-piperazino-1,4-naphthoquinone. This compound reacted with dansyl chloride to give red crystals of 2-chloro-3-[4-(5-dimethylaminonaphthalene-1-sulfonyl)-piperazine]-1,4-naphthoquinone (Scheme 1). The structure of this new molecule was derived from its ^1H and ^{13}C NMR, DEPT and HRMS data.[12]

In the ^{13}C spectrum of **1**, the two typical quinonic carbonyl absorptions were observed between 177 and 182 ppm, the piperazine methylenes between 46 and 50 ppm, the dimethylamino at 45 ppm and the aromatic carbons between 115 and 152 ppm. The structure of compound **1** was firmly established by X-ray crystal analysis (Fig. 1).[13] As can be seen, the dansyl and naphthoquinone ring systems do not reside on the same molecular plane. The non-planarity of the system is further manifested by an angle of 102.7° (N2–S3–C15)

Keywords: Quinone; Hydroquinone; Fluorescence quenching; Chemophotoswitch; Electrophotoswitch.
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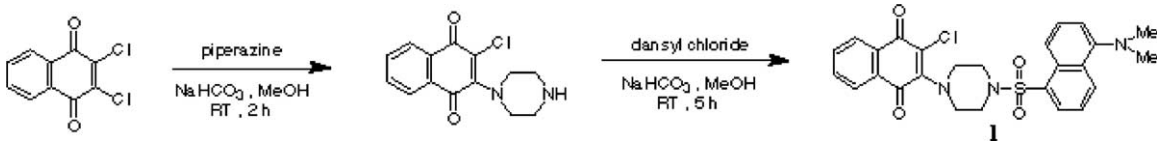
doi:10.1016/j.tetlet.2005.09.127



Scheme 1. Synthesis of the molecular switch **1**.

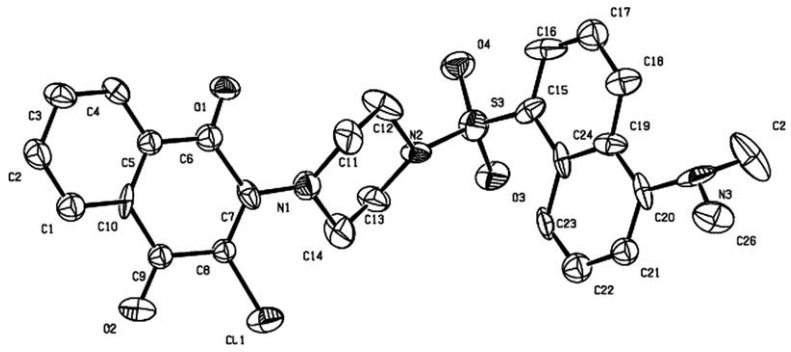


Figure 1. Crystal structure of the molecular switch **1**.

between the 5-dimethylaminonaphthalene moiety and the piperazine spacer. The monochloro-naphthoquinone ring is somewhat distorted from planarity. The two quinonic oxygen atoms are pointing in the same direction but are distorted differently (7.6° and 13.3°) from the plane of the ring. The non-conjugated piperazine subunit possesses a classical chair conformation.

A total quenching of the fluorescence emission was observed for **1** at room temperature. The intrinsic fluorescence emission of the dansyl excited state is strongly quenched, probably due to collisionless intramolecular electron transfer from the excited dansyl to the adjacent quinone acceptor. However, instant chemical 'on' fluorescence switching occurs upon addition of a reducing agent. Thus, the addition of one drop of sodium borohydride (from a 6.6×10^{-4} M solution) to the red solution of **1** in a UV cuvet (in ethanol or DMSO) caused a spontaneous chemical reduction and the formation of the colorless hydroquinone **1a** (Scheme 2). The process is reversible and unless kept under nitrogen, hydroquinone **1a** was slowly reoxidized to **1**. The reduction was accompanied by changes in UV–vis spectrum and most importantly by the appearance of an intense fluorescence emission. The reversibility of the system is very high and the fluorescent emission is switched off immediately by adding an appropriate oxidizing agent, for example, H_2O_2 to **1a** or gradually upon standing for 3–4 hours open to the air. Indeed, UV absorption measurements indicated high yields of chemical conversion of **1** to **1a** as well as in the opposite direction (95–100%).

This emission is vividly visualized when the reductant is added to a methanolic solution of **1** excited by UV-light (Fig. 3). In UV–vis spectra (Fig. 2), **1** shows four typical π–π* aromatic and amino-substituted quinonoid

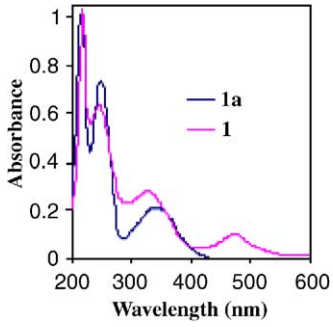


Figure 2. UV–vis absorption of **1** and **1a** in ethanol.

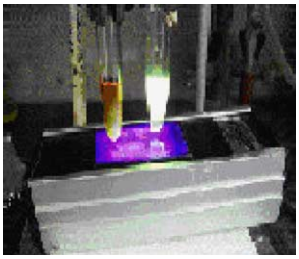
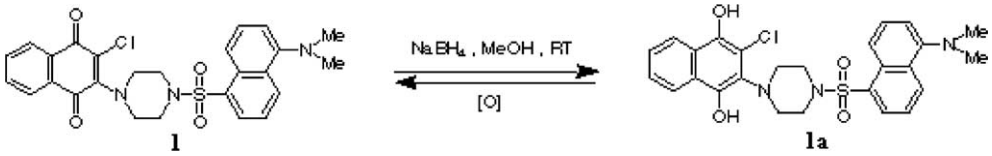


Figure 3. Switching fluorescence ON (right test tube) on addition of $NaBH_4$.



Scheme 2. Reversible chemical conversion of compound **1** to **1a**.

absorptions as expected for such a molecule.[14] The absorption at 474 nm is attributed to charge transfer and is typical to all amino-substituted benzoquinones and naphthoquinones.[15] Reduction of the quinonic moiety to the hydroquinonic form **1a** (Fig. 2) is followed by a complete disappearance of the absorption at 474 nm.

Typical fluorescence emission and exponential fit time scan spectra of **1** and **1a** in ethanol are shown in Figure 4. The fluorescence excitation and emission maxima along with life time quantum yields and Stokes shifts of hydroquinone **1a** in two solvents are summarized in Table 1. Obviously, fluorescence quenching is solvent dependent. It seems that the excited fluorophore is better quenched in aprotic media (DMSO) than in a protic one (ethanol).

The fluorescence lifetime is longer in DMSO than in ethanol. The Stokes shift is only slightly higher in DMSO, but the quantum yield is almost two times higher in ethanol than in DMSO. Indeed, fluorescence is totally quenched when **1** is dissolved in DMSO whereas low fluorescence emission is still observed in ethanol. All the above data justify considering this new material as a new molecular switching system, where the emission and the absorption properties are controlled by the redox state of the quinone moiety.

Apart from the chemo-photoswitching capability of the new system **1**/**1a**, it also exhibits electro-photoswitching properties and can act as an electrooptical signal generator. This attribute was demonstrated using a photoelectrochemical cell (indium-tin-oxide (ITO) on glass electrodes) connected to a 4.5 V battery. Direct voltage was applied to the electrodes immersed in a solution of **1** (3.9×10^{-4} M) in dichloromethane/acetonitrile and 0.1 M TBAP and at the same time, the solution was UV irradiated ($\lambda = 365$ nm). Within a few seconds, the solution started to fluoresce (pale green emission) at the negative electrode, while the positive electrode remained non-luminescent (Fig. 5, left). Inversing the voltage polarity resulted in glowing at the other electrode

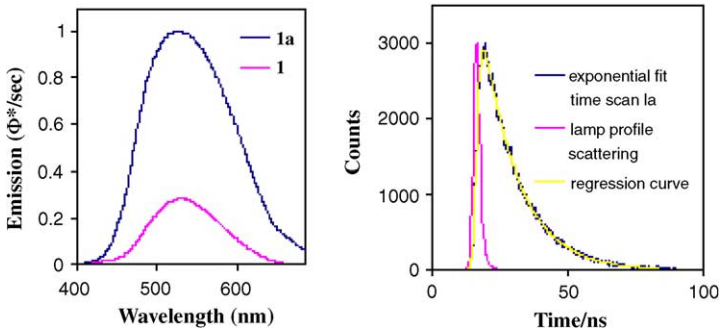


Figure 4. Fluorescence emissions of compounds **1** and **1a** in ethanol (left). Time-resolved fluorescence decay profile of **1a** in ethanol (right). (The experimental data were fitted after convolution with $\chi^2 = 1.416$.)

Table 1. Fluorescence parameters and quantum yields of compound **1a** in DMSO and in ethanol (measured using quinine sulfate in 0.1 M H_2SO_4 as a standard)

Compound	λ_{max} (ex) (nm)	λ_{max} (em) (nm)	Q.Y.[a]	Stoke's shift, cm^{-1}	Fluorescence lifetime (ns)
1a (DMSO)	360	532	0.24	8990	15.94 ($\chi^2 = 1.064$)
1a (ethanol)	360	522.5	0.40	8640	13.09 ($\chi^2 = 1.416$)

[a] Q.Y. = quantum yield.

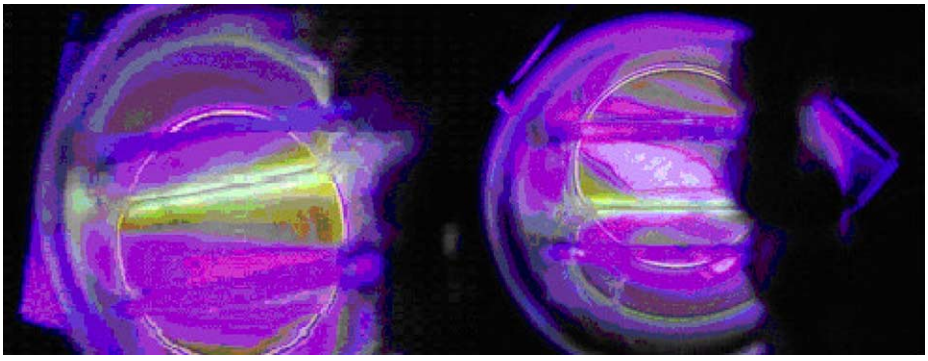


Figure 5. Electrophotoswitching. Pale green fluorescent band at the negative electrode upon providing a voltage of 4.5 V (left). Inversing the voltage polarity results in inverse electrode fluorescence (right).

(Fig. 5, right). This electrophotoswitching redox process was totally reversible and repeatable.

In conclusion, a new, all-organic compound was synthesized, constituting an electrochemical fluorescent switch. Using such systems should enable the manipulation of photochemical properties via redox states. It might also find use as a probe for redox processes in biochemical, biophysical and biotechnological investigations.

Acknowledgements

We wish to thank Mr. S. Keinan for fruitful discussions, Ms. E. Solomon for skillful technical help, Ms. A. Lebkovitch for NMR measurements, and both Ms. L. Shimon and Ms. S. Whiskerman for help in X-ray analysis.

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12. **1**: mp. 150–151 °C. ^{1}H NMR ($CDCl_3$, 500 MHz): δ 8.59–8.60 (d, 1H, $J = 8.5$ Hz), 8.39–8.41 (d, 1H, $J = 8.7$ Hz), 8.24–8.26 (dd, 1H, $J = 7.3$, 1.0 Hz), 8.08–8.09 (dd, 1H, $J = 7.6$, 1.1 Hz), 7.95–7.97 (dd, 1H, $J = 7.4$, 1.2 Hz), 7.50–7.59 (m, 2H), 7.64–7.70 (m, 2H), 7.20–7.22 (d, 1H, $J = 7.5$ Hz), 3.59–3.62 (t, 4H, $J = 9.8$, 1.2 Hz), 3.40–3.43 (t, 4H, $J = 9.8$, 1.2 Hz), 2.90 (s, 6H). ^{13}C NMR ($CDCl_3$, 125 MHz): δ 181.58 (C=O), 177.96 (C=O), 151.83, 149.58, 134.20, 133.35, 132.65, 131.37, 131.22, 130.94, 130.74, 130.32, 130.10, 128.20, 126.90, 126.68, 124.85, 123.17, 119.45, 115.33, 50.78, 46.1, 45.40; DEPT ^{13}C NMR ($CDCl_3$, 125 MHz): δ 133.22, 132.36, 129.92, 129.77, 127.2, 125.92, 125.70, 122.21, 118.52, 114.36, 49.8, 45.0, 44.42. HRMS (CI/I-Bu) (m/z): 509.1180 (M^+), calcd. Mass 509.117606 for $C_{26}H_{24}N_3O_4SCl$, 275.0480 (M^+-234.0700) for $C_{14}H_{12}ClN_2O_2$.
13. $C_{26}H_{24}ClN_3O_4S$, orthorhombic, space group *Pbca*; $a = 9.943(2)$ Å, $b = 11.781(2)$ Å, $c = 40.651(8)$ Å, $V = 4761.8(16)$ Å^3, $Z = 8$, $d = 1.426$ g × cm^{-3}, $T = 120(2)$ K. Diffractometer scan mode: Nonius Kappa CCD, monochromatized Mo-Kα radiation, 1413 unique reflections in the range $2.73 \leqslant 2\theta \leqslant 17.21°$. Full matrix least-squares refinement with 1413 reflections [$I > 2\sigma(I)$] and 278 variables; $R = 0.0943$, $Rw = 0.2168$; residual electron density 0.398 e × Å^{-3}. Crystallographic data (excluding structure factors) for the structure in this letter have been deposited with the Cambridge Crystallographic Data Centre as supplementary publication number CCDC 272993. Copies of the data can be obtained, free of charge, on application to CCDC, 12 Union Road, Cambridge CB2 1EZ, UK [fax: +44(0)-1223-33603 or e-mail: deposit@ccdc.cam.ac.uk]. Each request should be accompanied by the complete citation of this publication.
14. Spectral absorbance data of **1** and **1a** in ethanol. **1**: λ_{max} (nm): 220, 248, 332, 474. Molar absorptivity logε: 4.63, 4.43, 3.99, 3.64. **1a**: λ_{max} (nm): 216, 250, 342. logε: 4.63, 4.50, 3.95.
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