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OFF-ON-OFF Fluorescence Switch with T-Latch Function

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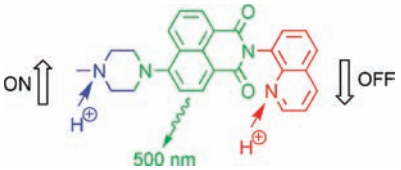
ABSTRACT



A novel molecular system with characteristics of an OFF-ON-OFF fluorescence switch was designed to integrate the function of a T-latch. In detail, a receptor$_1$-fluorophore-receptor$_2$ architecture was adopted to achieve fluorescence switching upon addition of protons.

The idea to use molecular systems for information processing has attracted a great deal of interest during the recent years.[1−5] This has been manifested by the availability of molecular mimics for all essential logic gates (AND, OR, NOR, NAND, INH, XOR, etc.)[1,3] and for rather complex logic devices such as adders/subtractors, encoders/decoders, and multiplexers/demultiplexers.[2,6−10] Such logic functions are of elevated interest for applications such as object coding,[11] intelligent materials,[12−14] pro-drug activation,[15−17] and diagnostics/actuation.[18−20] While these systems work independently of the order of input application (combinational logic), the molecular memorization of information is a precondition for applications which profit from a sequential application of input signals.[21,22] This behavior is reflected in the

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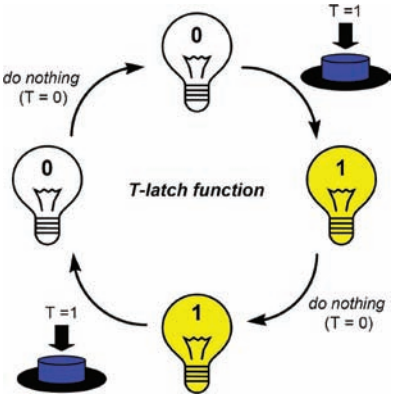
function of molecular keypad locks[10,23–28] and memory devices.[29–35]

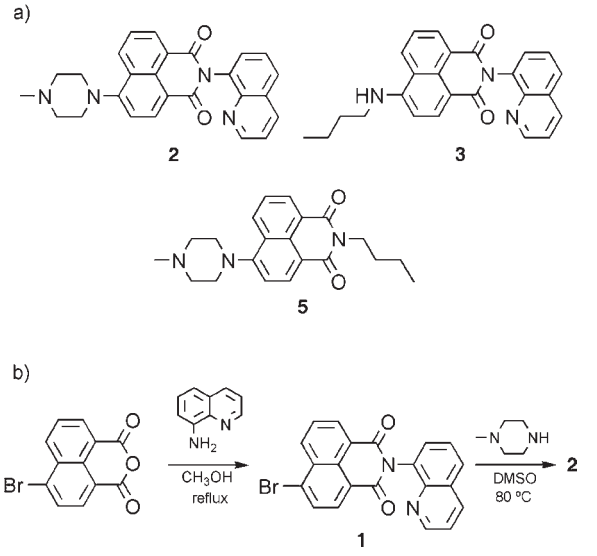
The set-reset (S-R) latch was one of the first memory devices that was implemented at the molecular level by using electrochemical, chemical, and photonic signaling.[29,31–35] The device is characterized by a high state (binary 1) whenever the set input is applied ($S = 1$) and which upon reset ($R = 1$) has a binary 0 (low) state. The herein described toggle-latch (T-latch) is a different logic switch with memory capacity. Its working principle is well illustrated with the function of a conventional light switch or of the push button of a ballpoint pen: every time the toggle input is activated, the state Q of the system changes (see Scheme 1). The device "remembers" if a 0 or a 1 state was memorized ($Q_{current}$) and upon each T input application, the new state (Q_{next}) has the opposite value (0 → 1 and 1 → 0). The "do nothing" situation leaves the system state unchanged.

Scheme 1. Presentation of the T-Latch Function



We anticipated that a molecular OFF-ON-OFF fluorescent switch could integrate this function. In detail, we needed a switch which upon single application of an input changes to the ON state and is set back to the OFF state by a second equal input. Fluorescent systems, which change their emission properties upon application of chemical input information, have been often explored in the design of logic switches and chemical sensors.[3,4,36–38] The integrated receptor$_1$-fluorophore-receptor$_2$ architecture **2** (Scheme 2a) was identified as an excellent candidate to put the molecular T-latch function into practice.

Scheme 2. (a) Structures of Triad **2** and the Naphthalimide Models **3** and **5** with One Receptor Unit and (b) Synthesis of Triad **2** (for Compound **4**, an Intermediary Product, see Supporting Information)



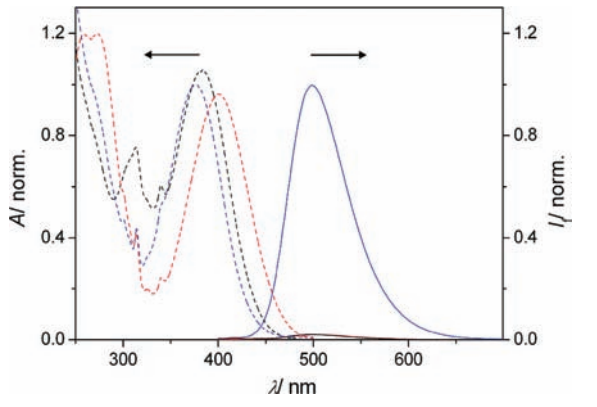


Figure 1. Relative absorption spectra (dashed lines) and normalized fluorescence spectra (solid lines) for **2** (red), $\mathbf{2}H^+$ (blue), and $\mathbf{2}H_2^{2+}$ (black). Note that the low fluorescence emissions of **2** and $\mathbf{2}H_2^{2+}$ are hardly distinguishable.

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The synthesis of the new triad **2** is briefly sketched in Scheme 2b. The sequence started with the commercial 4-bromo-1,8-naphthalic anhydride, which was condensed with 8-aminoquinoline (74% yield). Further aromatic nucleophilic substitution of the intermediary 4-bromo-1,8-naphthalimide derivative with *N*-methylpiperazine resulted in the final product **2** with a yield of 52%. The synthesis of the naphthalimide derivatives **3** and **5** (Scheme 2a), which served herein as model structures, is described in the Supporting Information.

Table 1. Photophysical Properties of Compounds **2**, **3**, and **5** and Their Protonated Forms in Aerated Acetonitrile Solution

	$\lambda_{abs,max}$/nm	ε/M^{-1} cm^{-1}	$\lambda_{fluo,max}$/nm	Φ_f	τ_f/ns
2	401	10100	504	0.017	[a]
2H$^+$	377	10500	499	0.67	8.90
2H$_2^{2+}$	383	11100	499	0.017	[a]
3	433	13000	520	0.56	10.00
3H$^+$	441	13400	519	0.006	[a]
5	398	9700	502	0.018	[a]
5H$^+$	374	10100	498	0.62	9.06

[a] Not determined due to low signal intensity.

Triad **2** contains two proton receptors: a piperazinyl and a quinolinyl moiety. The receptors have sufficiently different pK_a values (7.78 for *N*-benzoylpiperazine versus 4.60 for 8-methylquinoline as models)[39] so that they can be stepwise protonated. In accordance with this assumption and as shown in Figures 1 and 2, the addition of 1 equiv of protons (triflic acid; CF_3SO_3H) yielded a pronounced fluorescence enhancement (fluorescence quantum yield Φ_f = 0.67 versus 0.017 for **2**H$^+$ and **2**, respectively) of the 4-amino-1,8-naphthalimide chromophore ($\lambda_{fluo,max}$ = 504 nm for **2** and 499 nm for **2**H$^+$). However, the subsequent addition of a second equivalent of CF_3SO_3H caused practically quantitative fluorescence quenching (98% quenching). The photophysical properties of all investigated compounds and their protonated forms are summarized in Table 1. The independent actuation of both receptors in **2** was supported by the observation of the same differential photophysical effects upon protonation of the model compounds **3** and **5**, which contain each only one of the two receptors (Scheme 2a). In accordance with the fluorescence response of **2** upon stepwise protonation, **3** showed quenching and **5** enhancement of the emission for the addition of 1 equiv of protons (Supporting Information). The superposition of the photophysical trends of the model compounds in the triad was also noted for the absorption spectra.[40]

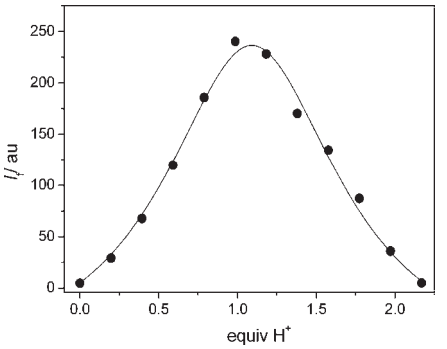

Figure 2. Fluorescence titration curve (λ_{exc} = 388 nm, λ_{obs} = 499 nm) of **2** (12.5 μM in acetonitrile) upon CF_3SO_3H addition.

Table 2. Truth Table for the Implemented Molecular T-Latch

T input (1 equiv H$^+$)	$Q_{current}$ (fluo)	Q_{next} (fluo)	control channel (abs, 313 nm)
0	0	0	0
1	0	1	0
0	1	1	0
1	1	0	1

The fluorescence switching of triad **2** can be mechanistically rationalized as follows. The electron-donating methyl-substituted piperazinyl nitrogen atom is protonated upon the addition of the first equivalent of protons, which leads to blocking of photoinduced electron transfer (PET) and consequently fluorescence ON switching.[41−43] The second equivalent of protons serves to transform the quinolinyl residue into a quinolinium cation. The hydrogen-bonding interaction of NH$^+$ with the imide carbonyl C=O is assumed to be at the origin of the fluorescence quenching of the 4-amino-1,8-naphthalimide derivative.[41] However, PET from the singlet-excited fluorophore to the electron-accepting quinolinium cation may also be involved in the observed fluorescence OFF switching.[44,45] Noteworthy, the control of 4-aminonaphthalimide fluorescence by a receptor linked to the "imide side" of the fluorophore has been rarely observed.[41,42,46−48]

(39) The pK_a data were taken from http://research.chem.psu.edu/brpgroup/pKa_compilation.pdf.

(40) The protonation of the piperazinyl residue leads to a blue shift (by 24 nm) of the long wavelength aminonaphthalimide absorption band (for **2** and **5**), which is indicative of the destabilization of the charge transfer state through the repulsive interaction between the protonated distant methyl-substituted N and the positive pole of the charge transfer state at the aromatic N (cf. ref 47). The protonation of the quinolinyl moiety has stabilizing effects on the charge transfer state, which is expressed by a red shift (by 6−8 nm) of the long wavelength absorption band (for **2** and **3**).

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The first three columns of the truth table (Table 2) describe the implementation of the T-latch function, which is mimicked by the above-discussed fluorescence switching. Starting with the triad in its unprotonated state (**2**), only low fluorescence is observed for $T = 0$ (no addition of acid). This situation corresponds to $Q_{current} = Q_{next} = 0$. However, protonation of **2** with 1 equiv of acid ($T = 1$) leads to $\mathbf{2H}^{+}$ and consequently a high fluorescence output (toggling from $Q_{current} = 0$ to $Q_{next} = 1$). Again, the "do nothing situation" ($T = 0$) preserves the Q state (i.e., $Q_{current} = Q_{next} = 1$ in this case). The second addition of 1 equiv of acid ($T = 1$) to $\mathbf{2H}^{+}$ yields $\mathbf{2H_2}^{2+}$ and concomitant fluorescence quenching, corresponding to a switching from $Q_{current} = 1$ to $Q_{next} = 0$.

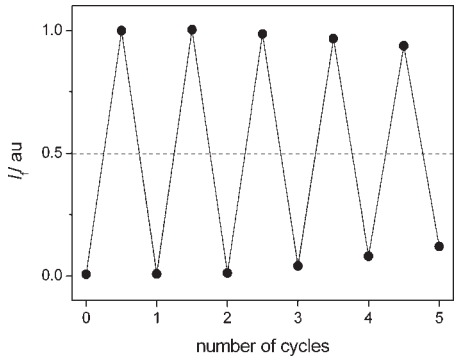

Figure 3. Recycling of fluorescence switching ($\lambda_{obs} = 499$ nm) of **2** (8.7 μM in acetonitrile) upon consecutive addition of 1 equiv of CF_3SO_3H followed by 1 equiv of P_2-Et phosphazene base. The dashed line marks the threshold. A conservative estimation yields that up to 10 cycles are possible, maintaining a dynamic switching range of $I(ON)/I(OFF) \geq 2$.

The protonation state of the triad can be easily reset by application of a strong base (P_2-Et phosphazene), leading to the inverse titration curve (see Supporting Information). The consecutive protonation/deprotonation of **2** with acid/base can be repeated for at least five cycles without significant loss of the dynamic fluorescence switching range (Figure 3). The correct functioning of the T-latch requires that the initial device state is represented by the unprotonated triad **2**. However, by solely reading the fluorescence output Q, it cannot be decided whether at a random point of operation $Q_{current} = 0$ corresponds to **2** or $\mathbf{2H_2}^{2+}$. The unambiguous assignment of an output to a concrete input situation can be resolved by reading a control channel, as has been shown previously for the implementation of reversible logic functionality.[10,28,49,50] This control signal is provided herein by the absorption of the quinolinium cation at ca. 313 nm (fourth column in Table 2).[51] This spectral signature only evolves when the quinoline unit becomes protonated (Supporting Information). Hence, when the fluorescence is low and the absorbance at 313 nm is high, 2 equiv of base is needed to reset the system to its initial state (unprotonated **2**). If the fluorescence output and the absorbance at 313 nm are both low, then the system is already in its initial state. Hence, the two $Q = 0$ situations are now clearly distinguishable.

In summary, we have shown that an OFF-ON-OFF fluorescence switch with two degenerate proton inputs can integrate the function of a molecular T-latch. The photophysical design of the switch is based on the control of electron transfer and hydrogen-bond interaction. Work on an all-optical version, exploring photoinduced proton transfer as relay mechanism, is underway.

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Supporting Information Available. Details on the synthesis of **1**–**5**, ^{1}H and ^{13}C NMR spectra, additional spectroscopic data. This material is available free of charge via the Internet at http://pubs.acs.org.

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