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Molecular Implementation of Sequential and Reversible Logic Through Photochromic Energy Transfer Switching

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In memoriam Rafael Suau

Abstract: Photochromic spiropyrans modified with fluorophores were investigated as molecular platforms for the achievement of fluorescence switching through modulation of energy transfer. The dyads were designed in such a way that energy transfer is only observed for the open forms of the photochrome (merocyanine and protonated merocyanine), whereas the closed spiropyran is inactive as an energy acceptor. This was made possible through a deliberate choice of fluorophores (4-amino-1,8naphthalimide, dansyl, and perylene) that produce zero spectral overlap with the spiro form and considerable overlap for the merocyanine forms. From the Förster theory, energy transfer is predicted to be highly efficient and in some cases of 100% efficiency. The combined switching by photonic (light

Keywords: energy transfer • logic gates • photochromism • spiro compounds • switches of $\lambda > 530$ nm) and chemical (base) inputs enabled the creation of a sequential logic device, which is the basic element of a keypad lock. Furthermore, in combination with an anthracene-based acidochromic fluorescence switch, a reversible logic device was designed. This enables the unambiguous coding of different input combinations through multicolour fluorescence signalling. All devices can be conveniently reset to their initial states and repeatedly cycled.

Introduction

The idea of using molecular systems for mimicking binary information processing has attracted considerable interest in recent years.^[1–4] On the one hand, such molecular entities could be imagined as building blocks for molecular computers. In practice, however, problems such as the concatenation of several logic devices create bottlenecks for such applications.^[4] On the other hand, the utility of molecular logic is not restricted to computing,^[5] but has, for example, emergent interest for smart materials,^[6] pro-drug activation,^[7,8] labelling of micro-objects,^[9] multiparameter sensing^[10] and molecular diagnostic tools.^[11,12]

Many of the numerous molecular logic devices reported so far use chemical signals as inputs and fluorescence signals

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as conveniently readable outputs.^[1–3] Photophysically, these systems are often based on well-understood energy-transfer and electron-transfer processes.^[13] This facilitates the rational design of such switches and enables effective control of the fluorescence output. The same excited state pathways were found to be modulated by the interaction of fluorophores with photochromic molecules in appropriately designed dyads, leading to novel photonic switches.^[14,15] Photochromes themselves can be understood as bistable or sometimes multistable systems, in which the states involved show considerable differences in properties such as UV/Vis absorption and redox potentials. One of the commonest applications for information processing with photochromes is their exploitation as molecular memories.^[16-23] Notably, even more complex logic operations such as those of multiplexers,^[24] demultiplexers,^[25] encoders, decoders,^[26] halfadders^[27,28] and keypad locks^[29] have been devised through combining the action of several photochromes. This has opened up a strategy for the design of all-photonic molecular logic devices using exclusively optical input and output signals.

One of the most popular classes of photochromic switches are spiropyrans such as **1-SP** (Scheme 1). For such a compound three different states are observed: SP (spiro form), ME (merocyanine form) and MEH⁺ (protonated merocyanine form). Thanks to the pronounced differences in the absorption spectra of these states, energy transfer switching has been used to control the fluorescence intensities of attached fluorescent units in spiropyran-based supramolecular

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Scheme 1. Structures of **1-SP**, **1-MEH**⁺ and **1-ME** and their interconversion through photonic and/or chemical inputs.

constructs (dyads etc.). This has been accomplished in liquid solution,^[30] in polymers,^[31] on nanoparticles^[32] and in live cells.^[33] As shown in Scheme 1, spiropyran photochromes combine the use of photonic and chemical input signals.

In this work, the covalent linking of a nitrospiropyran with carefully chosen fluorophores (dansyl, 4-amino-1,8-naphthalimide and perylene) has enabled fluorescence switching through the modulation of energy transfer processes through the action of chemical and photonic inputs. The rational design and comprehensive interpretation of the switching behaviour has been used here to achieve a fluorescent sequential logic device, which is the basic function of a molecular keypad lock.^[29,34–38] In combination with an anthracene fluorescence switch, a logically reversible gate was also devised.^[39,40]

Results and Discussion

Synthesis of the spiropyran-spacer-fluorophore dyads (2-SP, 3-SP, 4-SP) and model compounds: The complete synthesis sequence for the dyads is shown in Scheme 2a. The preparation of 1-SP was accomplished by starting with the commercially available 2,3,3-trimethylindolenine and following a three-step procedure, which was slightly modified with respect to the literature (see the Supporting Information).^[41,42] Alkylation of the indolenine with methyl 4-bromobutyrate gave the corresponding indolinium salt. In the second step this salt was treated with 5-nitrosalicylaldehyde to yield the nitrospiropyran in its methyl ester form. The ester was finally treated with sodium hydroxide in tetrahydrofuran, followed by acidification with citric acid to yield 1-SP. This compound was then further functionalized with the corresponding fluorophores through formation of amides. The best yields were obtained by prior acid activation by the NHS ester method (see the Supporting Information). Treatment of the NHS ester with the corresponding fluorophore amine derivatives yielded the target dyads 2-SP, 3-SP and 4**SP** (yields of 54, 57 and 68%, respectively). The fluorophore amine derivatives were prepared as described in the Supporting Information. The fluorophore model compounds (**2-M**, **3-M**, and **4-M**) were obtained by direct acetylation of the amines with acetyl chloride or acetic anhydride (Scheme 2b).

Photochromic behaviour of the model spiropyran 1-SP: Compound 1-SP can be considered a model spiropyran in our study, because it resembles the photochrome part of all the dyads investigated here. The corresponding absorption spectra of all three forms of 1 are displayed in Figure 1. As shown in Scheme 1, irradiation of the SP form (λ_{max} =



Figure 1. Absorption spectra of **1-SP** (dotted line), **1-MEH**⁺ (dashed line) and **1-ME** (solid line) in acetonitrile.

341 nm, $\varepsilon = 7500 \,\text{M}^{-1} \,\text{cm}^{-1}$) with UV light ($\lambda = 302 \,\text{nm}$, 210 s) leads to ring opening and the generation of the ME form (**1**-**ME**). This is characterized by a substantially red-shifted absorption band at $\lambda_{\text{max}} = 565 \,\text{nm}$ ($\varepsilon = 36800 \,\text{M}^{-1} \,\text{cm}^{-1}$). The distribution between the two forms in the photostationary state (PSS) was determined as 39 % SP and 61 % ME. The **1-ME** form reverts to **1-SP** either thermally ($\tau = 6.1 \,\text{min}$ at 20 °C) or, more rapidly, on visible light irradiation. The time required for the photoinduced isomerization depends, of course, on the light intensity. Here, irradiation at $\lambda > 530 \,\text{nm}$ with a light power density of about 18 mW cm⁻² required 210 s exposure time for the ME to SP conversion.

The addition of trifluoroacetic acid (TFA, 1 equiv) to **1-ME** generated the protonated MEH⁺ form (**1-MEH**⁺), which was accompanied by a blue shift of the long-wavelength absorption maximum to 404 nm ($\varepsilon = 22700 \text{ m}^{-1} \text{ cm}^{-1}$). This process can be reversed by addition of a strong phosphazene base (P₂-Et, 1 equiv). The open forms can be quantitatively transformed back to the closed SP form by irradiation with light of $\lambda > 420 \text{ nm}$ (ME and MEH⁺) or, for the selective conversion of ME, of $\lambda > 530 \text{ nm}$.

Photophysical properties and photochromic switching of the dyads: All relevant spectral data for the dyads in their dif-



Scheme 2. a) Synthesis of 1-SP and its functionalization with fluorophores (2-SP, 3-SP, 4-SP). DCC = N, N'-dicyclohexylcarbodiimide. b) Preparation of fluorophore model compounds (2-M, 3-M, 4-M).

ferent forms (SP, ME, MEH⁺) and for the fluorophore models are compiled in Table 1. Figure 2 compares the absorption spectra of the dyad 2-SP and the corresponding model compounds 1-SP and 2-M. The combination of the spectra of the models yields the spectrum of the dyad, which rules out significant ground-state interactions. The same observations were made for the other two dyads (see the Supporting Information). Notably, the fluorophore emission of the dyads in their SP forms is considerably quenched (ca. 90%) relative to the emission of the model chromophores (Figure 2 for 2-M versus 2-SP). The underlying fluorescence quenching process is dynamic in nature, as has been verified by the observation of the same effect in fluorescence lifetime measurements. For the 4-amino-1,8-naphthalimide fluorophore, for example, the quantum yield ($\Phi_{\rm f}$) drops from 0.44 for **2-M** to 0.056 for **2-SP** and the lifetime (τ_f) is 10.6 ns for 2-M and 1.40 ns for 2-SP (see Table 1). The mechanism for this fluorescence quenching is assumed to be photoinduced electron transfer (PET). Electronic energy transfer (EET) can be excluded because the dyads were designed to give a zero spectral overlap integral between the fluorophore emission and the SP absorption spectrum (see below). To validate the hypothesis of PET, the driving force (ΔG_{PET}) for the oxidative and reductive paths was calculated by application of the Rehm–Weller equation [Eq. (1)].^[30,43–46]

$$\Delta G_{\rm PET} = E_{\rm ox} - E_{\rm red} - E^* + C \tag{1}$$

In all cases, PET with oxidation of the fluorophore is exergonic and therefore thermodynamically feasible: $\Delta G_{\text{PET,ox}} =$ -0.31, -0.91 and -0.76 eV for **2-SP**, **3-SP** and **4-SP**, respectively (error ± 0.1 eV). Reductive PET was also considered, but with the exception of **2-SP** ($\Delta G_{\text{PET,red}} = -0.15 \pm 0.1 \text{ eV}$) this path is endergonic ($\Delta G_{\text{PET,red}} > 0$). Notably, despite the

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Table 1. Photophysical properties of model compounds and dyads.

	$\lambda_{abs,max} [nm] \\ (\epsilon/m^{-1} cm^{-1})$	$\lambda_{\rm f,max}$ [nm]	$arPsi_{ m f}^{[{ m a}]}$	$ au_{ m f}{}^{[b]}$	${\pmb{\varPhi}_{ ext{PET}}}^{[c]}$	PSS ^[d]	Q [%] ^[e]	$egin{array}{c} R_0 \ [m \AA]^{[m f]} \end{array}$	$arPsi_{ ext{EET}}^{[ext{g}]}$
2-M	416 (10400)	512	0.44	10.6 ns					
2-SP	416 (11000)	512	0.056	1.40 ns	0.87	55		0	
2-ME	[h]	[i]	0.035 ^[j]	13 ps		45	38	47	1.0
2-MEH ⁺	[h]	[i]	0.035 ^[j]	15 ps			38	20	0.85
3-M	338 (4600)	518	0.25	12.6 ns					
3-SP	341 (11000)	518	0.015	925 ps	0.94	54		0	
3-ME	[h]	[i]	$0.008^{[j]}$	8 ps		46	44	43	1.0
3-MEH+	[h]	[i]	$0.008^{[j]}$	9 ps			44	19	0.80
4-M	439 (33600)	446	0.76	4.0 ns					
4-SP	439 (32100)	447	0.079	560 ps	0.90	58		0	
4-ME	[h]	[i]	0.034 ^[j]	16 ps		42	57	38	1.0
4-MEH+	[h]	[i]	0.034 ^[j]	16 ps			57	35	0.99

[a] Fluorescence quantum yields of the model compounds measured with quinine sulfate in H_2SO_4 (0.05 M) as standard (Φ_t =0.55), 20% error. The values for the SP dyads were determined relative to those of the models. [b] Fluorescence lifetimes, 10% error. [c] Quantum yields for PET, calculated by Equation (2). [d] Distribution of spiropyran and merocyanine isomers (% SP/% ME) in the PSS (λ =302 nm). [e] Fluorescence quenching observed for the PSS (SP→ME/MEH⁺). [f] Critical radius of electronic energy transfer (Förster mechanism), calculated by Equation (3). [g] Quantum yields for electronic energy transfer estimated from the Förster formulation, with the assumption of a distance of 15 Å between fluorophore and photochrome. [h] The long-wavelength absorption maxima of the protonated merocyanine (MEH⁺) and the merocyanine (ME) forms of the dyad are determined by the photochrome part (see text for data for the model compounds 1-MEH⁺ and 1-ME). [i] The fluorescence maximum remains unaltered with respect to the fluorescence observed for the SP form of the Corresponding dyad. [j] Apparent fluorescence quantum yield, determined from the fluorescence quenching in the PSS (irradiation of the SP form with 302 nm light) and subsequent addition of TFA (1 equiv, for the MEH⁺ form).



Figure 2. Absorption spectra (three spectra on the left) of **2-M** (solid line), **1-SP** (dashed line) and **2-SP** (dotted line) in acetonitrile. On the right (above 450 nm) the fluorescence spectra of optically matched solutions of **2-M** (solid line) and **2-SP** (dotted line) in acetonitrile are shown (λ_{exc} =417 nm).

exergonic thermodynamics in the case of **2-SP**, the occurrence of reductive electron transfer is unlikely, because electron donors linked to the "imide side" of the chromophore do not quench the fluorescence of aminonaphthalimides.^[47,48] Oxidative PET is therefore a very likely possibility for the observed fluorescence quenching in the SP dyads. With the assumption that PET is the only competitive fluorescence quenching process in the SP dyads, the quantum yield can be given with $\Phi_{PET} \approx 0.9$ [Eq. (2)].

$$\Phi_{\rm PET} = 1 - \frac{\Phi_{\rm f,SP}}{\Phi_{\rm f,M}} \tag{2}$$

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As is discussed below, the dyads described here were designed to yield fluorescence switching dependent on the state of the photochrome moiety. This idea is based on the control of very efficient EET (see below) being suppressed in the SP forms of the dyads and activated for the other two forms (ME and MEH+): that is, ON/OFF fluorescence switching upon photoinduced ring opening of the SP forms. It should be stressed that to achieve the maximum ON/ OFF discrimination. EET in the ME and MEH+ forms of the dyads should be much more efficient than PET in the corresponding SP forms; from the lifetimes in Table 1 it can clearly be seen that this condition is fulfilled.

The fluorophores play the role of energy donors, whereas

the photochrome moiety is the energy acceptor. According to the Förster theory of energy transfer, the efficiency $(\Phi_{
m EET})$ of this process depends crucially on the spectral overlap integral (J) of the donor emission and the acceptor absorption [Eqs. (3) and (4)]. With Equation (3) the critical distance for energy transfer (R_0) can be calculated (the orientation factor κ^2 was assumed to be 2/3). This distance corresponds to a 50% EET efficiency. For all dyads, considerable R_0 values of 38–47 Å were found for their ME forms, whereas somewhat smaller values were determined for their MEH⁺ forms ($R_0 = 19-35$ Å). Importantly, and as intended, $R_0 = 0$ Å applies for the SP forms of the dyads, because the spectral overlap integral is zero. This means that EET does not occur in this photochromic state of the dyads. With the real distance between donor and acceptor the values for $\Phi_{\rm EET}$ can be calculated [Eq. (4)]. Because of the conformational flexibility of the linker, however, the actual distance between donor and acceptor is expected to follow a distribution function. For this reason we assume an estimated value of the maximum distance, corresponding to the most extended conformation, with R about 15 Å. Most probably the real average distances are even smaller, as can be judged from the occurrence of PET in the SP forms of the dyads (see above). This process would not be efficient (see Table 1) for a distance of 15 Å. In any case, this maximum distance is still significantly smaller than R_0 for both of the open forms. The lower limit values for EET efficiency thus show that for the ME form this process is expected to be quantitative $(\Phi_{\text{EET}}=1)$ for all fluorophores, whereas for the protonated merocyanine form (MEH⁺) considerably high values of $\Phi_{\rm EET} \ge 0.8$ should still result.

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$$R_0^6 = \frac{9\ln 10\kappa^2 \Phi_{\rm D}}{128\pi^5 n^4 N_{\rm A}} J \quad \text{with} \quad J = \int_0^\infty \frac{F_{\rm D}(\nu)\varepsilon_{\rm A}(\nu)\mathrm{d}\nu}{\nu^4} \tag{3}$$

$$\boldsymbol{\Phi}_{\text{EET}} = \frac{1}{1 + \left(\frac{R}{R_0}\right)^6} \tag{4}$$

The expected ON/OFF fluorescence switching upon conversion of the SP form to the ME form was experimentally verified for the irradiation of the dyads at $\lambda = 302$ nm. The conversion $2-SP \rightarrow 2-ME$, for example, resulted in fluorescence quenching of 38%. This effect is even somewhat more pronounced for the dansyl- and perylene-substituted spiropyrans (3-SP and 4-SP), for which the emission is reduced by about 44 and 57%, respectively, upon merocyanine formation. Clearly, the dynamic range of the fluorescence switching is dictated by the PSS distribution, which was found to be around 55:45 (% SP/% ME) for all three dyads. The similarity of the quenching and the ME contribution to the PSS is consistent with the prediction of very efficient energy transfer (see above). Comparison of the PSS distribution for the dyads and the spiropyran model compound 1-SP (% SP/% ME 39:61) reveals that the photochromic ring opening process is somewhat affected in the dyads, which is possibly the result of photochrome excited state quenching by the fluorophores (e.g., through PET). Quantitative fluorescence quenching by EET in the dyads in their open forms (ME and MEH⁺) was also verified by fluorescence lifetime measurements (see Table 1). For the example of the dansyl-substituted photochrome (3-SP) a drastic reduction of the lifetime from 925 ps for the SP form to a few picoseconds (8–9 ps for the component of shortest lifetime) for the ME and MEH⁺ forms was observed (see Figure 3).



Figure 3. Streak-camera fluorescence decays (λ_{exc} = 398 nm; averaged for λ_{obs} = 500–540 nm) for **3-M** (filled circles), **3-SP** (filled squares), **3-ME** (empty squares) and **3-MEH**⁺ (empty circles). The solid lines are to guide the eye, but do not correspond to the actual fits. Note that the model **3-M** shows essentially no decay on the timescale considered. The decay curve of **3-ME** contains still considerable contributions from the closed **3-SP** (photostationary state). The decay of **3-MEH**⁺ contains a higher proportion of the short-lived component than that of **3-ME**. This is probably the result of suppression of thermal closing of **3-MEH**⁺ during the course of the measurement.

The other two dyads showed the same lifetime quenching trend (Table 1). In other words, each dyad molecule, on conversion from the SP to the open ME/MEH⁺ forms, shows quantitative fluorescence quenching.

With the complete characterization of the photochromemodulated fluorescence switching available, we set out to achieve the following advanced logic functions: sequential molecular logic^[49,50] and reversible logic.^[39,40]

Implementation of sequential logic through chemical and photonic inputs: The outcome of a sequential logic operation is dependent not only on the correct combination of the inputs, but also on the order of their application. This implies the existence of a memory effect. Prominent examples of logic switching of this type are keypad locks and SR latches,^[51] for which a restricted number of molecular examples are known. Keypad locks are devices that activate only if the right input combination is applied in a certain sequence. With one exception,^[29] the molecular keypad locks reported to date rely on all-chemical input signals.^[35–38] This could imply problems for the repeated use of the molecular system, which would require mechanisms for resetting and recycling.

As shown in Scheme 1, not only do spiropyran photochromes offer the possibility of light-induced switching, but their open forms can also be interconverted by protonation/ deprotonation. Hence, three spectrally differentiated states (SP, ME, MEH⁺) can be observed for these photochromes. Effectively, a chemical (sensing) input and a remote-addressing photonic input are combined in a "hybrid approach" (neither all-chemical nor all-photonic). This can be used to devise comprehensive logic operations,[52-57] beyond the bistable photoswitching of spiropyrans (SP-ME and vice versa). It should be noted here that other classical photochromes, such as dithienylethenes or fulgimides, have only two differentiated states (closed and open form). Thus, to achieve complex logic functionality with these photochromes, several distinct units are commonly combined in a supermolecule conjugate.[24-26,28,29]

For the spiropyran-fluorophore dyads investigated here, fluorescence constitutes a convenient output signal (O_1) . As the initial state of our sequential logic device, the MEH⁺ form of the dyad was chosen. One input (In_2) is light of $\lambda >$ 530 nm, at which the initial MEH⁺ state shows no absorption, but the ME form does absorb (see Figure 1). To generate the SP form, the MEH⁺ form has to be converted into the ME form before irradiation with light of $\lambda > 530$ nm (see Scheme 3). This can be accomplished by deprotonation of the phenolic OH group with P_2 -Et base (1 equiv), which is defined as input In_1 . It thus results that only one input order $(In_1 \text{ followed by } In_2)$ yields the SP form and its corresponding high fluorescence output signal. Application of In2 and then In_1 leaves the fluorescence output low. Because of the efficient EET fluorescence quenching in the ME and MEH+ forms of the dyads, the binary input combinations 00, 01 and 10 also produce low-output signals (see Figure 4 for the example of 2-SP). In essence, this corresponds to a two-input

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Scheme 3. Switching of **2-MEH**⁺ (initial state) by sequential application of inputs In_1 and In_2 . Reversible logic by combinational switching of **2-MEH**⁺ (initial state) by application of In_1 and In_3 and of **5H**⁺ by application of In_1 .



Figure 4. Sequential logic with **2-MEH**⁺ as initial state and In_1 (phosphazene base) and In_2 (irradiation at $\lambda > 530$ nm) as inputs. The horizontal line shows the threshold. Fluorescence signals above the threshold are regarded as binary 1 and below as binary 0.

priority AND gate (2-PAND).^[29] The switching can be repeated for at least five consecutive cycles with an acceptable dynamic OFF/ON range (Figure 5). According to the interconversions shown in Scheme 1, resetting to the initial state (MEH⁺ form) is possible either through application of UV light and addition of trifluoroacetic acid TFA (SP \rightarrow MEH⁺) or solely through addition of TFA (ME \rightarrow MEH⁺). It is noteworthy that acid–base neutralizations are complete and fast reactions, producing just water and salts as byproducts. This is in contrast to some previously reported molecular keypad lock systems,^[35, 37, 38] in which metal ion or anion

inputs would have to be removed by addition of competitive ligands, which could potentially interfere in the repeated device operation.

Achievement of reversible molecular logic through reading of two compartmentalized logic gates: Reversible logic is based on unambiguous mapping of input vectors to output vectors and vice versa. Hence, in this logic scheme each binary input combination leads to a unique output combination. A visibly different fluorescence output for each input combination is a promising approach for photonic coding of multi-input events. On the other hand, any basic two-input logic gate, possessing one output channel, is irreversible and information is lost upon processing the inputs. To achieve reversibility, a second output that should enable ex-



Figure 5. Repeated switching cycles of **2-SP**. The application order of UV light (302 nm), acid (TFA), base (P₂-Et) and light of $\lambda > 530$ nm is shown for the first cycle and is identical for the subsequent cycles.

actly one non-repeated output combination per input vector is needed. It should be noted that the term "reversible logic" is not to be confused with "chemical reversibility", which is a precondition for recycling and resetting of a logic device (see, for example, Figure 5 for the case discussed above). In accordance with the necessity of two output channels, a PET-based anthracene fluorescence switch (compound **5**) and the spiropyran-fluorophore dyad **2-SP** were used. Each shows fluorescence in spectrally well-distinguish-

ed regions and was operated in a separate cuvette. This compartmentalization approach has been used previously by others for the achievement of logic networks.^[54–56,58]

As the initial states, compounds $5H^+$ and $2-MEH^+$ (Scheme 3) were chosen, and the inputs (Figure 6) consisted of the addition of P₂-Et base (1 equiv, In_1) and irradiation with light of $\lambda > 420$ nm (In_3). The outputs are defined as O_1 (aminonaphthalimide fluorescence) and O_2 (anthracene fluorescence). Irradiation of $2-MEH^+$ (In_3) converts this



Figure 6. Normalized fluorescence spectra (λ_{exc} =375 nm) of **5H**⁺ (left) and **2-MEH**⁺ (right) upon addition of base (In_1) and upon irradiation at $\lambda > 420$ nm (In_3). The input that actually leads to effective fluorescence switching is indicated for each system. The other input for the corresponding system (In_3 for **5H**⁺ and In_1 for **2-MEH**⁺) does not change the fluorescence. The dotted vertical lines mark the readout wavelengths.

dyad to its 2-SP form, which shows the highest fluorescence output. Deprotonation (application of In_1) yields 2-ME, in which EET still keeps the fluorescence output O_1 low. Application of both inputs (In_1 and In_3), regardless of their order, again yields the 2-SP form $(O_1 \text{ high})$. It is important to note that a change in the input irradiation wavelength to $\lambda > 420$ nm, at which both the ME form and the MEH⁺ form are simultaneously irradiated, removes the above designed sequential feature and leads to combinational logic. Indeed, no sequential logic is required for the design of the reversible logic device. The behaviour of 2-MEH⁺ conforms to a TRANSFER gate (see upper logic circuit with In_1 , In_3 , O_1 in Scheme 4).^[59] On the other hand, deprotonation through addition of base (In_1) to $5H^+$ as the initial state of the other switch activates PET from the appended amino function, yielding practically quantitative fluorescence quenching (>95%). The application of In_3 has no consequence for the anthracene switch, which lacks significant absorption above 400 nm. This is an important point, because the direct irradiation of anthracene could yield photoproducts, which is not desired in the present context of reversible logic. In this scenario 5H⁺ acts as an INVERTER gate with respect to In_1 (or to a more complex circuit with respect to both inputs In_1 and In_3 ; see lower part with output O_2 of the circuit in Scheme 4). The combination of both switches in one truth table (Table 2) shows that each input combination



Scheme 4. Representation of the logic circuit corresponding to the logically reversible switching of the **2-MEH⁺/5-H⁺** combination by In_1 and In_3 .

Table 2. Truth table of the reversible logic gate 5H⁺/2-MEH⁺.

$In_1^{[a]}$	$In_3^{[b]}$	$O_1^{[c]}(I_{\rm f,rel})$	$O_2^{[d]}(I_{\rm f,rel})$
0	0	0 (0.62)	1 (0.99)
1	0	0 (0.64)	0 (0.03)
0	1	1 (1.00)	1 (1.00)
1	1	1 (1.00)	0 (0.03)

[a] P₂-Et (1 equiv). [b] $\lambda > 420$ nm, 210 s. [c] Aminonaphthalimide fluorescence, $\lambda_{obs} = 512$ nm; threshold $I_{frel} = 0.7$. [d] Anthracene fluorescence, $\lambda_{obs} = 416$ nm; threshold $I_{frel} = 0.7$.

corresponds exactly to one unique output combination. The chemical processes (light-induced or acid-base-triggered) for **2-SP/2-MEH**⁺ are reminiscent of the data shown above (Figure 5; the selective irradiation of ME at $\lambda > 530$ nm is substituted by light of $\lambda > 420$ nm, which isomerizes both the MEH⁺ and the ME forms to the SP form). Hence, the recycling and reset capabilities of the system are identical. The recycling of the anthracene switch **5** for various alternating additions of acid and base is also possible (see the Supporting Information).

Conclusion

The emissions of carefully selected fluorophores (aminonaphthalimide, dansyl and perylene) appended to a spiropyran can be switched by control of electronic energy transfer. These dyads were designed to yield large spectral overlap between the fluorophore emission and the absorption of the open merocyanine forms of the photochrome, whereas the closed spiropyran form has a zero overlap integral. The dynamic range of the fluorescence switching is dependent on the photostationary state distribution of the spiro form and the merocyanine ME, which in all cases reached an approximate ratio of 55:45 (% SP/% ME). This corresponds to an OFF/ON switching factor of about 2. The fluorescence modulation can be used in the design of a sequential molecular logic device, working as a two-input priority AND gate (2-PAND), and in conjunction with an acidochromic anthracene PET switch a logically reversible gate resulted. Only a few examples of these two comprehensive logic functions

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have been achieved previously. The hybrid approach chosen here (combination of chemical and photonic signals) is a promising strategy for achieving high levels of logic functionality. The coinciding photonic natures of the output and one input should in principle allow concatenation. Finally, from a conceptual point of view, the chemical input serves as an example of a sensing input, whereas the photonic input opens the possibility for remote control of the device.

Experimental Section

Irradiation: Light with $\lambda > 420 \text{ nm}$ and with $\lambda > 530 \text{ nm}$ was generated with a Xe lamp (150 W) together with long-pass glass filters (λ cut-on = 420 nm and 530 nm). The resulting light power densities on the samples were $\approx 30 \text{ mW cm}^{-2}$ and $\approx 18 \text{ mW cm}^{-2}$, respectively. The 302 nm UV light was generated with a UVP handheld UV lamp (Model UVM-57, 1.5 mW cm⁻² power density). The irradiation time used for the photo-isomerisations was 210 s in all cases.

Photophysical measurements: All measurements were performed in airequilibrated acetonitrile solutions at room temperature. The UV/Vis absorption spectra were recorded with a UV-1603 spectrophotometer from Shimadzu or with a CARY 5000 UV/Vis/NIR spectrophotometer. The fluorescence spectra were recorded with a Cary Eclipse fluorimeter from Varian. The fluorescence quantum yields were determined with quinine sulfate (Φ_t =0.55 in H₂SO₄ (0.05 M))^[60] as standard and corrected for differences in the refractive indexes of the reference and sample solvents. The quantum yield of dansyl fluorescence in the dyad **3-SP** is corrected for the absorbance of the spiropyran at the excitation wavelength (341 nm).

The absorption spectra shown in Figure 1 were recorded with samples in which virtually 100% had been converted to the appropriate forms. The experimental protocol has been described in the literature previously.^[61]

The fluorescence lifetimes of **2-M**, **3-M** and **4-M** and the corresponding lifetimes of **2-SP**, **3-SP** and **4-SP** were measured by use of pulsed laser diodes at 377 nm or 405 nm (PicoQuant) with 10 MHz repetition rates as the excitation sources. The emitted photons were recorded at 505 nm under magic angle conditions and were detected with a thermoelectrically cooled microchannel plate photomultiplier tube (MCP-PMT R3809U-50; Hamamatsu). The fluorescence signals were recorded until 10000 counts were obtained in the top channel.

The lifetimes of the ME and MEH+ forms of the dyads (2-ME, 3-ME, 4-ME, 2-MEH⁺, 3-MEH⁺, 4-MEH⁺) were measured with a streak camera system. The excitation pulses were provided by a Tsunami Ti:sapphire laser (Spectra-Physics) that was pumped with a Millennia Pro X laser (Spectra-Physics). The Tsunami laser output was tuned to 796 nm and subsequently frequency-doubled to 398 nm. The photons emitted from the samples were passed through a spectrograph (Acton SP2300, Princeton Instruments) and were registered with a streak camera (C5680, Hamamatsu) with a synchroscan unit (M5675, Hamamatsu). Every single frame was measured and stored individually and the time-resolved fluorescence spectra were obtained after jitter correction. From these timeresolved fluorescence spectra, the fluorescence time profiles were extracted and fitted to biexponential expressions, including the instrument response function. The samples of the ME and the MEH+ forms of the dyads were repeatedly refreshed with doses of 302 nm light (1 min) during the time-resolved fluorescence measurements.

Representative procedure for the synthesis of the fluorophore-spiropyran dyads (compound 2-SP): A solution of the succinimidyl ester of 1-SP (50 mg, 0.1 mmol) and N-(2-aminoethyl)-4-amino-1,8-naphthalimide (26 mg, 0.1 mmol) in tetrahydrofuran/dichloromethane (2:3, 8 mL) and N,N-dimethylformamide (4 mL) was stirred at room temperature for 2.5 h. The resulting mixture was diluted with dichloromethane and washed with brine and water. The organic phase was dried over Na₂SO₄.

Removal of the solvent with a rotary evaporator yielded the crude product, which was purified by flash chromatography (SiO₂) with a mixture of dichloromethane/methanol (95:5) as eluent to afford 2-SP (34 mg, 54%). ¹H NMR (400 MHz, CDCl₃, 25 °C): δ = 8.57 (dd, J = 7.2, 0.8 Hz, 1H; Ar-H), 8.37 (d, J=8.4 Hz, 1H; Ar-H), 8.10 (dd, J=8.4, 0.8 Hz, 1H; Ar-H), 7.95 (dd, J=8.8, 2.4 Hz, 1H; Ar-H), 7.90 (d, J=2.4 Hz, 1H; Ar-H), 7.63 (t, J=8.0 Hz, 1H; Ar-H), 7.12 (dt, J=8.0, 1.2 Hz, 1H; Ar-H), 7.03 (dd, J=7.6, 0.8 Hz, 1 H; Ar-H), 6.88–6.76 (m, 3 H; Ar-H), 6.66 (d, J=8.8 Hz, 1H; Ar-H), 5.58 (d, J = 7.6 Hz, 1H; Ar-H), 6.34 (m, 1H; NH), 5.80 (d, J=10.4 Hz, 1 H; vinyl-H), 5.01 (brs, 2 H; NH₂), 4.40-4.32 (m, 2 H; CH₂), 3.22-3.06 (m, 2H; CH₂), 3.66-3.56 (m, 2H; CH₂), 2.22-2.08 (m, 2H; CH₂), 1.94–1.82 (m, 2H; CH₂), 1.22 (s, 3H; CH₃), 1.12 ppm (s, 3H; CH₃); ¹³C NMR (100.6 MHz, CDCl₃, 25 °C): $\delta = 172.7$, 165.3, 164.8, 159.8, 150.0, 147.1, 140.9, 135.9, 134.3, 131.9, 130.0, 128.2, 128.0, 127.5, 125.9, 125.0, 122.8, 122.7, 122.1, 121.7, 120.0, 119.6, 118.6, 115.6, 111.2, 109.6, 107.0, 106.9, 52.9, 43.3, 40.2, 39.3, 33.9, 26.1, 24.8, 20.0 ppm; HRMS (TOF, EI+): m/z: calcd for C₃₆H₃₃N₅O₆: 631.2431; found: 631.2422.

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ref. [41]); b) aminonaphthalimide: $E_{ox} = 1.20$ V, $E_{red} = -1.41$ V (both in butyronitrile, ref. [44]), $E^* = 2.7$ eV (determined for **2M** according to ref. [44]); c) dansyl: $E_{ox} = 0.9$ V, $E_{red} = -2.02$ V (both in acetonitrile, ref. [45]), $E^* = 3.0$ eV (determined for **3M** according to ref. [44]); d) perylene: $E_{ox} = 0.85$ V (in acetonitrile, ref. [46]), $E_{red} =$ -1.67 V (in *N*,*N*-dimethylformamide, ref. [46]), $E^* = 2.8$ eV (determined for **4M** from the intersection of the normalized absorption and emission spectra). The redox potentials refer to closely related model compounds as used in the cited references. The Coulomb term *C* was taken as -0.06 eV in acetonitrile.

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