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Signal Processing at the Molecular Level

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Human sensory receptors transduce chemical, light, mechanical, and thermal stimulations into nerve impulses, which are transmitted to the brain.[1] This sequence of events involves a concatenation of processes at the molecular level. At each step, input signals of one form are converted into output signals of another. This complex mechanism is related conceptually to the manipulation of binary data in microprocessor systems.[2] The data introduced into a computer are elaborated through a sequence of logic operations and converted in a specific output. In modern microprocessor systems, logic circuits are built integrating electronic devices. However, they could be fabricated combining mechanical, pneumatic, or other types of devices, including *molecular-sized switches*.[3]

Molecules able to perform simple logic operations are known.[4–6] Reliable and efficient methods to integrate organic compounds into simple circuits are starting to be developed.[7–10] The fabrication of nanoscaled logic circuits incorporating sequences of molecular switches can be envisaged. The resulting artificial systems will be able to reproduce the functions of their natural counterparts by detecting, elaborating, and transmitting signals at the molecular level. Their development requires first a fundamental understanding of the behavior of individual molecules in response to environmental stimulations. It is necessary to establish how (1) ultraminiaturized switches can be addressed precisely from the macroscopic level, (2) they can elaborate such input signals, and (3) they can transmit their response in the shape of measurable output signals. We have designed, synthesized, and investigated a three-state molecular switch. This relatively simple system combines light and chemical stimuli transducing them into optical outputs through a complex sequence of logic operations.

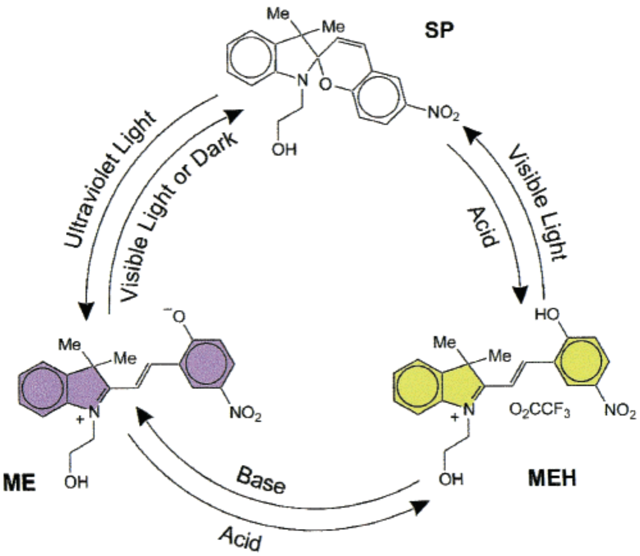

Figure 1. The switching cycle associated with the three states **SP**, **ME**, and **MEH**.

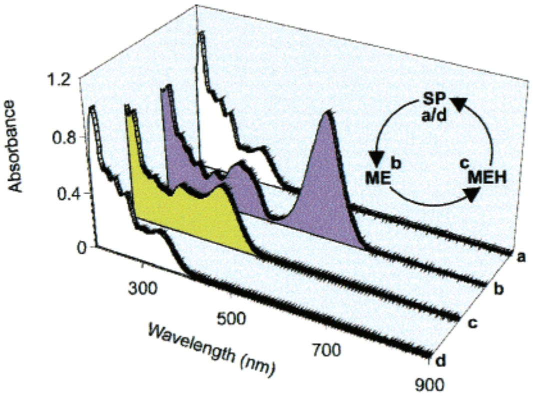

Figure 2. The absorption spectra of (a) a solution of **SP** (1.0×10^{-4} M, MeCN, 25 °C) and of the same solution after the consecutive (b) irradiation with ultraviolet light, (c) addition of 1 equiv of CF_3CO_2H, and (d) irradiation with visible light.

The spiropyran derivative **SP** was synthesized in three steps, starting from 2,3,3-trimethyl-3*H*-indole. Light and chemical stimulations induce the switching of **SP** (Figure 1) to the merocyanine forms **ME** and **MEH**. The differences in the absorption and emission properties of the three states can be exploited to follow anticlockwise (Figure 2) and clockwise (Figure 3) switching cycles starting and ending with **SP**.

The absorption spectrum of a colorless solution of **SP** (Figure 2a) does not show bands at wavelengths greater than 400 nm. Upon irradiation of this solution with ultraviolet light, the colorless **SP** switches to the purple **ME**.[11] The appearance of an absorption band at 563 nm (Figure 2b) and an emission band at 647 nm accompanies this process.[12] Upon addition of 1 equiv of CF_3CO_2H, the purple **ME** switches completely to the yellow-green **MEH**. Consistently, the absorption band at 563 nm and the emission band at 647 nm disappear. An absorption band at

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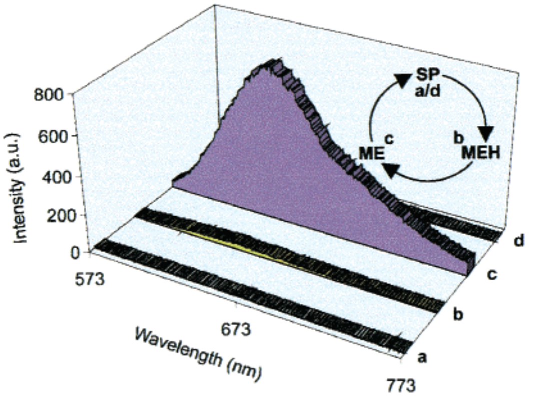

Figure 3. The emission spectra of (a) a solution of **SP** (1.0×10^{-5} M, MeCN, 25 °C, $\lambda_{exc.} = 563$ nm) and of the same solution after the consecutive (b) addition of 1 equiv of CF_3CO_2H, (c) treatment with K_2CO_3, and (d) irradiation with visible light.

401 nm is observed instead (Figure 2c). This band disappears (Figure 2d) when the solution is irradiated with visible light,[13] as **MEH** switches completely to **SP** closing the anticlockwise cycle.

Upon addition of 1 equiv of CF_3CO_2H to a colorless solution of **SP** maintained in the dark, **SP** switches to the yellow-green **MEH**. The appearance of a band at 401 nm in the absorption spectrum accompanies this process.[14] However, no emission bands are detected before and after acidification (Figure 3a and b). Treatment of a yellow-green solution of **MEH** with K_2CO_3 is followed by the formation of a purple color.[15] Under these conditions, **MEH** switches completely to **ME**. An absorption band at 563 nm and an emission band at 647 nm (Figure 3c) appear. The purple **ME** switches completely to the colorless **SP**, closing the clockwise cycle, when the solution is either irradiated with visible light or stored in the dark. The disappearance of the absorption band at 563 nm and the emission band at 647 nm (Figure 3d) accompanies this process.[16]

This three-state molecular switch detects three input signals. They are (**_I_1**) ultraviolet light, (**_I_2**) visible light and (**_I_3**) H^+. It responds to these stimulations generating two output signals. They are (**_O_1**) the absorption band at 401 nm of **MEH** and (**_O_2**) that at 563 nm of **ME**.[17] Each signal can be either *on* or *off* and can be represented by a binary digit, i.e. it can only take two values *1* or *0*. Thus, the molecular switch *reads* a string of three binary inputs and *writes* a specific combination of two binary outputs. For example, when the three stimulations **_I_1**−**_I_3** are all *off*, the input string is *000*. Under these conditions, the molecular switch is in state **SP**, which does not have absorption bands at wavelengths greater than 400 nm. As a result, the two output signals **_O_1** and **_O_2** are *off* and the output string is *00*. If the stimulations **_I_1** and **_I_3** are *on*, while **_I_2** is *off*, the input string is *101*. Under these conditions (ultraviolet light and H^+), the molecular switch is in state **MEH**, which shows the absorption band at 401 nm only. In this case, the output **_O_1** is *on*, while **_O_2** is *off*, and the output string is *10*. All the possible combinations of input data and the corresponding output strings are illustrated in Table 1.

Table 1. Truth Table for the Three-State Molecular Switch Where a *0* Indicates That the Corresponding Signal Is *Off* and a *1* That It Is *On*

Input Data			Output Data	
Ultraviolet Light _I_1	**Visible Light _I_2**	**H^+ _I_3**	**Absorption at 401 nm _O_1**	**Absorption at 563 nm _O_2**
0	*0*	*0*	*0*	*0*
0	*0*	*1*	*1*	*0*
0	*1*	*0*	*0*	*0*
1	*0*	*0*	*0*	*1*
0	*1*	*1*	*0*	*0*
1	*0*	*1*	*1*	*0*
1	*1*	*0*	*0*	*1*
1	*1*	*1*	*1*	*0*

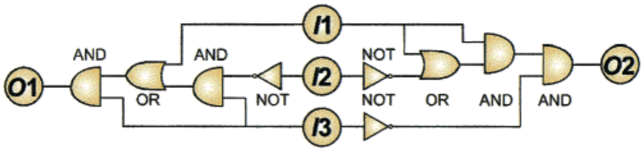

Figure 4. The logic circuit equivalent to the three-state molecular switch transduces the inputs **_I_1**−**_I_3** into the outputs **_O_1** and **_O_2** through AND, NOT, and OR operations.

The combinational logic circuit (Figure 4) equivalent to this truth table illustrates the complexity of the operations executed by the three-state molecular switch. *Nine logic elements are necessary to reproduce the functions performed by a single molecule.* In this circuit, the three inputs **_I_1**−**_I_3** are elaborated through a series of AND, NOT, and OR operations to produce the two outputs **_O_1** and **_O_2**. The eight possible combinations of input data are transduced into three of the four potential strings of output data. The logic circuit *excludes* the output string *11*, which is never produced. Indeed, the two output signals cannot be *on* simultaneously. They correspond to two distinct states of the molecular switch that cannot coexist in solution.

The next step in the development of molecule-based logic circuits will be the attachment of molecular switches to appropriate supports. The resulting solid-state devices will be able to elaborate information by detecting inputs of one form and transducing them into outputs of another. Ultraminiaturized nanoprocessors formed by arrays of integrated molecular switches are coming.

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Supporting Information Available: Experimental procedures for the synthesis of **SP** and for the determination of the rate constants (PDF). This material is available free of charge via the Internet at http://pubs.acs.org.

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(11) The solution was irradiated for 5 min at 254 nm using a Mineralight UVGL-25 lamp. During irradiation, the ratio between **SP** and **ME** changed from the initial 100:0 to a stationary 80:20. These values were derived from the absorbance measured at 563 nm using the molar extinction coefficient of the merocyanine form of the parent compound 1′,3′-dihydro-1′,3′,3′-trimethyl-6-nitrospiro[2*H*-1-benzopyran2.2′(2*H*)-indole]. Sakuragi, M.; Aoki, K.; Tamaki, T.; Ichimura, K. *Bull. Chem. Soc. Jpn.* **1990**, *63*, 74−79.

(12) These absorption and emission bands decrease gradually when the solution is either irradiated with visible light (15 min, 524 nm, Cole-Parmer Fiber Optic Illuminator 9745-99) or maintained in the dark. Under both conditions, the purple **ME** switches completely back to the colorless **SP**. The rate constant for the switching from **ME** to **SP** in the dark at 25 °C is $(41 \pm 1)\cdot 10^{-4}\ s^{-1}$.

(13) This absorption band reappears upon irradiation with ultraviolet light, as **SP** switches to **MEH** through the formation of **ME**. During this switching process, the ratio between **SP** and **MEH** changes from the initial 100:0 to a stationary 70:30. These values were derived from the absorbance measured at 401 nm using the molar extinction coefficient determined in the kinetic studies described in ref 14.

(14) The rate constant for the switching from **SP** to **MEH** in the dark at 25 °C is $(8 \pm 2)\cdot 10^{-2}\ M^{-1}\cdot s^{-1}$. During this switching process, the ratio between **SP** and **MEH** changes from the initial 100:0 to a stationary 70:30.

(15) The solution was filtered through a plug of K_2CO_3.

(16) After treatment with base, the rate constant for the switching from **ME** to **SP** in the dark at 25 °C is $(36 \pm 3)\cdot 10^{-4}\ s^{-1}$.

(17) Instead of the absorption band at 563 nm of **ME**, its emission band at 647 nm can be used as output signal **_O_2**.