Light-Gated Rotation in a Molecular Motor Functionalized with a Dithienylethene Switch

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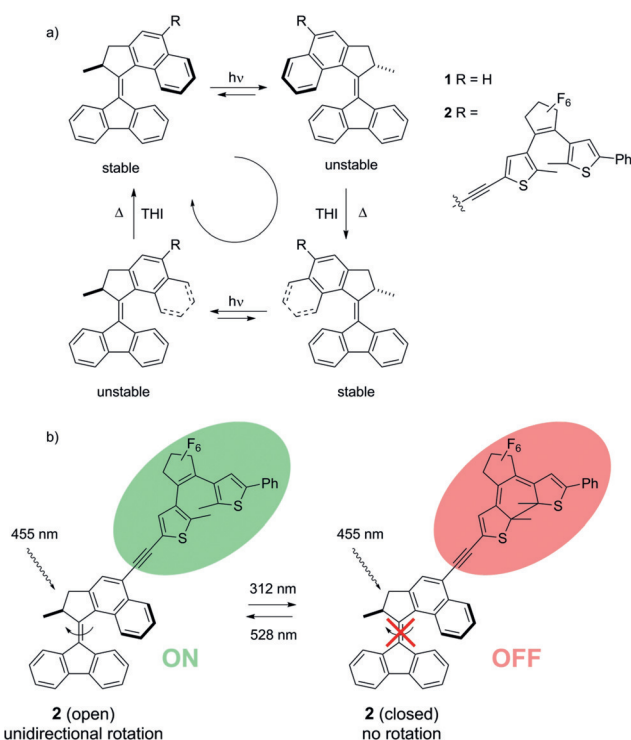
Abstract: *A multiphotochromic hybrid system is presented in which a light-driven overcrowded alkene-based molecular rotary motor is connected to a dithienylethene photoswitch. Ring closing of the dithienylethene moiety, using an irradiation wavelength different from the wavelength applied to operate the molecular motor, results in inhibition of the rotary motion as is demonstrated by detailed ^{1}H-NMR and UV/Vis experiments. For the first time, a light-gated molecular motor is thus obtained. Furthermore, the excitation wavelength of the molecular motor is red-shifted from the UV into the visible-light region upon attachment of the dithienylethene switch.*

*I*nspired by the wealth of molecular machines found in nature, which drive and regulate a wide range of processes such as muscle contraction and ATP synthesis, a large collection of synthetic molecular machines has been developed over the last decades.[1–15] Prominent examples of such artificial machines include a molecular elevator,[9] a molecular brake,[10] a nanocar,[11] a molecular walker,[12] and a synthesizer,[13] which are all powered by either chemical fuel, redox processes, or light. The use of light as a stimulus offers the advantage that it is non-invasive and does not produce any waste products.[6,8] Moreover, it can be easily tuned in terms of wavelength and intensity and it can be applied with high spatiotemporal control. These advantages have stimulated the application of light-driven molecular switches[14] and motors in functional materials[8,15–20] and biological systems.[21–24] However, potentially harmful UV light is typically used for their operation while, for practical applications, the use of visible light is often desired.[25–31]

One of the major contemporary challenges in the development of light-driven switches and motors is to design systems that can be controlled by more than one stimulus, thereby offering a higher level of control. Gated photo-

chromism, which is the ability to turn photoswitching processes on and off using a stimulus that is complementary to light, provides such control. Different stimuli have been used in the past to achieve gated photochromic systems, for example ion complexation,[32–35] pH change,[36,37] redox processes,[38–40] or host–guest interactions.[41] We envisioned that the use of light of a different wavelength than the wavelength that is used for photoswitching could be a viable alternative. However, to our best knowledge, no successful examples of light-gated photochromism have been reported so far, which is most probably due to a lack of orthogonality.[42]

Light-driven molecular motors based on overcrowded alkenes represent unique photoresponsive systems in the sense that they undergo unidirectional rotation around their central double bond (Scheme 1a).[43–45] Promising applications have been demonstrated in nanotechnology,[11,46,47] catalysis,[48,49] and anion binding,[50,51] amongst others. Unidirectional rotation is achieved by sequential photochemical E–

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Scheme 1. a) A full 360° rotary cycle of molecular motors **1** and **2** (note that the isomer generated after 180° rotation is identical to the starting isomer, but has a different viewpoint). b) Representation of light-gated rotary motion through switching between the open and closed form of the appending DTE moiety.

Z isomerization and thermal helix inversion steps (Scheme 1a). In the first step, an unstable isomer is generated photochemically in which the methyl substituent at the stereocenter adopts an energetically unfavored pseudo-equatorial orientation. The strain that is built up around the double bond is subsequently released by a thermal helix inversion (THI) process, in which the aromatic moieties of the upper and lower half slide along each other. After this thermal step, the thermodynamically favored pseudo-axial orientation of the methyl group is restored. A second photochemical *E–Z* isomerization, followed by a THI, completes a full 360° rotation.

Several approaches have been taken to dynamically control the rotary behavior of molecular motors with a second stimulus, all of which have required chemical additives. Illustrative examples are the locking of rotation using an acid/base-responsive self-complexing pseudorotaxane[52] and the reversal of the rotary direction by base-catalyzed epimerization.[53] More recently, we reported an allosteric approach in which the rotational speed can be regulated by metal complexation.[54] Whereas all of these approaches rely on chemical additives, we considered the development of a non-invasive approach to be an important next step. We now present the first example in which the rotary behavior of a light-driven molecular motor can be controlled by an additional light source. In our design, a second-generation molecular motor is connected to a dithienylethene (DTE) switch to give a multiphotochromic hybrid system (Scheme 1b). Interestingly, the molecular motor can be operated with visible light ($\lambda_{irr} = 455$ nm) instead of the generally used UV light. Upon closing of the DTE switch by UV light ($\lambda_{irr} = 312$ nm), the rotation of the molecular motor is inhibited, a process that can be reversed by irradiation with light of a longer wavelength ($\lambda_{irr} = 528$ nm), which opens the switch.

For the synthesis of target molecule **2**, a DTE switch bearing a TMS-protected acetylene moiety was first obtained by following a modified reported procedure (see the Supporting Information for full synthetic details).[55] Subsequent TMS removal followed by a palladium-catalyzed Sonogashira coupling with a bromo-substituted molecular motor (**1**, R = Br) afforded hybrid **2**.

The possible photochemical and thermal isomerization steps of **2**, as illustrated in Scheme 2, were first followed by ¹H-NMR spectroscopy. Figure 1i shows the ¹H-NMR spectrum of the stable open (**so**) isomer of hybrid **2** in CD₂Cl₂. Upon irradiation with 455 nm light at −25°C, a new species appeared (Figure 1ii). In analogy to the unsubstituted parent motor **1**,[56] the clear shifts of ¹H-NMR signals H_a, H_c, and $H_{c'}$ are characteristic for the photochemically induced formation of the unstable **2uo** (Scheme 2). Moreover, the doublet signal for H_d has a clearly distinct chemical shift for each isomer. The sample was irradiated until no further changes were observed, that is, the photostationary state had been reached. The ratio of unstable/stable at this photostationary state (PSS₄₅₅) was found to be 66:34. When the sample was warmed up to room temperature, the THI was allowed to take place, resulting in quantitative conversion to the stable state (that is, isomer **2so**).
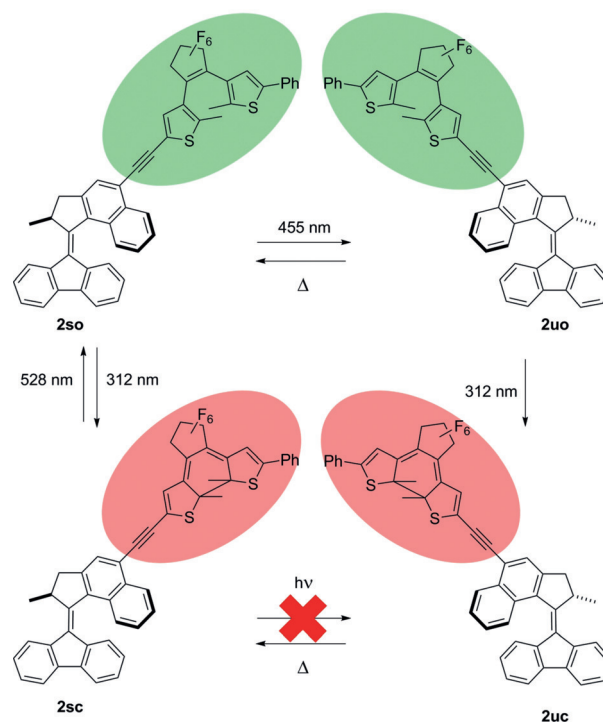
Scheme 2. Photochemical and thermal isomerization steps of hybrid **2**.

The same NMR sample was then irradiated with 312 nm light at room temperature to isomerize the DTE moiety to its closed isomer **2sc** (Figure 1iii). The expected formation of isomer **2sc** was evident from the shifts of protons H_e, belonging to the methyl substituents of the thiophene moieties, and proton H_d. At the PSS₃₁₂, the ratio of closed/open isomer was found to be approximately 70:30.[57] The sample was subsequently irradiated with 455 nm light at −25°C to test whether the closed hybrid **2sc** could be isomerized to the unstable state **2uc** (Figure 1iv). If isomerization would be allowed, the unstable **2uc** should be observed along with the unstable **2uo**. These are the photochemical isomerization products of **2sc** and **2so**, respectively, which were present in a 70:30 ratio. After irradiation, the sample contained **2uo**, but **2uc** was absent, thus revealing inhibition of isomerization in the closed form. It should be noted that at the same time, some opening of the DTE switch also occurs when the sample is irradiated with 455 nm light, which is unusual for DTE switches at this wavelength. The rate of the opening of the DTE switch is, however, significantly lower than when the sample is irradiated with 528 nm light.

The unstable closed isomer **2uc** could be accessed by another route. That is, by first irradiating a sample of **2so** with 455 nm light at −25°C to give isomer **2uo**, and subsequently with 312 nm light at the same temperature to close the DTE switch (Scheme 2). The spectrum in Figure 1v corresponds to this experiment and reveals a fourth doublet of H_d belonging to the unstable closed isomer. Allowing the sample to warm up to room temperature leads to quantitative conversion of **2uc** back to **2sc** and of the remaining **2uo** back into **2so**. These combined NMR experiments reveal that the motor
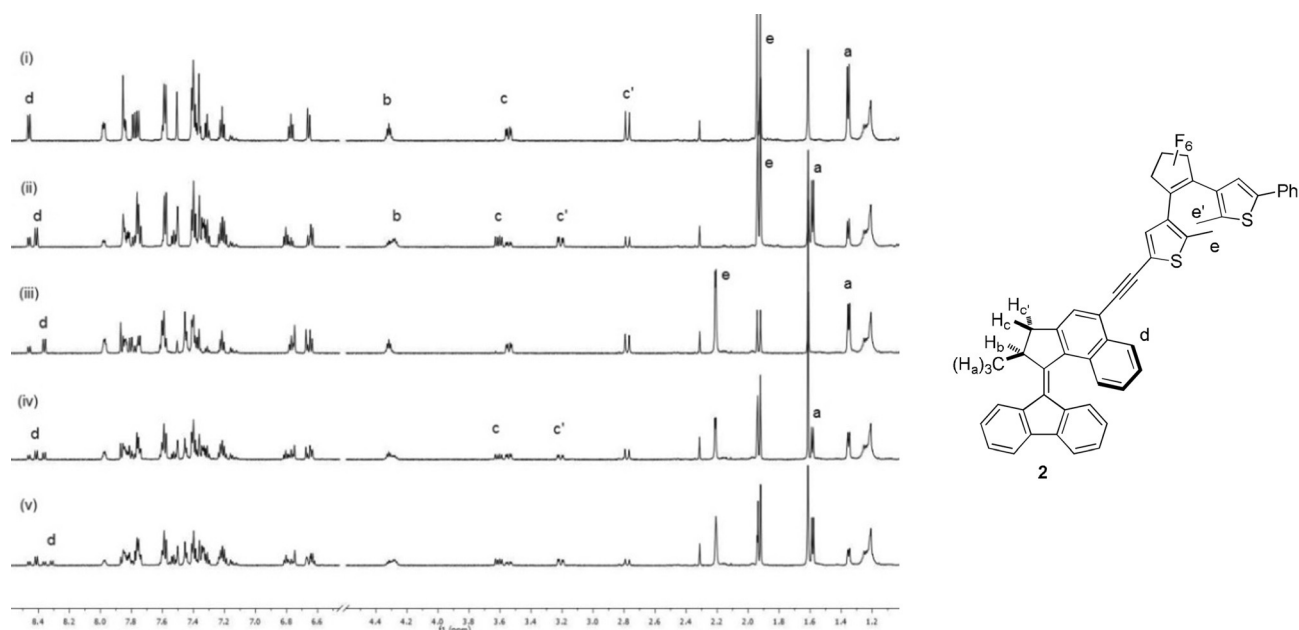
Figure 1. ¹H-NMR spectra of **2** in CD₂Cl₂. i) Before irradiation; ii) PSS 455 nm; iii) PSS 312 nm; iv) sample from (iii) irradiated with 455 nm; v) sample from (ii) irradiated with 312 nm.

functions as usual when the DTE switch is in the open state, but that rotation is impeded when it is closed. Thus, the rotary function can be controlled by light of a different wavelength than the wavelength that is used to operate the molecular motor. This gated photochromic behavior is most likely due to an energy-transfer process from the motor to the DTE moiety in analogy to other multiphotochromic systems.[42,58]

The isomerization behavior of hybrid **2** was additionally studied by UV/Vis spectroscopy. The UV/Vis spectrum of a solution of **2so** in CH₂Cl₂ shows an absorption band with a maximum at $\lambda = 423$ nm (Figure 2). This absorption band is bathochromically shifted compared to the parent unsubstituted molecular motor **1**, which has an absorption maximum at $\lambda = 395$ nm.[56] Most likely, this bathochromic shift is caused by extension of the π system. Aromatic extension has been shown before to be suitable to shift the excitation wavelength of molecular motors into the visible-light region.[59]

Upon irradiation of a UV/Vis sample of **2so** with 455 nm light at −9 °C, a bathochromic shift was observed (Figure 2 a), which is characteristic for the formation of the unstable isomer **2uo**.[56] A clear isosbestic point at $\lambda = 447$ nm (Figure S1 in the Supporting Information) revealed that this photochemical isomerization is a unimolecular process. The quantum yield for this photochemical step ($\Phi_{so\to uo}$) was estimated by comparing the rate of formation of **2uo**, which was determined by following the absorption increase at $\lambda = 505$ nm at a concentration high enough to absorb all incident light, with that of Fe²⁺ ion formation from potassium ferrioxalate under identical conditions (Figures S2 and S3). A quantum yield of $\Phi_{so\to uo} = 5.6\%$ was measured and the quantum yield for the reverse photochemical isomerization step ($\Phi_{uo\to so}$) was then calculated using the PSS₄₅₅ ratio, giving $\Phi_{uo\to so} = 3.3\%$. These values are in a similar range as the quantum yields that have been measured for structurally
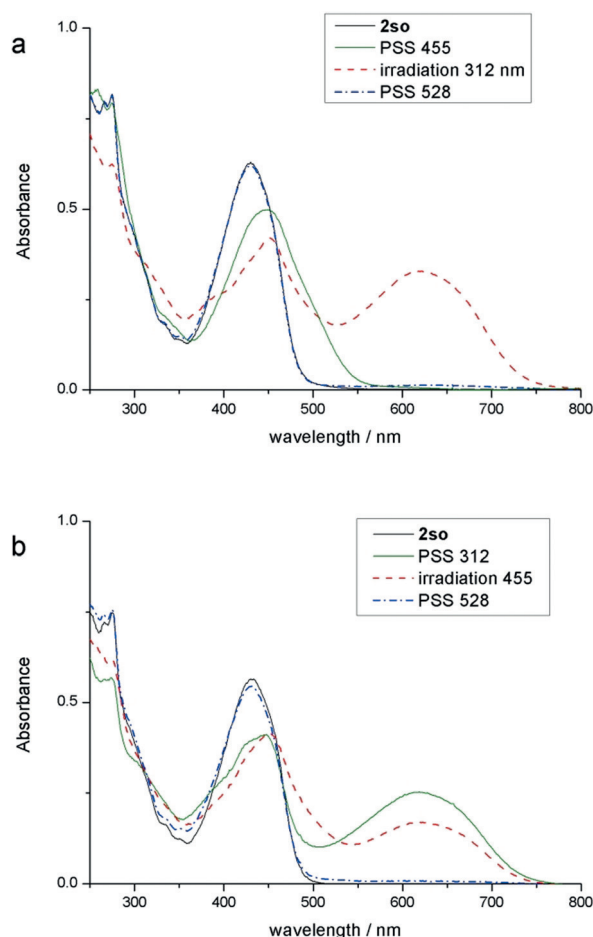

Figure 2. UV/Vis spectra of hybrid **2** in CH₂Cl₂ ($c = 1.8 \times 10^{-4}$ M). a) After irradiation with 455 nm (−9 °C) followed by 312 nm (−9 °C) and 528 nm (20 °C). b) After irradiation with 312 nm (20 °C) followed by 455 nm (−9 °C) and 528 nm (20 °C).

related molecular motors with and without substituents in the same position.[60] When the UV/Vis sample was allowed to warm to room temperature, the original spectrum was recovered, thus indicating that the THI had taken place. The rates for this thermal isomerization step were determined at five different temperatures (ranging from 0 to 20 °C) by monitoring the decrease in absorption at $\lambda = 500$ nm. Using the Eyring equation (Figure S4), the activation parameters for this process were determined. The Gibbs free energy barrier $[\Delta^{\ddagger}G(20\,°C)]$ was found to be 87.1 kJ mol^{-1}, which corresponds to a half-life ($t_{1/2}(20\,°C)$) of 370 s. These values are of the same order of magnitude as the ones determined for the unsubstituted parent molecular motor **1**, for which an energy barrier of 85 kJ mol^{-1} and a half-life of 190 s have been reported.[56] Moreover, multiple cycles of these photochemical and thermal isomerization steps could be repeated without any major signs of fatigue (Figure S5).

When a UV/vis sample of **2so** was first irradiated with 312 nm light at 20 °C, a broad band around $\lambda_{max} = 602$ nm appeared (Figure 2b, green line). This band is characteristic for the formation of the closed, more conjugated isomer of the DTE switch (isomer **2sc**),[57] the formation of which was also observed by ^{1}H-NMR spectroscopy (see above). This closed state of the DTE switch is thermally stable under the experimental conditions used and multiple close/open isomerization cycles showed only minor signs of fatigue (Figures S5 and S6).

Subsequent irradiation of this sample, containing a mixture of **2so** and **2sc**, with 455 nm light at -9 °C caused relatively small changes in the absorption band located around $\lambda_{max} = 423$ nm. The broad band in the visible region decreased, revealing some concomitant opening of the DTE switch. These results are fully consistent with the ^{1}H-NMR studies, showing that only the open isomer **2so** is able to undergo E–Z isomerization, whereas this process is inhibited for the closed isomer **2sc**. Subsequent irradiation with 528 nm light triggered almost quantitative opening of the DTE switch, as is clear from the disappearance of the absorption around $\lambda_{max} = 602$ nm.

As also described for the ^{1}H-NMR studies, isomer **2uc** could be accessed by irradiation of a sample containing **2so** with 455 nm light to afford **2uo**, followed by irradiation with 312 nm light, which caused the emergence of a broad band in the visible region (Figure 2a, red line). The emergence of this band is indicative of the formation of the closed DTE moiety. Again, opening of the DTE switch could be triggered by irradiation with 528 nm light.

In summary, we have presented a photochromic hybrid system consisting of an overcrowded alkene-based molecular motor and a DTE switch. Interestingly, by aromatic extension, the excitation wavelength is red-shifted into the visible region. Visible-light excitation leads to the usual rotary motor behavior when the DTE is in the open form. However, when closed, the rotary motion is inhibited and thus, light-gated photochromism is observed. This is the first system in which the rotary function can be switched on and off in a non-invasive manner by using an additional light source. Gated systems, like the one presented here, offer an increased level of control over photoswitching processes, which will be

essential for the development of more complex and sophisticated molecular machinery in the future. Studies on the exact mechanism of the inhibition of the rotary motion by the closed isomer of the DTE switch, which require detailed investigation of the electronic coupling of both photochromes,[58] are underway in our laboratory.

Conflict of interest

The authors declare no conflict of interest.

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