Photochromic molecular switches
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Document Version
Publisher's PDF, also known as Version of record

Publication date:
2015

Link to publication in University of Groningen/UMCG research database

Citation for published version (APA):

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Chapter 4

Photochemical Study of Hemi-Thioindigo Photoswitches

In this Chapter the photochemical isomerisation and thermal relaxation reaction of a series of hemi-thioindigo (HTI) switches are described. HTIs are a hybrid class of photochromic switches composed of a thioindigo halve and a stilbene switch halve. Upon UV irradiation, an unstable isomer is formed, which reverts to its original form. Kinetic studies using arrayed $^1$H-NMR spectroscopy revealed for HTI switches that the rate of thermal E to Z isomerisation is dependent on the solvent polarity. More polar solvents result in a higher thermal isomerization rate. The presence of EDG on the stilbene half and EWG on the thioindigo halve of the molecule has a similar lowering effect on the activation barrier to the thermal E→Z isomerization. The ability to tune the thermal stability of the E-isomer through the solvent polarity, as well as via substitution on the stilbene or thioindigo halve of the switch, make them interesting candidates as molecular probes or for switching in responsive materials and make these switches especially attractive compared to e.g. azobenzenes and stilbenes.
4.1 Introduction

Hemi-thioindigo switches are a hybrid class of photochromic switches that are composed of half of a thioindigo switch and half of a stilbene switch (Figure 4.1). The central double bond undergoes Z to E isomerization upon irradiation with UV light (Scheme 4.1). Generally the E-isomer is less stable than the Z-isomer and reverts thermally to the Z-form as a result of steric hindrance between the phenyl ring of the stilbene half and the carbonyl moiety of the thioindigo half. Since the E-form absorbs at longer wavelength than the Z-form it is possible to convert the E-isomer to the Z-isomer by irradiation with visible light (λ > 500 nm).

![Figure 4.1: Hemithioindigo, composed of a thioindigo and a stilbene half. UV/Vis absorption spectrum of the Z and E isomer of a hemithioindigo switch reproduced with permission from ref. 3](image)

The rate of the Z to E photoisomerization and the thermal E to Z isomerization can be tuned by varying the substituents on both the thioindigo and stilbene half of the molecule. Variations in the substitution of the stilbene half has a pronounced influence on the rate of Z to E and E to Z photoswitching.

![Scheme 4.1: Z to E photoswitching of hemithioindigo switches 1-4.](image)

Electron donating groups in the para-position lead to higher rates of photoisomerization. However, electron donating groups in the meta-position have a negligible effect, as this position is not in direct conjugation with the central double bond. Electron withdrawing substituents (EWG) in the para-position have a stabilizing effect on the life time (τ) of the exited state and lead to lower rates of photoisomerization. The effect of a para bromo substituent (τ = 336 ps) is minor compared with the effect of a cyano subituent (τ = 2650 ps). Whereas, a bromo...
substituent at the meta-position stabilizes the exited state and has a large effect on the rates of the Z to E ($\tau = 1480$ ps) and E to Z photoisomerization. Variations in the substitution of the thioindigo half of the switch also influence the isomerization mainly through inductive effects,$^5$ EWG (Br) have a less pronounced destabilizing effect and lead to a small decrease in time constants of the Z to E isomerization and EDG (OMe) lead to a small increase in the time constants for the isomerization. Thermal $E \to Z$ isomerization of HTI switches functionalized with a carboxyl group on the indigo half and an EDG in the meta position results in half-lives of ca. 47 h in methanol.$^6$ An EDG in the para position of the stilbene half results in a half-life of around 20 h in methanol.$^6$ A more pronounced push-pull system bearing an ammonium chloride salt in the para-position exhibits a drastic increase in the speed of the thermal relaxation, and could only be observed by time resolved spectroscopy.$^6$ In dichloromethane HTI switches bearing an ester moiety on the thioindigo part show retarded $E \to Z$ isomerization with a $t_{1/2} = 138$ h. Additionally it has been reported that functionalization with fluorine at the ortho-position of the stilbene half can lead to ring closure via the carbonyl oxygen of the thioindigo half and the ortho carbon of the stilbene moiety as a result of fluorine elimination upon photoisomerization.$^8$

Many of the aspects influencing the thermal relaxation of $E \to Z$ isomerization of HTI switches, such as substituent and solvent effects have remained unidentified. In this Chapter the synthesis and characterization of the photochemical properties of a series of HTI switches 1-4 is determined. HTI switches undergo $Z \to E$ isomerization upon irradiation at 405 nm. The $E$-isomer of HTI switches is thermally unstable, and reverts back to the stable $Z$-isomer. The thermal relaxation of the unstable $E$-isomer was investigated. Attention was given to the effect of solvent polarity on the speed of the thermal $E \to Z$ isomerization and the thermal stability of the $E$-isomer as a result of functional groups.

### 4.2 Synthesis and characterization

#### 4.2.1 Synthesis

Hemi-thioindigo (HTI) switches 1-4 were synthesised using the procedure described below.$^9$ **Para-substituted thiophenols** 5 and 6 were alkylated with bromoacetic acid under basic conditions in acetone in 91% and 95% yield, respectively. Carboxylic acids 7 and 8 were converted to their acyl chlorides, which were subsequently cyclized under Friedel-Crafts acylation conditions. The thiioindoxyls obtained were reacted with para-substituted benzaldehyde under Knoevenagel condensation reaction conditions yielding hemi-thioindigo switches 1 and 2 over three steps in 46% and 45% yield, respectively. Phenol substituted hemi-thioindigo 9 proved to be only sparingly soluble and was
protected directly as its TBDMS ether, by treating 9 with TBDMS-Cl. Ester functionalized HTI 4 was synthesized using the following procedure.\(^{8,10}\) 2,2-Dithiodisalicylic was treated with sodium dithionite to provide the corresponding thiophenol. This mixture was treated subsequently with chloroacetic acid providing the di-carboxylic acid 11 in 70% yield. Compound 11 was treated with an excess of thionylchloride resulting in the di-acyl chloride, which was cyclized to its corresponding thioindoxyl. The thioindoxyl formed was treated with 4-methylbenzaldehyde under the Knoevenagel reaction conditions to form HTI 4 in 67% yield over 3 steps.

![Scheme 4.2: Synthesis of HTI photo switches 1-4.](image)

### 4.2.2 Structural characterization

HTI switches 1 to 4 were characterized by \(^1\)H, COSY, NOESY, \(^{13}\)C, HSQC and HMBC-NMR spectroscopy. The \(^1\)H-NMR spectrum of 1 is shown in Figure 4.2. The aromatic signals of \(k\) and \(l\) at 7.26 and 7.58 ppm, respectively, both integrate to two hydrogens and correlate in the COSY-NMR spectrum (Figure 4.3), indicating that these signals correspond to the aromatic hydrogens of the stilbene part of the HTI switch. There is a correlation arising from the aromatic signals \(b\) and \(c\) at 7.36 ppm identifying these signals as hydrogens of the thio-indigo half of the switch. The signal \(k\) has NOE-correlation with signal \(i\) (Figure 4.3). Signal \(i\) is assigned as being from the alkene. Signal \(l\) was identified by its correlation with the aliphatic CH\(_3\) signal \(n\).
The NOE-correlation between the aliphatic signal at 2.39 and the aromatic signals at 7.36 ppm and at 7.72 ppm identify as the aromatic signals as protons c and e. Switches 2-4 show similar characteristics to 1 (Figure 4.6).

Figure 4.2: Calculated and experimental a) $^1$H-NMR and b) APT-NMR spectrum of 1 in CDCl$_3$. 
The $^1$H and $^{13}$C NMR spectra of 1 were calculated using B3LYP/cc-pV(T+d)Z (gas phase) for determining the geometry and GIAO/VTZ+(aug)-pcS-2/COSMO(CH$_2$Cl$_2$ or CHCl$_3$), aug-pcS-2 on O and S, pcS-2 on C and H, software: NWChem 6.1.1 for the NMR calculations. The obtained calculated isotropic chemical shift was then referenced to the experimentally obtained spectra by means of the CH$_3$ signal (2.41 ppm) on the thioindigo half. The calculated $^1$H-NMR spectrum of 1 in CDCl$_3$ corresponds reasonably well with the spectrum of 1 (Figure 4.2). Especially the down field shifted signals show similarities, the alkane signal (i) is determined to be at 8.07 ppm in the calculated spectrum, while it is observed at 7.91 ppm. The signals of the stilbene half of the switch are found at 7.78 ppm (as a doublet for hydrogens k) and 7.54 ppm (as a doublet for hydrogens l), experimentally these signals were determined to be at 7.58 and 7.26 ppm, respectively. The calculated signal for hydrogen e (7.76 ppm) in the thioindigo half of the switch corresponds very well to the experimentally determined value 7.72 ppm. Signals for hydrogens c and e were calculated to be at 7.63 and 7.53 ppm as doublets, and were obtained as a singlet integrating for two hydrogens at 7.36 ppm. The spectral characterization of switches 2 to 4 is similar to that of 1.
Table 4.1: Calculated chemical shifts in dichloromethane.*

| atom | signal | calc. isotropic shift (ppm) | | atom | signal | calc. isotropic shift (ppm) |
|------|--------|-----------------------------|------|--------|-----------------------------|
| **Z-isomer** | | | **E-isomer** | | |
| i | 1H, s | 23.28 | 8.07 | k | 2H, d | 22.47 | 8.87 |
| k | 2H, d | 23.56 | 7.78 | e | 1H, s | 23.57 | 7.78 |
| e | 1H, s | 23.59 | 7.76 | c | 1H, d | 23.73 | 7.62 |
| c | 1H, d | 23.67 | 7.67 | l | 2H, d | 23.79 | 7.55 |
| l | 2H, d | 23.78 | 7.56 | b | 1H, d | 23.87 | 7.47 |
| b | 1H, d | 23.79 | 7.56 | i | 1H, s | 24.04 | 7.31 |
| n | 3H, s | 28.88 | 2.46 | n | 3H, s | 28.86 | 2.48 |
| o | 3H, s | 28.93 | 2.41 | o | 3H, s | 28.92 | 2.43 |

* Geometry calculations in the gas phase using: B3LYP/cc-pV(T+d)Z. Subsequent NMR calculation: GIAO/KT2/(aug)-pcS-2/COSMO(CH2Cl2), aug-pcS-2 on O and S, pcS-2 on C and H. Using NWChem 6.1.1 software. The obtained calculated isotropic chemical shift was then referenced to the experimentally obtained spectra by means of the CH3 signal (2.41 ppm) on thioindigo half. Signals are denoted as following singlet; s, doublet; d.

4.3 Photochemical and thermal properties

The photochemical and thermal properties of switches 1 to 4 were determined in 1,2-dichloroethane, dichloromethane, dimethylsulfoxide and p-xylene by UV/Vis absorption, IR, Raman, fluorescence and 1H-NMR spectroscopy. Under irradiation ($\lambda_{\text{max}} = 410 \text{ nm}$) a sample of 1 (4 × 10^{-5} M in dichloroethane) undergoes Z to E photoisomerization (Figure 4.4). This isomerization generally leads to a bathochromic shift of the long wavelength absorption in the UV/Vis absorption spectrum. Irradiation of the PSS mixture of 1 at $\lambda = 485 \text{ nm}$ results in the recovery of the original UV/Vis absorption spectrum (Figure 4.4b). Photoswitching of HTI switches 1-4 from the Z to the E isomer results in a decrease in fluorescence intensity (Figure 4.5, Table 4.2).
Figure 4.4: UV/Vis absorption spectroscopy of 1 in dichloromethane (4 × 10⁻⁵ M) a) under irradiation λ = 410 nm. b) Photostationary state mixture of 1 at λ = 485 nm, insert shows switching cycles.

Figure 4.5: Fluorescence spectra of Z-1 and Z-2 in DCM. a) Z-1, b) Z-2 and their PSS mixtures at λ = 405 nm. The bands at λ_max = 690 nm represent Raman scattering from the excitation wavelength.

The fluorescence quantum yield of switches Z-1 to Z-4 is relatively low, and of the order of 0.01-0.3%. While the photochemical quantum yields of Z to E isomerisation are low and of the order of 1-5%. These results correspond well to previously reported quantum yields for HTI switches in benzene. ¹¹ Nenov et al. have reported quantum yields for switching Φ_E-Z of 23% for a non-substituted HTI. ¹⁶a

Table 4.2: Spectroscopic parameters of a series of HTI switches.

<table>
<thead>
<tr>
<th></th>
<th>λ_max Z (nm)</th>
<th>ε_Z (10^3 M⁻¹ cm⁻¹)</th>
<th>λ_max Fl (nm)</th>
<th>ΦZ</th>
<th>PSS</th>
<th>λ_max E (nm)</th>
<th>ε_E (10^3 M⁻¹ cm⁻¹)</th>
<th>ΦE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>442</td>
<td>12.0</td>
<td>503 (430)</td>
<td>2.7×10⁻⁵</td>
<td>82%</td>
<td>448</td>
<td>7.5</td>
<td>0.01</td>
</tr>
<tr>
<td>2</td>
<td>445</td>
<td>13.5</td>
<td>498 (440)</td>
<td>1.1×10⁻³</td>
<td>80%</td>
<td>453</td>
<td>7.8</td>
<td>0.04</td>
</tr>
<tr>
<td>3</td>
<td>451</td>
<td>17.9</td>
<td>495 (455)</td>
<td>1.4×10⁻³</td>
<td>82%</td>
<td>457</td>
<td>10.7</td>
<td>0.03</td>
</tr>
<tr>
<td>4</td>
<td>436</td>
<td>14.3</td>
<td>480 (417)</td>
<td>6.7×10⁻⁴</td>
<td>88%</td>
<td>448</td>
<td>7.5</td>
<td>0.05</td>
</tr>
</tbody>
</table>

PSS as a result of irradiation (λ, 365 nm, CD₂Cl₂, -20°C) of stable Z-isomer to the E-isomer were determined by ¹H NMR spectroscopy.
Irradiation of a sample containing 1 (1.4 × 10⁻³ M, dichloromethane-d₂) to the PSS at \( \lambda = 410 \text{ nm} \) led to shifts of the aromatic signals in its \(^1\text{H-}\text{NMR} \) spectrum. At the PSS\(_{410 \text{ nm}} \), 82% of the sample consists of \( E-1 \) isomer. The most notable shifts in the \(^1\text{H-}\text{NMR} \) spectrum correspond to the alkene signal, which shifts upfield from 7.91 to 7.23 ppm as a result of increased shielding of the hydrogen. The signal of hydrogen \( e \) at 7.72 ppm shifts to 7.63 ppm. Whilst the signal at 7.58 ppm shifts downfield to 8.01 ppm as a result of deshielding of hydrogen \( k \) (Figure 4.6, Table 4.1). The singlet of hydrogens \( b \) and \( c \) at 7.36 ppm shift upfield to 7.41 and 7.33 ppm and split up in doublets. The doublet of hydrogen \( l \) (in the stilbene half of the molecule) experiences a slight upfield shift to 7.24 ppm. These data correspond well with the calculated data (Table 4.1). The shifts in the \(^1\text{H-}\text{NMR} \) spectrum of 1 upon photochemical \( Z \) to \( E \) isomerization are typical for the whole range of HTI switches 1-4. No precipitation occurred as a result of irradiation at 405 nm.

Figure 4.6: \(^1\text{H-}\text{NMR spectroscopy of HTI switches 1-4 in CD}_2\text{Cl}_2 \) as a result of irradiation \( \lambda = 405 \text{ nm} \) a) \( Z-1 \) to PSS mixture. b) \( Z-2 \) to PSS mixture. c) \( Z-3 \) to PSS mixture. d) \( Z-4 \) to PSS mixture.
Changes as a result of $Z$ to $E$ photoisomerization can also be monitored by FTIR-spectroscopy. A thin film of 1 was prepared from a DCM solution. Changes in the C=O and C=C stretching bands, occurred upon irradiation (Figure 4.7).

The Raman spectrum of a solution of thermally stable $Z$-1 shows several strong aromatic bands at 1604 cm$^{-1}$, 1588 cm$^{-1}$ and 1561 cm$^{-1}$, a carbonyl (C=O) stretching at 1678 cm$^{-1}$ and a strong aromatic (C-H) wagging band at 1187 cm$^{-1}$. The experimental spectra are in good agreement with the calculated spectra, both with respect to relative band intensities and band positions. In the calculated Raman spectrum of $Z$-1 in addition the ring vibrations at 1588 cm$^{-1}$, 1557 cm$^{-1}$ and a C-H band wagging at 1189 cm$^{-1}$, several weaker bands are observed at 1415 cm$^{-1}$, 1306 cm$^{-1}$, 1225 cm$^{-1}$ and 475 cm$^{-1}$.
HTI Z-2 and Z-4 show similar Raman spectra to that of 1 with aromatic bands at 1589 cm\(^{-1}\) and 1559 cm\(^{-1}\), and corresponds well with the calculated spectra of Z-2 and Z-4 in which the aromatic bands are found at 1589 cm\(^{-1}\) and 1557 cm\(^{-1}\), respectively. Notably, the Raman spectrum of Z-3 features a similar intensity pattern as 1, however several of the bands are shifted to lower wavenumbers. For example the aromatic in plane modes at 1587 cm\(^{-1}\), 1577 cm\(^{-1}\) and 1555 cm\(^{-1}\) and the C-H wagging band at 1173 cm\(^{-1}\). Similarly this shift is apparent in the calculated Raman spectrum of 3, where the bands were predicted to be at 1588 cm\(^{-1}\), 1552 cm\(^{-1}\) and 1172 cm\(^{-1}\).

When 1-4 were irradiated (in 1,2-dichloroethane, \(\lambda = 405\) nm) to a photostationary state and the Raman spectra at 785 nm of the solutions were recorded. The spectra of the pure thermally unstable HTI switches (E-isomer) were obtained by subtraction of the contribution (ca. 50\%) of the Z-isomers, to the Raman spectra obtained at the PSS. The fingerprint region below 1500 cm\(^{-1}\) in the Raman spectrum of E-1 is similar to that of Z-1 in the. There are however pronounced differences in the region between 1500 and 1650 cm\(^{-1}\), three strong bands at 1545 cm\(^{-1}\), 1579 cm\(^{-1}\) and 1606 cm\(^{-1}\) are observed and can be attributed to the C=C bridging unit (1545 cm\(^{-1}\)), and the aromatic C=C mode of the stilbene-half of the switch (1606 cm\(^{-1}\)) based on quantum mechanical calculations (Figure 4.9). Similar patterns can be observed in the Raman spectra of the E-isomer of

\[\text{Figure 4.8: Raman spectra of switches 1-4 in 1,2-dichloroethane. The Z-isomers (top) and E-isomer (bottom), experimentally obtained Raman spectra (black, } \lambda_{\text{exc}} = 785 \text{ nm, solvent signals are subtracted) and calculated Raman spectra (red) are overlaid for comparison. The Raman spectrum of 2 was obtained at } \lambda_{\text{exc}} 1064 \text{ nm, due to phosphorescence of the sample at } \lambda_{\text{exc}} 785 \text{ nm.} \]
switches 2-4. There are, however, some shifts in the positions of the bands due to the variation in substitution pattern and the various functional groups. The C=C stretching mode of the bridging alkene is observed at the same position (1545 cm\(^{-1}\)) for switches 1, 2 and 4. This similarity indicates that the electronic properties of the central C=C bond are unaffected by the functional groups on the thioindigo half of the molecule. There is, however, a shift in the position of the C=C stretching mode (1537 cm\(^{-1}\)) for switch 3, which is substituted on the stilbene half. The aromatic modes of 1, 2 and 4 are observed at 1606 cm\(^{-1}\), while they are observed at 1600 cm\(^{-1}\) in the case of switch 3. The shifts of the strongest bands for both the \(E\) and \(Z\)-isomers of 3 indicate that the OTBDMS functionality is electron donating.\(^{13}\)

![Figure 4.9: Calculated Raman spectra and contribution of the vibrations to the Raman spectrum of stable \(Z\)-1 and thermally unstable \(E\)-1. Blue arrows indicate displacement vectors.](image)

**Resonance Raman spectroscopy**

The Raman spectra of 1-4 were obtained in dilute solutions with excitation resonant with optical absorption bands. When the laser used is at a wavelength close to an electronic transition of a molecule considerable enhancement of the Raman scattering from vibrational modes of the chromophore is often observed. The Raman spectrum was obtained at \(\lambda_{ex}: 244, 355, 405\) and 473 nm, (Figure 4.10 to Figure 4.13). At 244 nm,
switch 1 exhibits enhancement of Raman scattering at 1620, 1610 and 1232 cm\(^{-1}\). Whereas for 2 to 4 only a single signal at 1600 cm\(^{-1}\) is enhanced. Switch 4 only, shows signals around 1600 cm\(^{-1}\) at all excitation wavelengths. The bands at ca. 1650 cm\(^{-1}\) correspond to \(\alpha,\beta\)-unsaturated C=O vibrations, while signals at 1600 and 1500 cm\(^{-1}\) are associated with the aromatic C=C stretching modes.

Figure 4.10: Resonance Raman spectroscopy of 1 in 1,2-dichloroethane (\(\lambda_{ex} 244\) nm).

Figure 4.11: Resonance Raman spectroscopy of 2 and 3 in 1,2-dichloroethane (\(\lambda_{ex} 355\) nm).
Thermal $E$ to $Z$ isomerization of HTI switches

The thermal $E$ to $Z$ isomerization of 1-4 occurs at half-lives in the order of hours and it was therefore possible to study the process at elevated temperatures in DMSO and in $p$-xylene using $^1$H-NMR spectroscopy (Table 4.3). A sample of switch 1 in either DMSO-$d_6$ or $p$-xylene-$d_{10}$ was irradiated ($\lambda_{\text{max}} = 405$ nm) to the PSS. The recovery of the signals from the $E$-isomer enriched PSS mixtures to the thermally stable $Z$-isomers of 1-4 were subsequently followed by $^1$H-NMR spectroscopy in a thermal array experiment (Figure 4.14). The decay in intensity of the aromatic signals was recorded as a function of time.
and a first order exponential decay was fitted (Figure 4.15). The rate constants \( k \) for the thermal \( E \) to \( Z \) isomerisation was extracted from the fits at each of the temperatures. From the fitted data (Figure 4.15, right) the rate constant for thermal \( E \) to \( Z \) isomerisation of the thermally unstable isomers can be determined at 20°C (Table 4.3). The activation barrier (\( \Delta G^\ddagger \), Table 4.3) for each thermal isomerisation was calculated using the Eyring equation (2.1)

**Figure 4.14:** Time dependent \(^1\text{H}-\text{NMR} \) spectroscopy of \( E-1 \) in DMSO-\( d_6 \) at 25°C (left) and \( p\)-xylene-\( d_{10} \) at 100°C. Spectra were recorded 127 and 158 s apart, respectively.

**Figure 4.15:** Decay in \(^1\text{H}-\text{NMR} \) signal intensity of \( E-1 \) in DMSO-\( d_6 \) as a function of time at 25°C. Eyring plot for the thermal relaxation of \( E-1 \) to \( Z-1 \) in \( p\)-xylene-\( d_{10} \) at 70, 80, 85, 95 and 100°C.
Table 4.3: Thermodynamic parameters for the thermal $E \rightarrow Z$ isomerization of switches 1-4 in DMSO-$d_6$ and para-xylene-$d_{10}$.

<table>
<thead>
<tr>
<th>#</th>
<th>solvent</th>
<th>calc. $\Delta G^\ddagger$ (kJ/mol)</th>
<th>$\Delta G^\ddagger$ (kJ/mol)</th>
<th>$\Delta H^\ddagger$ (kJ/mol)</th>
<th>$\Delta S^\ddagger$ (J/mol)</th>
<th>$t_{1/2,20^\circ C}$ (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>DMSO-$d_6$ *</td>
<td>146.9</td>
<td>92.6</td>
<td>-</td>
<td>-</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>$p$-xylene-$d_{10}$</td>
<td>146.9</td>
<td>102.2 (±0.3)</td>
<td>31(±3)</td>
<td>-239 (±9)</td>
<td>25</td>
</tr>
<tr>
<td>2</td>
<td>DMSO-$d_6$</td>
<td>n.a.</td>
<td>99.9</td>
<td>56</td>
<td>-185</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>$p$-xylene-$d_{10}$</td>
<td>n.a.</td>
<td>101.4</td>
<td>36</td>
<td>-218</td>
<td>18</td>
</tr>
<tr>
<td>3</td>
<td>DMSO-$d_6$ *</td>
<td>n.a.</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>$p$-xylene-$d_{10}$</td>
<td>n.a.</td>
<td>102.3</td>
<td>36</td>
<td>-222</td>
<td>26</td>
</tr>
<tr>
<td>4</td>
<td>DMSO-$d_6$</td>
<td>n.a.</td>
<td>97.6</td>
<td>50</td>
<td>-160</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>$p$-xylene-$d_{10}$</td>
<td>n.a.</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>11</td>
<td>DMSO-$d_6$ *</td>
<td>n.a.</td>
<td>92.7</td>
<td>-</td>
<td>-</td>
<td>0.5</td>
</tr>
</tbody>
</table>

The Gibbs free energy of activation ($\Delta G^\ddagger$) and half-life time ($t_{1/2}$) for the thermal relaxation of $E$ 1-4 and 11 were determined by $^1$H-NMR spectroscopy in $p$-xylene-$d_{10}$ and DMSO-$d_6$ at five temperatures. * Geometries and thermochemistry (298.15K): CASSCF(10,10)/6-31G(d), SCF energy: XMCQDPT2/cc-pVTZ, Software: Firefly 8.0.0 beta. Calculations were performed in the gas phase. a) Data was obtained directly at 25°C.

From the data in Table 4.3 it is apparent that there is an effect of the polarity of the solvent on the thermal $E$ to $Z$ isomerization of HTI switches 1-4. The effect is especially large for switches 1 and 4. The change from DMSO-$d_6$ (polar) to $p$-xylene-$d_{10}$ (apolar) results in a substantial retardation of the rate of thermal $E$ to $Z$ isomerization of all the tested HTI switches (Table 4.3 and Figure 4.17). Such behavior has also been observed for azobenzene switches (see Chapter 2, section 2.3) 14,15 In $p$-xylene, the unstable $E$-isomer takes significantly longer to recover to the stable form than in DMSO. It is possible that the isomerization proceeds through a charge separated state (zwitterion), as has been suggested for the $E \rightarrow Z$ photoisomerisation of HTI switches. 16 The use of polar solvents would stabilize such a state, resulting in a lower activation barrier to the thermal $E \rightarrow Z$ isomerization. The charge density will be oriented towards the electron withdrawing carbonyl, of the central bond of the HTI. A positive charge in this position can be stabilized by electron donating groups on the stilbene half of the switch, resulting in a lower barrier of activation for the thermal relaxation. Similarly electron withdrawing groups on the thioindigo half stabilize the zwitterion state, 17 resulting in higher rates of thermal $E \rightarrow Z$ isomerisation as is observed for 4. The Br- substituent has a strong negative inductive effect and a weak positive resonance effect.18
The effect of solvent polarity on the UV/Vis absorption spectra of Z-4 and E-4 was studied in a series of solvents of varying solvent polarities. The UV/Vis absorption spectrum of 4 was not significantly different in 1-butanol compared to DMSO. In 1,4-dioxane, p-xylene and dodecane an additional shoulder at ± 462 nm in the UV/Vis absorption spectrum appears. Irradiation of 1 at \( \lambda = 405 \text{ nm} \) in most solvents led to a red shift of the maximum of the lowest absorption band in the UV/Vis absorption spectrum. However, a trend of the \( \lambda_{\text{max}} \) of the long wavelength absorption band vs the dielectric constants of the solvent could be observed. These data suggest solvent stabilization of the ground states of 4 is limited.
Table 4.4: Changes in the UV/Vis absorption spectrum of 4 as a function of solvent polarity

<table>
<thead>
<tr>
<th>Solvent</th>
<th>Dielectric constants</th>
<th>( \lambda_{\text{max}, Z-4} )</th>
<th>( \lambda_{\text{max}, \text{PSS}_{405}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-butanol</td>
<td>17.5</td>
<td>437</td>
<td>460</td>
</tr>
<tr>
<td>DMSO</td>
<td>47.0</td>
<td>439</td>
<td>463</td>
</tr>
<tr>
<td>1,2 dichloroethane</td>
<td>10.5</td>
<td>438</td>
<td>460</td>
</tr>
<tr>
<td>1,4-dioxane</td>
<td>2.3</td>
<td>436</td>
<td>460</td>
</tr>
<tr>
<td>( p )-xylene</td>
<td>2.2</td>
<td>437</td>
<td>463</td>
</tr>
<tr>
<td>Dodecane</td>
<td>2.0</td>
<td>436</td>
<td>460</td>
</tr>
</tbody>
</table>

Figure 4.18: Solvatochromism of switch 4 in solvents of different polarity by UV/Vis spectroscopy.

Photochemical switching of 3 in DMSO is clearly different from the photo switching of 1, 2 and 4. In DMSO the UV/Vis absorption bands of 3 are considerably (117 nm) red shifted compared to the absorption spectrum in 1,2-dichloroethane. Resulting in a colour change from yellow to red in DMSO. Irradiation of 3 in DMSO at \( \lambda = 405 \) nm did not result in a change of the UV/Vis absorption or \(^1\)H-NMR spectra. However, under air the absorption band at \( \pm 575 \) nm disappears over time, while the absorptions at 360 and 460 nm moderately increase in intensity (vide infra). The colour of the solution changed from deep red to yellow.
Figure 4.19: a) UV/Vis absorption spectrum of Z-3 in 1,2-dichloroethane and DMSO. b) Z-3 in DMSO (—) hydrolysis by H₂O (---) and subsequent irradiation at λ = 405 nm (—).
Figure 4.20: UV/Vis absorption spectrum of 9 in DMSO. a) PSS mixture of 9 after irradiation with $\lambda = 405$ nm and subsequent irradiation $\lambda = 510$ nm.
Figure 4.21: UV/Vis absorption spectroscopy of 3 in DCM. top) Deprotection of 3 to 9 using aq. NaOH (--) and subsequent protonation of 9 using acetic acid. bottom) Changes in the UV/Vis spectrum as a result of titration of 3 to 9 using a 1.2 \times 10^{-5} \text{ mmol/mL} \text{ NaOH/H}_2\text{O} solution. Insert shows changes in the UV/Vis spectrum at 575 nm.
To gain a clear understanding of the spectroscopic changes of 3 in DMSO a sample of 3 in d$_6$-DMSO was studied in a sealed tube using $^1$H-NMR spectroscopy. Upon addition of DMSO the solution turns red and UV/Vis absorption spectrum of the initial solution exhibits an absorption band at 575 nm. Irradiation of the sample at $\lambda$ = 405, 523 and 625 nm for up to 60 min did not lead to any changes in the $^1$H-NMR spectrum. However, leaving the sample overnight under air in the dark at rt resulted in a colour change from deep red to yellow. In the $^1$H-NMR spectrum the colour change is manifested by a down-field shift of all the aromatic hydrogen signals. Whereas, a sealed sample of 3 did not exhibit a change in its spectroscopic properties. This experiment suggests that the addition of water results in the disappearance of the band at 575 nm. Closer investigation of the addition of DMSO to a sample of 3 revealed that the initial spectroscopic changes only occur when the solution of 3 comes into contact with the surface of disposable glass pipettes. Such changes do not occur when the solutions are handled with plastic Eppendorf pipettes, quartz cuvettes or glass NMR tubes. It is therefore postulated that the basicity of the surfaces of disposable glass results in basic deprotection of the TBDMS group in DMSO. However, such deprotection does not occur in DCM. The basicity of the glass could be verified by facile deprotection of the TBDMS group by a solution of NaOH in H$_2$O (Figure 4.21). Figure 4.21 illustrates the titration of the TBDMS deprotection using a $1.2 \times 10^{-5}$ mM NaOH solution.

Passing a DMSO solution of 3 over a column of crushed glass, results in the complete deprotection of the TBDMS group. The same spectral changes as for basic treatment with NaOH are obtained, which suggest the glass surface is basic as has been previously described for quartz and vitreous silica. The deprotected form 9$^-$ has a deep red colour and is not photoactive, i.e. the molecule has lost the capability to be switched by photo irradiation. The switching capacity of the switch can be restored by the addition of water or acid protonating 9$^-$ to 9 (Figure 4.22).

![Deprotection of 3 under basic conditions and subsequent protonation under neutral or acidic conditions.](image)
4.4 Conclusion

Hemithioindigos prove to be a promising class of photoswitches. They show good photochemical switching at 405 nm, generally resulting in an $E$-enriched PSS of $\geq 80\%$. However the quantum yields of photo switching are low, of the order 1%, requiring relative long irradiation times to reach the $E$-enriched photostationary state. The thermal stability of the $E$-isomer of HTI switches is good, especially in apolar solvents, approximately in the order of 20 h. Interestingly the speed of the thermal relaxation of the $E$-isomer can be tuned by the polarity of the solvent and can be accelerated up to 50 times upon going from $p$-xylene to dimethylsulfoxide. Suggesting these switches are better suited for apolar environments when they are used for data storage. As a result of the fast isomerization of the $E$-isomer in polar solutions the usefulness of HTI switches biological samples is rather limited. However, the solvent polarity dependent stability of the $E$-isomer might be used for sensing the polarity of samples.

It is thought that this acceleration is the result of stabilization of a charge separated state through which the isomerization must proceed. EDG on the stilbene half and EWG on the thioindigo half of the molecule have a similar lowering effect on the activation barrier to the thermal $E\rightarrow Z$ isomerization. A third state can be added to the switching cycle, by the ability to lock HTI switch bearing a phenol on the stilbene half of the switch in the $Z$-isomer.

The ability to tune the thermal stability of the $E$-isomer through the solvent polarity, as well as the nature of the substitution on the stilbene or thioindigo half of the switch, make them interesting candidates as molecular probes or for switches in materials and make these switches especially attractive compared to, e.g., azobenzenes and stilbenes.

4.5 Experimental section

General remarks

For general information of the experimental work see Chapter 2.5, experimental section.

2-((4-bromophenyl)thio)acetic acid (7). 4-Bromothiophenol (1.04 g, 8.40 mmol) was dissolved in dry acetone (40 mL). 1-Bromoacetic acid (1.34 g, 9.6 mmol) and K$_2$CO$_3$ (2.90 g, 74.84 mmol) was added and the mixture was subsequently heated at reflux overnight. The reaction mixture was cooled to room temperature and the solution was filtered over a P4 glass filter. The solid in the filter was washed with aqueous HCl (10%) and ice cold H$_2$O. The solid was then taken up in acetone, subsequently the organic layer was removed $\text{in vacuo}$ and ethyl acetate (50 mL) was added. The organic layer was washed with H$_2$O (2 $\times$ 50 mL).
The organic layer was collected and dried over MgSO₄. The organic solvent was removed under reduced pressure to afford 7, (1.51 g, 8.28 mmol, 99%) as white crystals. M.p. 94-95 °C. 1H NMR (400 MHz, d₆-DMSO) δ: 7.24 (d, J = 8.1 Hz, 2H), 7.11 (d, J = 8.1 Hz, 2H), 3.70 (s, 2H), 2.24 (s, 3H). 13C NMR (101 MHz, d₆-DMSO) δ: 171.1 (C), 136.13 (C), 132.3 (C), 130.1 (CH), 129.1 (CH), 36.1 (CH₂), 20.9 (CH₃). m/z (APCI pos.) = 183 (+H⁺); HRMS (EI): calcd. for C₉H₁₁O₂S H⁺: 183.0474, found: 183.0472.


(Z)-5-methyl-2-(4-methylbenzylidene)benzo[b]thiophen-3(2H)-one (1). 7 (1.51 g, 8.31 mmol) was dissolved in thionylchloride (5.3 mL) and the mixture was stirred with heating at reflux for 2 h. The excess thionylchloride was removed under reduced pressure, after which 1,2-dichloroethane (16.0 mL) was added and the mixture was cooled to 0 °C. Upon the addition of aluminium trichloride (1.34 g, 10.07 mmol) in 6 portions over 10 min the solution was allowed to reach room temperature. After stirring the reaction mixture at room temperature for 1.5 h, the reaction mixture was poured onto an ice/H₂O mixture (200 mL). The aqueous phase was extracted with CH₂Cl₂ (3x 150 mL), the organic phases were combined and dried under reduced pressure. Benzene (55 mL) was added to the residue. To the benzene solution 4-methylbenzaldehyde (0.52 g, 4.16 mmol) and piperidine (5 drops) were added. Subsequently the mixture was heated at reflux for 3 h, after which the reaction mixture was allowed to cool to room temperature. A saturated aqueous solution of NH₄Cl (200 mL) was added, and the aqueous phase was extracted with EtOAc (3x 150 mL). The organic phases were combined and dried over MgSO₄ and concentrated under reduced pressure. The crude material was further purified by column chromatography (SiO₂, pentane/EtOAc = 4:1) to provide a yellow solid which was further purified by recrystallization (ethanol/heptane = 20/80) to afford 628 mg (46% over 3 steps) of 3 as a yellow solid. 1H NMR (400 MHz, CDCl₃) δ: 7.91 (1 H, s), 7.72 (1 H, s), 7.58 (2 H, d, J = 8.1 Hz), 7.36 (2 H, s), 7.26 (2 H, d, J = 8.0 Hz), 2.39 (3 H, s), 2.38 (3 H, s). 13C NMR (126 MHz, CDCl₃) δ: 143.3 (C), 141.0 (C), 136.6 (CH), 135.8 (C), 133.7 (CH), 131.8 (C), 131.3 (CH), 130.8 (C), 130.0 (s, 11H), 127.3 (s, 6H), 123.7 (s, 5H), 21.8 (CH₃), 21.1 (CH₃). HRMS (ESI): calcd. for C₁₇H₁₄OS H⁺: 267,0844, found: 267.0838.

2-((4-bromophenyl)thio)acetic acid (8). 4-Bromothiophenol (11.00 g, 58.17 mmol) was dissolved in dry acetone (800 mL). 1-Bromoacetic acid (10.40 g, 9.66 mmol) and K₂CO₃ (2.87 g, 74.84 mmol) were added and the mixture was subsequently heated at reflux overnight. The reaction mixture was cooled to room temperature and the solution was filtered over a P4 glass filter. The solid in the filter was washed with aqueous HCl (10%) and ice cold H₂O. The solid was then dissolved in ethyl acetate and dried on
Photochemical study of hemi-thioindigo photoswitches

MgSO₄ and concentrated in vacuo to afford 8, 11.80 g (91%) as white crystals (mp. 117 °C). ¹H NMR (400 MHz, D₆-dmso) δ: 7.49 (ddd, J = 8.5, 3.3, 1.7 Hz, 2H), 7.28 (dd, J = 8.5, 3.3, 1.7 Hz, 2H), 3.82 (dd, J = 3.2, 1.7 Hz, 2H). ¹³C NMR (101 MHz, D₆-dmso) δ: 170.4 (C), 135.5 (C), 131.8 (CH), 129.7 (CH), 118.9 (C), 34.9 (CH₂). HRMS (ESI): calc. for C₈H₈BrO₂S H⁺: 246.9423, found: 246.9426. Elemental Analysis calculated: C, 38.9; H, 2.9. Measured: C, 38.9; H, 2.8.

(Z)-5-bromo-2-(4-methylbenzylidene)benzo[b]thiophen-3(2H)-one (2). 8 (1.05 g, 42.49 mmol) was dissolved in thionyl chloride (5.0 mL) and the mixture was stirred with heating at reflux for 2 h. The thionyl chloride was removed under reduced pressure, after which 1,2-dichloroethane (20.0 mL) was added and the mixture was cooled to 0°C. Upon addition of aluminum trichloride (0.75 g, 5.60 mmol) in 4 portions over 5 min the solution was allowed to reach room temperature. After stirring the reaction mixture at room temperature for 1.5 h, the solution was poured onto an ice/H₂O mixture (200 mL). The aqueous phase was extracted with CH₂Cl₂ (3x 150 mL), the organic phases were combined and dried over MgSO₄ and concentrated under reduced pressure. Benzene (25 mL) was added to the product followed by 4-methylbenzaldehyde (0.54 g, 4.52 mmol) and piperidine (5 drops). Subsequently the mixture was heated at reflux for 3 h, after which the reaction was allowed to cool to room temperature. A saturated aqueous solution of NH₄Cl (200 mL) was added, and the aqueous phase was extracted with EtOAc (3x 150 mL). The organic phases were combined and dried over MgSO₄ and concentrated under reduced pressure. The crude material was further purified by column chromatography (SiO₂, pentane/EtOAc = 4:1) providing a green solid, which was further purified by recrystallization from heptane to afford 628 mg (46% over 3 steps) of 3 as green crystals. M.p. 210 °C. ¹H NMR (400 MHz, CD₂Cl₂) δ: 8.02 (d, J = 2.0 Hz, 1H), 7.93 (s, 1H), 7.70 (dd, J = 8.4, 2.0 Hz, 1H), 7.62 (d, J = 8.1 Hz, 2H), 7.44 (d, J = 8.4 Hz, 1H), 7.32 (d, J = 8.0 Hz, 2H), 2.42 (s, 3H). ¹³C NMR (101 MHz, CDCl₃) δ: 187.2 (C), 144.8 (C), 141.3 (C), 137.7 (CH), 134.8 (CH), 132.3 (C), 131.3 (C), 131.7 (CH), 129.9 (CH), 129.7 (CH), 129.0 (C), 125.2 (CH), 119.4 (C), 21.6 (CH₃). m/z (APCI pos.) = 333 (+H⁺); HRMS (EI): calc. for C₁₆H₁₂BrO₂S H⁺: 332.9766, found: 332.9766. Elemental Analysis calculated: C, 58.0; H, 3.4. Measured: C, 58.0; H, 3.3.

(Z)-methyl 2-(4-methylbenzylidene)-3-oxo-2,3-dihydrobenzo[b]thiophene-7-carboxylate (4). Under a nitrogen atmosphere 2-((carboxymethyl)thio)benzoic acid 10 (3.05 g, 14.4 mmol) was heated at reflux in SOCl₂ (18 mL). The excess SOCl₂ was removed under reduced pressure. To the product, 1,2-dichloroethane (40 mL) was added, and the resulting mixture was cooled to 0°C. To the cooled solution, AlCl₃ (5.30 g, 39.7 mmol) was added in 8 portions. The mixture was stirred under inert atmosphere for 1 h at 0°C. Subsequently the mixture was allowed to attain
room temperature and was stirred overnight. Water (0°C) was added and the aqueous layer was extracted with dichloromethane (3 x 50 mL). The organic layer was washed with water and dried over anhydrous Na₂SO₄. The solvent was removed in vacuo to yield an orange solid. Subsequently the solid was dissolved in benzene (60 mL) and 4-methylbenzaldehyde (2.08 g, 17.3 mmol), methanol (2 mL) and piperidine (10 drops) were added and the mixture was heated at reflux overnight under a nitrogen atmosphere. The reaction mixture was allowed to cool to r.t. and was acidified with acetic acid to pH 1-2. The reaction mixture was extracted with ethyl acetate (3 x 50 mL). The combined organic phases were washed with water (50 mL) and dried over Na₂SO₄ and concentrated under reduced pressure to give a yellow solid. The solid was further purified by flash chromatography (SiO₂, EtOAc/pentane 1:24, \( R_f = 0.18 \)). Switch 4 was obtained as a solid after recrystallization from ethyl acetate/heptane (3.0 g, 9.6 mmol, 67 %). M.p. 205-206 °C. \( ^1 \)H NMR (400 MHz, CD₂Cl₂) \( \delta \): 8.30 (dd, \( J = 7.6, 1.3 \) Hz, 1H), 8.10 (dd, \( J = 7.6, 1.3 \) Hz, 1H), 8.03 (dd, \( J = 8.1 \) Hz, 2H), 7.42 (t, \( J = 7.6 \) Hz, 1H), 7.35 (d, \( J = 8.1 \) Hz, 2H), 4.01 (s, 3H), 2.43 (s, 3H). Elemental Analysis calculated: C, 69.66; H, 4.55, Measured: C, 69.30; H, 4.50. \( m/z \) (APCI pos,) = 311 (+H +); HRMS (EI): calcd. for C₁₈H₁₅O₃S H+: 311.0737, found: 311.0736.

(Z)-5-bromo-2-(4-((tert-butyldimethylsilyl)oxy)benzylidene)benzo[b]thiophen-3(2H)-one (3).

Acid 8 (2.05 g, 8.31 mmol) was dissolved in thionyl chloride (5.3 mL) and the mixture stirred while heating to reflux for 2 h. The excess thionyl chloride was removed under reduced pressure, after which 1,2-dichloroethane (16.0 mL) was added and the mixture was cooled to 0 °C. After addition of aluminium trichloride (1.34 g, 10.07 mmol) in 6 portions over 10 min, the solution was allowed to reach room temperature. After stirring the reaction mixture at room temperature for 1 h, the reaction mixture was poured onto an ice/H₂O mixture (250 mL). The aqueous phase was extracted with CH₂Cl₂ (3x 150 mL), the organic phases were combined and dried over MgSO₄ and concentrated under reduced pressure. Benzene (40 mL) was added to the resulting solid. To the benzene solution 4-methylbenzaldehyde (1.07 g, 8.72 mmol) and piperidine (5 drops) were added to the obtained crude material. Subsequently the mixture was heated at reflux for 2 h, after which the mixture was allowed to cool to room temperature. A saturated aqueous solution of NH₄Cl (200 mL) was added, and the aqueous phase was extracted with EtOAc (3x 150 mL). The organic phases were combined and dried over MgSO₄ and concentrated under reduced pressure. The crude material was further purified by column chromatography (SiO₂, pentane/EtOAc = 4:1) yielding an orange solid which was further purified by recrystallization from ethanol to afford 11 as an orange solid. Switch 11 (903 mg, 2.71 mmol), imidazole (461 mg, 6.78 mmol) and tert-butyldimethylsilyl chloride were added to dimethylformamide (50 mL). The reaction mixture was heated to reflux and stirred overnight. Subsequently the reaction mixture...
was allowed to cool to room temperature and H₂O (50 ml) was added. The aqueous layer was extracted with dichloromethane (3 × 50 mL). The organic phases were combined and dried over Na₂SO₄. The resulting solid was loaded onto celite and purified by column chromatography (SiO₂, pentane/dichloromethane 24:1, Rf = 0.613). Switch 3 was obtained as an orange solid (1.03 g, 2.30 mmol, 85%). ¹H NMR (300 MHz, CDCl₃): δ: 8.00 (d, J = 1.8 Hz, 1H), 7.89 (s, 1H), 7.60 (dd, J = 8.4, 1.9 Hz, 1H), 7.56 (d, J = 8.6 Hz, 2H), 7.33 (d, J = 8.3 Hz, 1H), 6.91 (d, J = 8.6 Hz, 2H), 0.98 (s, 9H), 0.23 (s, 6H). ¹³C NMR (101 MHz, CDCl₃): δ: 187.2 (C), 158.3 (C), 144.7 (C), 137.5 (CH), 134.8 (CH), 133.1 (CH), 132.5 (C), 129.7 (CH), 127.9 (C), 127.2 (C), 125.2 (CH), 120.8 (CH), 119.3 (C), 25.6 (CH₃), 18.3 (C), -4.3 (CH₃). m/z (EI) = 448; HRMS (ESI): calcd. for C₂₁H₂₃BrO₂SSiH⁺: 449.0444, found: 449.0404.

Photochemical Z to E isomerization using NMR spectroscopy

Samples used for arrayed ¹H-NMR experiments were prepared as following; A 1 ml solution of the HTI switch (2 mg/mL in C₂D₄Cl₂, at 20°C) was irradiated at λₑₓc 405 nm using a Power technology 405 nm (50 mW) laser for 1 h under stirring in a quartz cuvette (pathlength 1 cm). Thermal arrayed ¹H-NMR experiments were recorded on a Varian Unity Plus (500 MHz) or a Varian inova (600 MHz) NMR system using Varian, VnmrJ version 2.2, revision D 2008.

Photochemical Z to E isomerization using UV/Vis absorption spectroscopy

The Z to E photo isomerization was performed by irradiating a solution of Z-HTI switch (4.06 × 10⁻⁵ M in CH₂Cl₂, at 20°C) at λₑₓc 405 nm in a 1 cm quartz cuvette under stirring.

Photochemical E to Z isomerization using UV/Vis absorption spectroscopy

The E to Z photo isomerization was performed by irradiating a PSS solution (vide supra) of HTI switch (4.06 × 10⁻⁵ M in CH₂Cl₂, at 20°C) at λₑₓc 450 nm in a 1 cm quartz cuvette under stirring.

Thermal E to Z isomerization using NMR spectroscopy

Changes in the ¹H-NMR spectra upon thermal reversion form the thermally less stable E-isomer were determined by irradiating a sample of Z-HTI switch to the PSS as previously indicated. Subsequently the sample was heated at various temperatures in a Varian Unity Plus (500 MHz) or a Varian inova (600MHz) NMR system. The ¹H-NMR spectrum was recorded as a function of time in an arrayed experiment using Varian, VnmrJ version 2.2, revision D 2008.
Quantum flux

Stock solutions of ferrioxalate (A), \(\alpha\)-phenanthroline (B) and sodium-acetate-trihydrate (C) were prepared.

(A) In a graduated flask of 10 mL, ferrioxalate trihydrate (1.474 g, 3.0 mM) was dissolved in water 8 mL, after which 2 mL of a 1 N sulfuric acid solution yielding a 0.3 M ferrioxalate solution (Caution: \textit{light sensitive, store in the dark}).

(B) In a graduated flask (50 mL) \(\alpha\)-phenanthroline (50.6 mg, 0.3 mM) was dissolved in water 50 mL. (Caution: \textit{do not use metal spatulas})

(C) Sodium-acetate-trihydrate (3.41 g, 25.1 mM) was dissolved in 25 mL water, 15 ml were taken from this solution and were added to 9 mL 1 N sulfuric acid solution. The resulting solution was diluted to 25 mL, yielding a buffer of pH 3.5.

For the quantum flux experiment 2.3 ml of the actinometer solution (A) was added to a quartz cuvet (l =1cm). Subsequently 0.1 mL was pipetted out in the dark and added to a vial containing 0.1 mL of solution (B), 0.05 mL of solution (C) and 1.75 mL water. The solution was irradiated at 405 nm ± 5 nm for 3 min under stirring using a JASCO FP-6200 spectrofluorometer. Subsequently 0.1 mL was removed and added to a second vial containing 0.1 mL of solution (B), 0.05 mL of solution (C) and 1.75 mL water and was irradiated as described previously. This procedure was repeated till 4 such samples were collected (irradiation times 3, 6, 9 and 12 min). All samples were stored at rt in the dark for at least one hour, after which the UV/Vis absorption spectra were recorded. The quantum flux (\(Q_{\text{flow}}\), number of photons per second) could be determined using the following equation.

Quantum yield of Z to E photo switching

A solution of Z-HTI switch (8.3 \(\times\) 10\(^{-4}\) M) in 1,2-dichloroethane was irradiated under stirring at 405 nm ± 5 nm for 10 min intervals. The quantum yield could be determined using the following equation.

\[
\Phi = \frac{DV_i V_j N 10^{-3}}{t Q_{\text{flow}} ed V_e}
\]

In which \(D\) is the optical density of the solution, \(t\) is the irradiation time (600 s), \(Q_{\text{flow}}\) is the quantum flow of the irradiation setup (determined by a actinometer), \(e\) is the molar absorptivity at 405 nm, \(d\) is the cuvette path length (1 cm), \(N\) is the Avogadro number \(6.02214 \times 10^{23}\) mol\(^{-1}\), \(V_i\) the irradiated volume (2 mL), \(V_j\) the volume (0.2 mL) of \(V_i\) used and \(V_e\) the end volume (0.2 mL) used for the measurement.
Quantum yield of fluorescence

Measurements for the quantum yield of fluorescence ($\Phi_\text{fl}$) for 1-4 were generally obtained from a solution containing HTI switch (4.1 × $10^{-5}$ M) in 1,2-dichloroethane at 20°C. The sample was excited at 455 nm ± 5 nm under stirring. Anthracene was used as a reference with a reported $\Phi_\text{fl} = 0.27$ in ethanol.\(^{20}\)

$$\Phi = \frac{\eta A_{\text{ref}} I}{A I_{\text{ref}}}$$

In which $\eta$ is the refractive index $n_D^{20}$ of the solvent (1.4448 for 1,2-dichloroethane and 1.3614 for ethanol), $A$ is the absorbance at the excitation wavelength and $I$ is the integrated fluorescence intensity.

Infrared spectroscopy

ATR FTIR spectra were collected on a Perkin Elmer Spectrum 400, FT-IR/F-FIT Spectrometer with liquid nitrogen cooled MCT detector and a universal ATR sampling accessory. Samples were measured as solids or as thin films formed from a dichloromethane solution.

Raman spectroscopy

Raman spectra were recorded on a Perkin Elmer 400F Raman station at $\lambda_{\text{exc}}$ 785 or 1064 nm. Spectra were typically recorded with 1 to 5 exposures of 2-40 s. The obtained spectra were baseline corrected and normalized for analysis. Resonance Raman spectra were obtained from 1,2-dichloroethane solution (4.06 × $10^{-5}$ M) using with $\lambda_{\text{exc}}$ 244, 355, 405 or 473 nm and were recorded by an Andor technology DV420A-BU2 CCD camera.

4.6 Acknowledgment

Thomas C. Pijper is acknowledged for the quantum mechanical calculations of the $^1$H-NMR spectra of Z and E-1 in sections 3.2.2 and the Raman spectra of Z and E of 1-4 in section 3.3, as well as calculating the theoretical barriers of E to Z isomerisation of E-1 to Z-1. Oleksii Ivashenko is acknowledged for his help with the Raman spectroscopy measurements described in this Chapter.
4.7 References

12. Geometry optimization and frequency calculations were performed with B3LYP/cc-pVTZ in the gas phase (Gaussian 09 C.01). Where cc-pVTZ is cc-pVTZ for H, C, and O), cc-pV(T+d)Z for Si, and S and cc-pVTZ-PP for Br. The spectra were plotted using a locally modified version of GaussSum 2.2.5 (750 points, FWHM = 10). Wavenumbers obtained were scaled by 0.976.