Photostability of 4,4'-Dihydroxythioindigo, a Mimetic of Indigo**

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Abstract: The photochemical properties of indigo, a widely used industrial dye, has attracted both experimentalists and theoreticians from the beginning. Especially the high photostability of indigo has been the subject of intensive research. Recently, it was proposed that after photoexcitation an intramolecular proton transfer followed by a nonradiative relaxation to the ground state promote photostability. In indigo the hydrogen bond and the proton transfer occur between the opposing hemiindigo parts. Here, we provide experimental and theoretical evidence that a hydrogen transfer within one hemiindigo or hemithioindigo part is sufficient to attain photostability. This concept can serve as an interesting strategy towards new photostable dyes for the visible part of the spectrum.

ndigo (1) has been used as brilliant dye for centuries. After the determination of its structure and its chemical synthesis by Adolf von Baeyer,^[1] indigo was and still is produced industrially because of its characteristic color and most importantly its high photostability. In recent times new applications have been proposed for this "old" dye. For example, an ambipolar organic field-effect transistor on the basis of indigo has been developed.^[2] Derivatives of indigo like hemithioindigo^[3] are promising tools in the competitive field of chemical optogenetics.^[4]

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The photochemical properties of indigo, for example its long-wavelength absorption maximum and its photostability, have attracted the interest of experimentalists as well as theoreticians from the beginning and have resulted in an abundance of publications over the past decades. Quite early on, in theoretical studies using LCAO molecular orbital calculations (LCAO = linear combination of atomic orbitals) a basic chromophore structure of indigo was proposed^[5] which was later confirmed by chemical synthesis.^[6]

The photostability of indigo was attributed originally to the lack of *trans-cis* photoisomerization.^[7] In contrast, indigo derivatives like thioindigo (2) readily isomerize about the central double bond^[8] and, unlike indigo, show strong fluorescence.^[9] It was proposed that the *trans* isomer of indigo is stabilized by hydrogen bonds formed between the NH and CO groups connecting the two halves of the molecule.^[7,10] It was also discussed that after photoexcitation an intramolecular proton transfer followed by a nonradiative relaxation to the ground state occurs.^[11] However, in picosecond infrared experiments Elsaesser et al. detected only small changes and they concluded that a proton transfer does not occur in the S1 state.^[12] Recent work reexamined indigo photochemistry. Iwakura et al.^[13] reported on the fast photoexcited proton transfer which should occur on the femtosecond time scale. Interestingly the back reaction should be completed already at 0.5 ps, which explains the results of Elsaesser et al.^[12] Computational analysis on the photostabilty of indigo addressed the role of isomerization and excited-state proton transfer and found that rapid internal conversion is induced by intramolecular single-proton transfer.^[14] In indigo the hydrogen bond and the proton transfer occur between the opposing hemiindigo parts. The question whether a hydrogen transfer within one hemiindigo (HI) or hemithioindigo part would be sufficient to ascertain photostability is addressed herein.

Here we report on the synthesis and photophysical properties of the newly synthesized 4,4'-dihydroxythioindigo as well as 4,4'-dimethoxythioindigo (3), which was first



prepared by Friedländer.^[15] The spectroscopic properties of these compounds are similar to those of indigo (1) and thioindigo (2), respectively. Like indigo, 4,4'-dihydroxythioindigo does not undergo photoisomerization and displays a fast internal proton transfer. However, the possible proton transfer occurs only within the hemithioindigo units.

4,4'-Dihydroxyindigo (**3**) and its dimethyl ether **4** were synthesized in six and five steps, respectively, using a strategy proven successful for the synthesis of thioindoxyls.^[16,17] Oxidation of thioindoxyls resulted in the formation of the thioindigo derivatives with overall yields of 25% for **3** and 30% for **4**. 4-Methoxy-4'-hydroxythioindigo (**5**) was obtained by partial hydrolysis of (**4**) and purified by thin-layer chromatography (see the Supporting Information).

Stationary irradiation experiments yielded the following results. Table 1 summarizes the results from long-term irradiation experiments. The samples were illuminated with a lamp (15 W) equipped with a yellow filter (for experimental

	DMSO	DMF	CHCl₃	Benzene
Thioindigo	_	_	+	+
4,4'-Dimethoxythioindigo	+	+	-	+
4,4'-Dihydroxythioindigo	_	_	-	-
Indigo	_	_	_	_
4-Methoxy-4'-hydroxythioindigo	-	n.d.	_	n.d.

[a] "+": photoisomerization $trans \rightarrow cis$; "-": no photoisomerization $trans \rightarrow cis$; n.d.: not determined.

details and use of another irradiation system see the Supporting Information). As expected, indigo (1) was photostable after 2 h of irradiation. Even after six weeks of exposure to daylight dihydroxythioindigo (3) showed no detectable signs of decomposition. A *trans-cis* isomerization yielding a stable product was not observed. In contrast, under identical conditions the dimethoxy derivative 4 and thioindigo (2) decomposed completely. In addition, the fluorescence of 3 and 5 was considerably weaker than that of 2 and 4. Interestingly, isomerization of thioindigo (2) and dimethoxythioindigo (4) is quite dependent on the solvent (Table 1). Generally, more polar solvents inhibit *trans-cis* isomerization. When a strong acid (trifluoroacetic acid, TFA) was added to a solution of thioindigo, practically no isomerization was observed after two hours.

The strong change in fluorescence intensity is directly related to the lifetime of the light-emitting S_1 state, as can be seen from the time dependence of the fluorescence emission recorded with a streak camera (Figure 1 a, light red and light blue symbols; for experimental details see the Supporting Information). For compound **4** we observe a decay of the fluorescence emission with a time constant of approximately 11 ns (dots). The decay time of compound **3** of 50 ps (triangles) is roughly 200 times faster. Data recorded at 618 nm (**4**) and 597 nm (**3**) show that the absorption transients evolve with the same decay times as those found for fluorescence emission (Figure 1 a). Additional information was obtained from time-resolved absorption spectra recorded at distinct delay times. The transient difference spectra of



Figure 1. a) Time-dependent absorption change (Trans. Abs., red, blue) and fluorescence emission (light red and light blue) for **4** (red) and **3** (blue). b, c) Transient absorption difference data for the two compounds. Excitation wavelengths 525 nm (emission) and 550 nm (absorption experiments). For details of the experiments see the Supporting Information.

compound **3** (Figure 1 b) evolve on the picosecond time scale and finally disappear with the same time constant (50 ps) as that found for the decay of the excited electronic state. No absorption change remains at later times. At early times the transient absorption spectrum displays a strong and narrow peak at 600 nm due to excited-state absorption. A weaker and broader excited-state absorption band is found in the blue part of the spectrum around 430 nm. At longer wavelengths (630–700 nm) stimulated emission is visible and around 550 nm, the bleaching of the original ground state absorption is found. A global fitting procedure reveals additional absorption dynamics with a time constant of roughly 8 ps, which can be related to motions on the excited-state potential energy surface away from the originally populated Franck– Condon region.

Dimethoxythioindigo (4) shows very similar spectral features in the excited electronic state. Again there is a pronounced excited-state absorption peak for compound 4 at 618 nm. The decay of the absorption changes occurs much slower than in compound 3. This long-term behavior can be well fitted with the same time constant as that found in the emission experiments.

The experiments on the two thioindigo compounds are summarized as follows: Dihydroxythioindigo (3) has higher photostability, a much shorter excited-state lifetime, and a weaker fluorescence quantum yield than dimethoxythioindigo (4). The excited electronic state of both compounds, which is reached after 8 ps, shows very similar absorption and emission spectra. The major difference in the two molecules is the lifetime of this state. No indication of a long-lasting absorption change is found for compound 3. Apparently isomerization at the central double bond of the molecule does not take place. Since compounds 3 and 4 differ only by the substitution at positions 4 and 4', the hydroxy group and a transient proton transfer as suggested for indigo should play a major role in the differences in photostability and reaction dynamics. The nearly identical features of the excited-state spectra of the two compounds suggest that the first relaxation out of the Franck-Condon region leads to similar intermediate states. A reaction along the proton-transfer coordinate of compound 3 should only occur afterwards and mediates the relaxation out of the S₁ state. For dimethoxythioindigo (4) the methyl group prevents this reaction path and relaxation to the ground state occurs predominantly by fluorescence emission. The long lifetime of the S_1 state may also increase the importance of other, destructive decay routes in compound 4.

To support these qualitative interpretations, quantumchemical computations were performed on suitable model molecules (for details see the Supporting Information). For both model molecules a conical intersection with the groundstate surface is found, located slightly below the energy at the Franck-Condon geometry. To reach this conical intersection the molecules must undergo a proton/methyl cation transfer and an out-of-plane deformation of the phenyl ring. The methyl cation transfer (red line), however, involves a large barrier (TS_{Scan}), which obstructs access to this conical intersection. In contrast, the proton transfer (blue line) occurs without a barrier in the model system and exhibits only a small barrier in the full system (compound 3). Thus theoretical modeling indicates that both molecules 3 and 4 leave the Franck-Condon range in the direction of a nearby local minimum (Min_{S1}) on the S₁ potential surface due to the rearrangement of the π system. Only for compound **3** is the conical intersection accessible after passing the global minimum on S_1 (Min P_{S_1} ; see Figure 2). The shape of the potential energy surfaces in the vicinity of this conical intersection guides the molecule back to the planar structure. Back transfer of the proton from a first and shallow local groundstate minimum (MinP_{s0}) completes the photophysical process. For compound 4 the large barrier in the S_1 state prohibits access to the conical intersection, the excited electronic state becomes long-lived, and a high fluorescence quantum yield results.

A direct consequence of the long lifetime of the excited electronic state of compound **4** is the possibility that slow and destructive reaction channels in the nanosecond time domain may gain importance. Another implication may be photodecomposition induced by the absorption of another photon during the long population of the S_1 state. The possibility of an excited-state proton transfer in compound **3** opens a new path for internal conversion, shortens the lifetime of the excited electronic state, and finally leads to the observed large gain in photostability.

The vastly different photochemical properties of the two thioindigo compounds **3** and **4** demonstrate that excited-state proton transfer within the rigid ring system of only one



Figure 2. Critical points of the ground- and excited-state potential energy surfaces for the photoreaction of model systems of **3** and **4**. The process is illustrated along two reaction coordinates, the proton transfer or methyl cation transfer and the out-of-plane deformation of the phenyl ring. Although both conical intersections (CoIn) are situated energetically below the Franck–Condon point (FC), the CoIn can only be reached by compound **3**. The excited-state intramolecular proton/methyl⁺ transfer is prerequisite to reach the CoIn. In compound **4** the related methyl cation transfer is hindered by a substantial barrier.

hemithioindigo moiety improves photostability. To prove this point the monomethoxy derivative of thioindigo (5) was synthesized by partial hydrolysis of 4. Indeed, the photostability of 5 in CHCl₃ was comparable to that of dihydroxythioindigo (3). No photo-isomerization was found and the fluorescence emission was as weak as that of 3 (see the Supporting Information). The basic promoting mechanism excited-state proton transfer—is the same as that in indigo and in many UV stabilizers (see Ref. [18] for the photochemistry of highly photostable compounds). However, the results on 3 show that suitably arranged proton donating and accepting groups promote excited-state proton transfer even if they are within rigid ring systems. This concept can serve as an interesting strategy towards new photostable dyes for the visible part of the spectrum.

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