Indigodiimine: A Highly Fluxional Molecule that Tautomerizes via Double Proton Transfers

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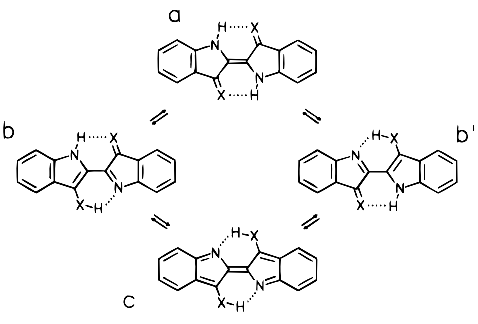
Proton transfers in the ground and excited state continue to draw interest from many branches of chemistry.[4] In particular, the photochemistry and photophysics of indigo (**1**) (Scheme 1) and its derivatives have been a matter of long-standing interest.[5] In this paper we show by dynamic NMR that its isoelectronic nitrogen analog indigodiimine (**2**) adopts a highly fluxional structure even in its electronic ground state.

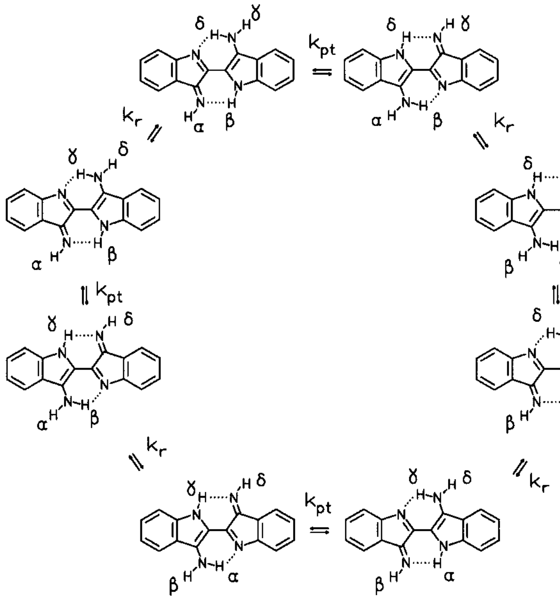
For indigo in the electronic ground state only the centrosymmetric *trans*-structure **1a**, characterized by a *trans* configuration with respect to the central double bond and two intramolecular (C=O···H−N) hydrogen bonds, has been observed.[5,6] Semiempirical quantum-mechanical calculations[7] have confirmed that the degenerate forms **1b** and **1b′** have substantially higher energy than **1a**, and **1c** higher energy than **1b** and **1b′**. However, as acid−base properties are often significantly altered in electronic excited states[8] phototautomerization of **1a** to **1c** has been postulated as a radiationless pathway which effectively quenches fluorescence of **1**.[9] By contrast, the quantum-mechanical calculations[7] indicate preferential formation of **1b** over **1c** in the excited state. An extremely weak fluorescence in **1** has since been detected and a combination of fluorescence and infrared studies indicates the absence of proton transfers in the first excited state of **1**.[10]

Scheme 1



X=O, Indigo (1a, 1b=1b', 1c)
X=NH, Indigodiimine (2a, 2b=2b', 2c)

Scheme 2



By contrast, IR measurements of the NH-stretching band of **2** and its ^{15}N-labeled isotopomers indicate that indigodiimine adopts the tautomeric form **2b**.[11] This implies a possible rapid intra- or intermolecular tautomerization to the degenerate form **2b′**, either as stepwise single proton transfers via **2a** or **2c** or as a concerted double proton transfer. Additionally, **2b** may be subject to an internal rotation of the NH_2 group. The combination of proton tautomerization and NH_2 group rotation leads potentially to eight interconverting molecular states according to Scheme 2. By performing variable-temperature ^1H NMR experiments on indigodiimine (**2**)[12] in a mixed freon solvent,[13] we were able to confirm Scheme 2 and report preliminary rate constants for both processes.

Some typical superposed experimental and calculated spectra are shown in Figure 1. The predominance of **2b** is verified by four singlets at $\nu_1 = 10.7$, $\nu_2 = 9.8$, $\nu_3 = 7.1$ (partly obscured by aromatic proton signals), and $\nu_4 = 5.1$ ppm. The signal assignment was obtained by ^{15}N-labeling at the exocyclic nitrogen sites and by inference from changes in the line shape. As temperature is increased from 140 K the two high-field signals first broaden and then coalesce to a broadened singlet at $(\nu_3 + \nu_4)/2 = 6.1$ ppm from which the value of ν_3 could be inferred. The rate constant $k_r \approx 10^{10.2\pm0.5} \exp(-5.0 \pm 0.3\ \text{kcal mol}^{-1}/RT)$, $140\ \text{K} \le T \le 190\ \text{K}$, for the NH_2 rotation[14] could be obtained by fitting the theoretical to the experimental spectra.[15] As the temperature is further increased all remaining three singlets broaden and coalesce into a single line at 8.1 ppm, indicating the onset of the tautomerization between **2b** and **2b′**. The associated rate constant $k_{pt} \approx 10^{9.6\pm0.4} \exp(-5.8 \pm 0.3\ \text{kcal mol}^{-1}/RT)$, $160\ \text{K} \le T \le 270\ \text{K}$, for this double proton transfer[16] was obtained again by line shape analysis. The aromatic proton signals also exhibit temperature-dependent changes that confirm

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[4] For numerous examples see Michael Kasha special issue: *J. Phys. Chem.* **1991**, *95*, 10215−10524. For a more recent example see: Chudoba, C.; Lutgen, S.; Jentzch, T.; Riedle, E.; Woerner, M.; Elsässer, W. *Chem. Phys. Lett.* **1995**, *240*, 35.

[5] For a review of the properties of indigo and its derivatives see: (a) Haucke, G.; Pätzoldt, R. *Nova Acta Leopoldina Suppl.* **1978**, *11*, 7 (photophysics and photochemistry). (b) Süsse, P.; Steins, M.; Kupcik, V. *Z. Kristallographie* **1988**, *184*, 269 (crystallography). (c) Tatsch, E.; Schrader, B. *J. Raman Spectrosc.* **1995**, *26*, 476 (vibrational spectroscopy). (d) Klessinger, M.; Lüttke, W. *Chem. Ber.* **1966**, *99*, 2136 (electronic structure).

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[11] Lüttke, W.; Sieghold, H. *Angew. Chem.* **1975**, *87*, 63; *Angew. Chem., Int. Ed. Engl.* **1975**, *14*, 52.

[12] Indigodiimine was prepared from indole according to the literature methods: Madelung, W. *Liebigs Ann. Chem.* **1914**, *58*, 405. Sieghold, H. Dissertation, Universität Göttingen, 1973.

[13] The NMR solvent for these studies, a 1:5:5 mixture of $CDCl_3$, $CDCl_2F$, and $CDClF_2$, is liquid down to 130 K. It was prepared according to: Siegel, J. S.; Anet, F. A. L. *J. Org. Chem.* **1988**, *53*, 2629.

[14] $\Delta H^\ddagger = 4.7 \pm 0.3\ \text{kcal mol}^{-1}$, $\Delta S^\ddagger = -13 \pm 2\ \text{cal mol}^{-1}\ \text{K}^{-1}$.

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this analysis and the fluxionality of indigodiimine expressed by Scheme 2. The values of the frequency factors of both kinetic processes are of the order expected for intramolecular proton transfers,[17] whereas the lower values characteristic of intermolecular exchange pathways involving a catalyst or a second indigodiimine molecule are not observed.

Why does the asymmetric form predominate so strongly? Indigodiimine **2b** is a vinylogous *N*-arylamidine and it is well established that the amino form of *N*-arylamidines is favored over the imino form because of inductive and resonance effects.[18] Furthermore, **2b** exhibits a canonical form which contains an aromatic indole ring which is absent in the symmetric structure **2a**. We have performed preliminary semiempirical AM1 calculations which show that **2b** is more stable than **2a** by 2.1 kcal mol^{-1} (H_f(**2b**) = 138.4 kcal mol^{-1} and H_f(**2a**) = 140.5 kcal mol^{-1}, respectively), although the calculated difference may not be large enough to support these conclusions.

In the future we will try to measure the kinetic HH/HD/DD isotope effects on the double proton transfer.[14] Such studies are potentially able to provide information about the question whether the reaction path involves a consecutive stepwise or a synchronous transfer of both protons, as well as whether proton tunneling is involved. Finally, the effects of solvent and solid state environment on the structure and dynamics are also under investigation.

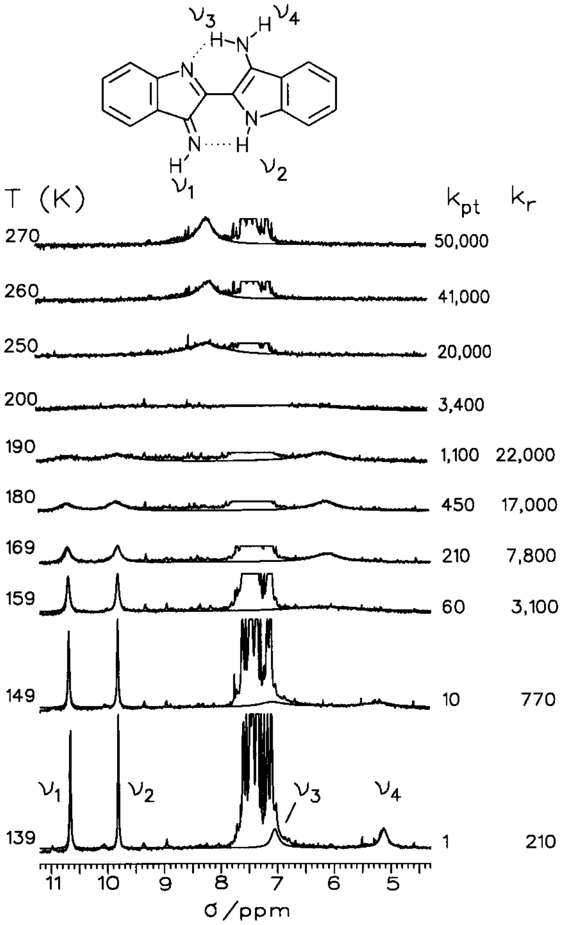

Figure 1. Variable-temperature ^{1}H NMR spectra of indigodiimine in a freon mixture (1:5:5 $CDCl_3/CDFCl_2/CDF_2Cl$).

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(15) Indigodiimine involves proton exchange between four sites, for which the matrix, M_o, is given by

$$\begin{vmatrix} -k_{pt}-\pi W_{o1}+i2\pi\nu_1 & 0 & 0 & k_{pt} \\ 0 & -k_{pt}-\pi W_{o2}+i2\pi\nu_2 & k_{pt} & 0 \\ 0 & k_{pt} & -k_{pt}-k_r-\pi W_{o3}+i2\pi\nu_3 & k_r \\ k_{pt} & 0 & k_r & -k_{pt}-k_r-\pi W_{o4}+i2\pi\nu_4 \end{vmatrix}$$

The line widths were estimated from the low-temperature spectrum: W_{o1} = 13 Hz, W_{o2} = 11 Hz, W_{o3} = 12 Hz, W_{o4} = 12 Hz. The chemical shifts, ν, were taken to be temperature independent. For details see ref 17a.

(16) $\Delta H^{\ddagger} = 5.4 \pm 0.3$ kcal mol^{-1}, $\Delta S^{\ddagger} = -16 \pm 2$ cal mol^{-1} K^{-1}.

(17) (a) Limbach, H. H. Dynamic NMR Spectroscopy in the Presence of Kinetic Isotope Effects, In *NMR Basic Principles and Progress*; Springer: Berlin, 1991; Vol. 26 Chapter 2. (b) Braun, J.; Schlabach, M.; Wehrle, B.; Köcher, M; Vogel, E.; Limbach, H. H. *J. Am. Chem. Soc.* **1994**, *116*, 6593.

(18) Prevorsek, D. C. *J. Phys. Chem.* **1962**, *66*, 769. Häfelinger, G.; Kuske, F. K. H. In *The Chemistry of Amidines and Imidates*; Patai, S., Rappoport, Z., Eds.; J. Wiley & Sons: New York, 1991; Vol. 2, pp 66−70. The tautomeric preferences reverse in *N*-alkyl amidines where the imino form is preferred over the amino form.