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ARTICLE TYPE

Reversible Photo-, Metallo- and Thermo-induced Morphological Dynamics of Bis-acylhydrazones

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A reversible interconversion-cycle, making use of the multiple dynamic properties of bisacylhydrazones is presented. It features photo-, metallo- and thermo-induced configurational and conformational changes and involves reversible cation binding and release of potential interest for photo-induced metal signal generation or catalysis.

Configurational dynamics of the C=N double bond endow iminoid molecules with the ability to undergo reversible photochemically or thermally activated E-Z isomerizations. Coupled with other features, such as metal cation binding and/or constitutional exchange, they present multiple dynamics potentially allowing for the storage and release of "physicochemical information".[1,2] Acylhydrazones contain such a switchable group and present additional sites that extend further the features of the switching process.[3] In earlier work, we investigated the behaviour of acylhydrazones as configurationally and constitutionally dynamic molecules, underlining their status as valuable entities for applications in dynamic chemistry.[2] These studies focused on the possibilities of implementing acylhydrazones as information storage systems via triple dynamic features: E-Z isomerisation, component exchange and metal cation coordination. The different states of the system/compounds are connected through interconversion processes that are photo-, thermo- or chemo-responsive to physical and chemical stimuli (see Scheme 8 in ref. 2). Such processes may give rise to changes in physical state as illustrated by an acylhydrazone-based system that could be photo-switched reversibly between K^+-containing metallosupramolecular fibrous assemblies and the uncomplexed switching unit in solution. Another recent example demonstrated the implementation of acylhydrazones in a reversible phase separation process.[4]

We here extend these studies to bis-acylhydrazones **1**, thus allowing for the involvement of two such groups in the interconversion processes, and achieve a full interconversion cycle by introducing the missing link, namely the transitions between the internally hydrogen-bonded (*EZ*-**1**) and the complexed (**1**-M) bisacylhydrazone states, thus providing a cyclic process: ion binding, photoisomerizarion, ion release (Figure 1).[5]

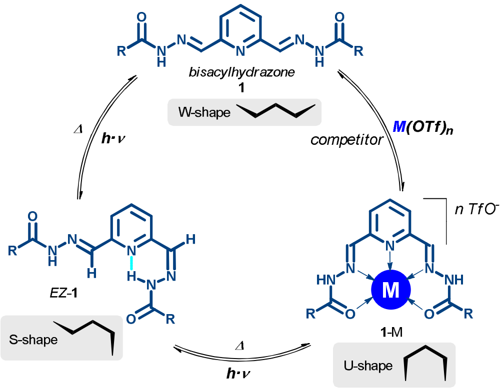

Figure 1. Full interconversion cycle of 2,6-pyridine-derived bis-acylhydrazones **1** undergoing photo-, metallo- and thermo-induced configurational and conformational isomerizations.

Bis-acylhydrazones **1**, derived from 2,6-pyridinedialdehyde, previously only studied for their coordination properties,[6] offer the required features. Furthermore, they are efficiently accessible by double condensation of the easily available starting dialdehyde with substituted aromatic hydrazides to give compounds **1**-Ph, **1**-NO_2, **1**-Cl and **1**-MeO (Fig. 2).

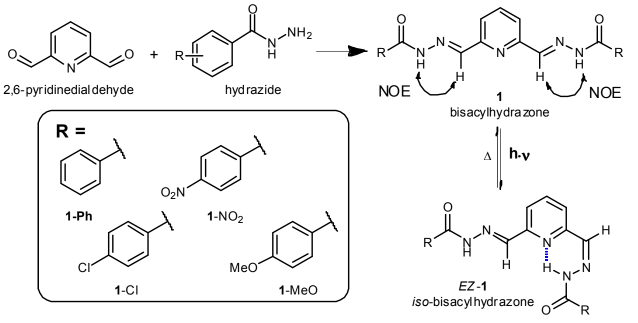

Figure 2. Formation and structures of the 2,6-pyridinedialdehyde-derived bis-acylhydrazones investigated.

Apart from their five point binding in complexation, they furthermore contain two –C=N-bonds, both potentially susceptible to undergo photo-induced *EZ* isomerisation, processes that have, to the best of our knowledge, not been studied in detail up to now. In their *EE* configuration, they undergo a double conformational change from W-shape to U-shape morphology upon cation complexation as a penta-dentate ligand.[7] On the other hand, light irradiation may be expected to cause an E to Z switch on a single double-bond, producing an S-shaped *EZ* bisacylhydrazone, with stabilization of the Z arm by an internal hydrogen bond.[2]

These structural features could be substantiated by detailed NMR studies (see ESI for detailed spectra), *e.g.* on model compound **1**-Ph. ‡[1] Further confirmation of the structural features of a simple form presenting a mixed *EZ*-configuration was obtained by determination of the molecular solid state structure on the nitro derivative *EZ*-**1**-NO_2. Although the double bond isomerisation of acylhydrazones was reported extensively, a crystal structure of this or similar systems, structurally illustrating the internal hydrogen-bonding, remained elusive so far.[8]

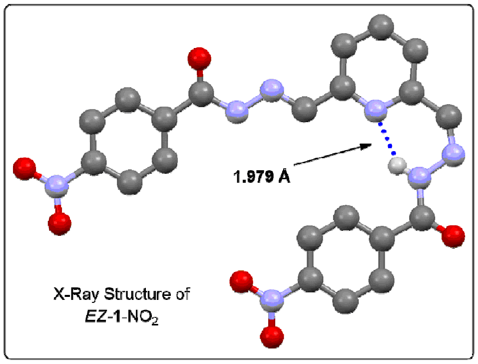

Figure 3. Solid state molecular structure of the isomerized bis-acylhydrazone *EZ*-**1**-NO_2, showing the CONH···N(pyridine) hydrogen bond on the Z half of the molecule.

Suitable crystals were obtained from a heat-saturated solution of freshly synthesized **1**-NO_2 in DMSO after several days. The crystallographic structure determination showed, that the compound that had crystallized was the isomerized *EZ*-**1**-NO_2, obtained without the additional action of UV-irradiation, displaying an N-H···N(pyridine) hydrogen bond on the Z half of the molecule (Figure 3).‡[2]

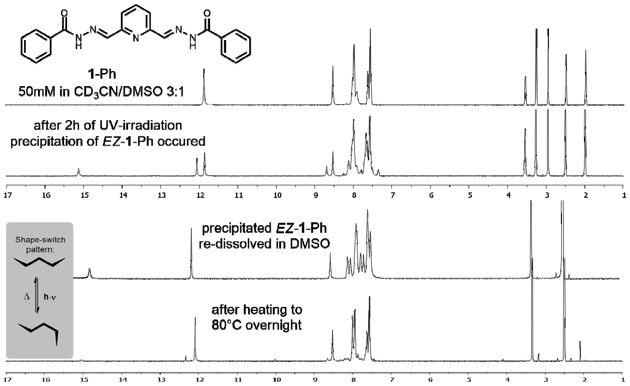

Figure 4. ^1H NMR spectra of the photo-isomerisation of the bis-acylhydrazone **1**-Ph under UV irradiation, showing the shifted signals of the proton of the CONH···N(pyridine) hydrogen bond and the back-conversion of the isolated switched material.

The *EE* to *EZ* isomerisation under irradiation with UV light could be clearly followed by ^1H NMR spectroscopy for the model compound **1**-Ph.‡[3,4] After irradiation of a 50mM-sample of **1**-Ph in CD_3CN/DMSO 3:1 a markedly shifted -NHCO- proton signal appeared at 15.1 ppm, in line with the formation of a strong hydrogen bond. The isomerized *EZ*-**1**-Ph precipitated from this solution, but the reversibility of the isomerisation could be demonstrated by heating a solution of pure *EZ*-**1**-Ph in DMSO to 80°C overnight, which led to an almost quantitative back-conversion to the corresponding *EE*-form of **1**-Ph (Figure 4). The reversible switching of **1**-MeO and **1**-Cl could also be demonstrated, but proceeded rather sluggishly for both cases (see ESI for corresponding spectra).

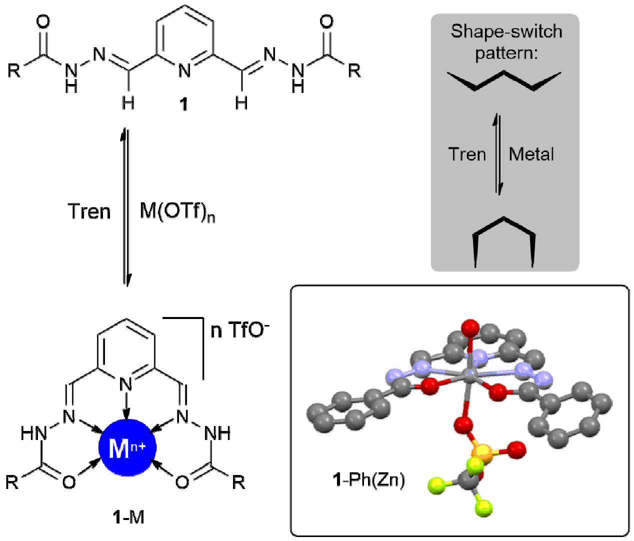

Figure 5. Interconversion between the free bis-acylhydrazone ligand **1**-Ph and its metal complex **1**-M (*left*), with a change in shape of the ligand from W to U (*top right*). Solid state molecular structure of the **1**-Ph(Zn)-complex (*bottom right*).

To investigate the interconversion between the metal complexed bisacylhydrazones **1**-M and unbound **1** as well as *EZ*-**1**, the respective metal complexes were prepared by mixing the ligands with the corresponding metal triflates in CD_3CN/DMSO. On subsequent diffusion of *i*-Pr_2O into these solutions, several complexes could be crystallized and the crystal structures were determined for **1**-Ph(Zn), **1**-NO_2(Zn) and **1**-NO_2(Sc) (see ESI).[9] As seen for the case of **1**-Ph(Zn), the bis-acylhydrazone Ph-**1** acts as a pentadentate ONNNO ligand, with the coordination shell being completed by a water molecule and a triflate anion (Figure 5, see ESI for details of other structures).

Upon treatment of the U-shaped complex **1**-Ph(Zn) with 1.0 equivalent of the competitive ligand Tren [tris(2-aminoethyl)amine], the metal cation was removed from the complex, and the ^1H NMR spectrum showed the restoration of the original W-shaped ligand **1**-Ph. With the addition of two further equivalents of Tren (3.0 total equivalents), the proton signals of the –NH-groups disappeared, most probably reflecting the full deprotonation of the hydrazone (see ESI for spectra).

To study whether the transition between complexes **1**-M and isomerized bis-acylhydrazones *EZ*-**1** could be induced directly by UV-irradiation without passing through **1** via competitive decomplexation, 25mM samples of the complexes in CD_3CN/DMSO-mixtures (1:1 or 3:1) were irradiated with UV light. As expected from the results obtained with the ligands themselves, the isomerisations of **1**-Cl(Zn) and **1**-MeO(Zn) occurred only very sluggishly, whereas the irradiation of **1**-Ph(Zn) led to a smooth isomerization to a photostationary state at 70-80% of the isomerized *EZ*-**1** product (as determined by integration of the ^{1}H-NMR signals; see ESI). This stationary state was reached after about 30 mins of irradiation. The reversibility of the process was demonstrated as well: heating the same sample at 80°C for 12h led to an almost quantitative back-isomerization to **1**-Ph(Zn) (see Fig. 6). We studied this behaviour on corresponding Ca^{2+}, Mg^{2+} and Sc^{3+}-complexes as well (not shown), however these complexes did not exhibit the smooth isomerisation of **1**-Ph(Zn).

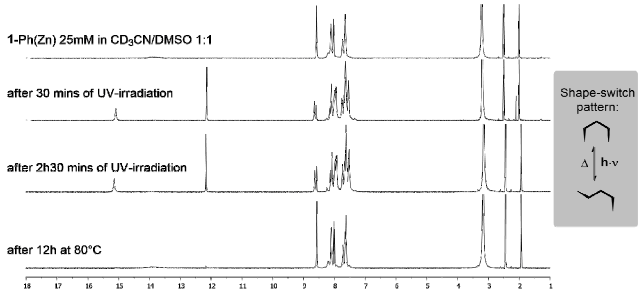

Figure 6. (*From top to bottom*) Interconversion between the U-shaped complex **1**-Ph(Zn) and the S-shaped bisacylhydrazone Ph-**1** and back-conversion to the U-shaped complex **1**-Ph(Zn) by heating.

In conclusion, we have demonstrated that the bis-acylhydrazones **1** give rise to a fully reversible interconversion cycle. The interconnections implement thermo-, photo- and metallo-triggered responses. The molecules reversibly switch between a W-shape in **1** to a U-shape in **1**-M and an S-type shape for the *EZ* form of **1**.[6c,d] A special feature of the bis-acylhydrazone complexes investigated resides in the reversible binding and release of metal ions upon UV-irradiation, which is potentially of interest for metal cation signal generation, reversible metal scavenging and photomodulated metal ion catalysis.

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Notes and references

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‡1 We attempted to follow the conversion by UV-spectroscopy (absorption) as well, however the conversion between the two species led only to a rather small shift of roughly 20 nm (see ESI), leaving us to focus on NMR-spectroscopy for the further studies.

‡2 Since the solubility of the isomerized form *EZ*-**1**-NO_2 is extremely low in any solvent, it can only be speculated, if the isomerisation occurred during synthesis or after, since corresponding signals are only visible in trace amounts.

‡3 All irradiations were performed with a Müller Elektronik Optik Light Source Model LAX 1000 / SVX 1000 and a xenon short arc lamp XBO 1000 W / HS OFR from Osram. Experiments were conducted in a thermostated glass bath at 25°C.

‡4 The insolubility of **1**-NO_2 made the detailed study of its light-switching behaviour impossible. During the study of its corresponding metal complexes, trace amounts of the switched *EZ*-**1**-NO_2 became apparent in the ^{1}H-NMR-spectrum (see ESI). The irradiation of the **1**-NO_2(Zn)-metal complex led to an immediate and heat-reversible precipitation of the switched ligand (see picture in the ESI).

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