

Supramolecular isomerism in multivalent metal-templated assemblies with topochemical influence in the regioselective synthesis of tetrakis(2-pyridyl)cyclobutane isomers†

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An unprecedented example of supramolecular isomerism based on 2D hydrogen-bonded multi-component networks that leads to the preparation of different photoproducts via a topochemical transformation is reported.

Covalent synthesis performed in the solid state is considered an important alternative for the preparation of new and conventional compounds.^{1–3} In particular, the topochemical [2 + 2] cycloaddition of olefins represents an interesting route for the preparation of multitopic organic molecules. Such compounds are very attractive as tectons for the design of unusual supramolecular metal assemblies.⁴ The assembly of olefins in the solid state offers a unique possibility for the regiocontrolled access to single cyclobutane isomers in quantitative yields. However, in spite of the well known advantages of solid state reactions with respect to the same reactions in solution, the development of strategies to design potentially reactive solids continues to be an exciting challenge for crystal engineering.

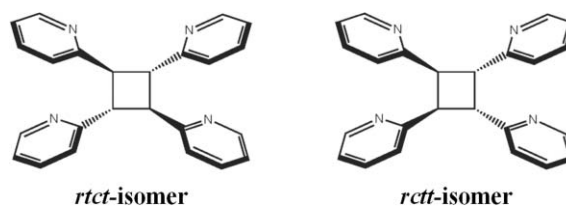
In recent times, systematic and ingenious strategies, based on the use of auxiliary molecules as directing agents (template-directed covalent synthesis) and their combination with directional supramolecular synthons, have been incorporated. Both well-engineered tools serve to offer molecular assemblies bearing the perfect geometrical prerequisites necessary for the solid state photoreaction of active centres.^{2,5–10} In particular, MacGillivray and co-workers have introduced an elegant modular method, based on the use of resorcinol derivatives as molecular templates, to direct the topochemical reactivity of (pyridyl)ethylene compounds.² This approach has been extended by using coordination driven self-assembly,^{4a,b,11} in which the well known coordination geometry preference of metal centres is exploited to lead to preorganized photoreactive molecules. Interestingly, both organic and metal assisted strategies have been particularly successful in the regioselective synthesis of *rcct*-cyclobutane-like compounds. In order to design potentially reactive metal–organic solids,¹² we have also explored this second approach and focused our attention on the use of multivalent templates¹³ as a strategy to direct reactivity in the solid state. Multivalent metal–ligand interactions provide a

means of engineering simple building blocks into multi-component aggregates such as discrete supermolecules^{14a} and/or multiple and well defined supramolecular architectures for a given set of molecular components (supramolecular isomerism).^{14b} The intrinsic structural flexibility and diversity of these arrays affords a range of geometrical possibilities for obtaining stereocontrolled dimers of stilbene that are difficult access, either in solution or by known solid state routes (*i.e.*, *rtct* and/or head-to-tail isomers).

Herein, the potential of such a strategy is demonstrated by the synthesis, structural characterisation and solid state reactivity of the two supramolecular isomers of $[\text{Mn}(\text{NCS})_2(\text{OH}_2)_4]\cdot 4(\text{bpe})$ (bpe: *trans*-1,2-bis(2-pyridyl)ethylene), **1** and **2**. The UV irradiation of these multi-component assemblies leads to the regioselective topochemical formation of distinctive photoproducts: **1** produces exclusively the *rtct*-tpcb molecular isomer (tpcb: tetrakis(2-pyridyl)cyclobutane), whereas **2** generates the *rcct*-tpcb compound (Scheme 1). The study of Co-complex **3**, whose crystal structure is isomorphous with that of **2**, is also presented.

Isomers **1** and **2** were prepared by a one-pot reaction of $\text{MnCl}_2\cdot 2\text{H}_2\text{O}$, NaNCS and bpe in a mixture of water and ethanol (2 : 1), using metal : bpe molar ratios of 1 : 2 and 1 : 1, respectively. Interestingly, when the Mn : bpe molar ratio is 1 : 2, isomer **1** is obtained as a single phase (see ESI†). However, when a ratio 1 : 1.5 is used, the concomitant crystallisation of both supramolecular isomers, **1** and **2**, is observed. Additionally, if **1** is recrystallised, the formation of both isomers is also observed. Furthermore, highly pure **2** is obtained exclusively by using a starting 1 : 1 molar ratio. This suggests that the selective formation of these isomers depends on the concentration. A similar example of supramolecular isomerism has been reported recently.¹⁵ In contrast, when the reaction is carried out using Co^{II} , only compound **3** is formed, independent of the molar ratio used.

The asymmetric unit of **1**† contains one half of the neutral complex $[\text{Mn}(\text{NCS})_2(\text{OH}_2)_4]$, and two bpe molecules; one occupies a full general site and two halves of crystallographically independent bpe are located on centres of symmetry. The metal complex displays C_2 symmetry, with an octahedral environment in



Scheme 1

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which four water molecules are located in the equatorial plane (Mn–O_w range: 2.145(3)–2.217(2) Å), and the axial positions are occupied by the N atoms of two thiocyanate ligands (Mn–N: 2.207(3) Å). In the crystal structure, each metallic entity is linked to eight bpe molecules (see Fig. 1(a)) *via* O–H···N hydrogen bonds involving coordinated water molecules and pyridine nitrogen atoms (O···N range: 2.767(4)–2.956(6) Å). This supramolecular building block is extended in the (202) plane, leading to a hydrogen bonded layer, as displayed in Fig. 1(a).

The 2D network can be seen as a supramolecular assembly of [Mn(NCS)₂(OH₂)₄] moieties linked to bpe molecules through hydrogen bonds using the O1_w atoms of coordinated water molecules. This takes place in such a way that a rhomboidal array (see Fig. 1(a)) of metal centres connected by bpe molecules is produced (Mn···Mn distances 10.5 × 10.5 Å). Two other bpe molecules are accommodated in the middle of the metallic rhomboids, located just above and below the plane defined by the metal centres (Fig. 1(b)). These two molecules are related by a two-fold axis and show the shortest contacts (centroid-to-centroid: 3.23(2) Å) observed between adjacent double bonds in the entire packing. This length is noticeably shorter than the limiting value proposed by Schmidt as the appropriate distance for topochemical [2 + 2] photocycloaddition (4.2 Å).¹⁶ In cooperation, their close contact and the two-fold symmetry anticipate the formation of the *rtct*-isomer during the photoreaction (*vide infra*). The remaining molecules may not be photoactive due to the unfavourable geometrical conditions for photodimerisation.

The crystal structure of **2** is isomorphous with that of **3** and their asymmetric units display the same components as those found in **1**.[‡] In these structures, the metal centre (Mn^{II} or Co^{II}) is located on an inversion centre, in contrast to the crystal structure of **1**. These metal complexes maintain the same octahedral coordination geometry as that observed for **1**, with four coordinated water molecules (Mn–O_w range: 2.184(2)–2.226(2) Å) and two N-atoms from two thiocyanate ligands (Mn–N: 2.176(3) Å). As is observed in the crystal structure of **1**, the metal complex is connected to eight bpe molecules (see Fig. 2(a)) *via* O–H···N hydrogen bonding (O···N range: 2.779(5)–2.891(6) Å). However, the final supramolecular building block shows differences in the relative orientation of the pyridines around the metal complex, which makes its crystal

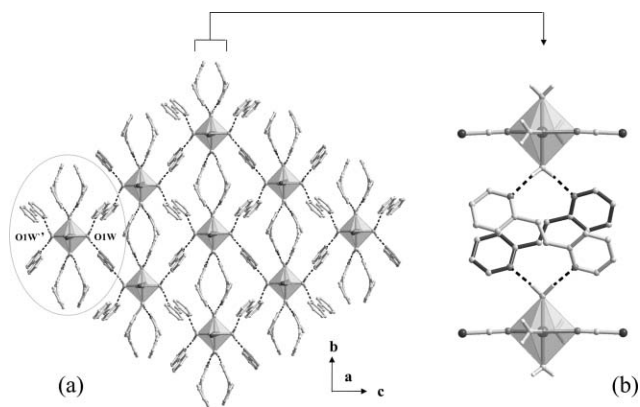


Fig. 1 (a) View of the hydrogen bonded 2D network observed in the crystal structure of **1**. A transparent gray oval shows the building block. (b) Side view along the b-axis showing the geometrical disposition of bpe molecules related by two-fold symmetry.

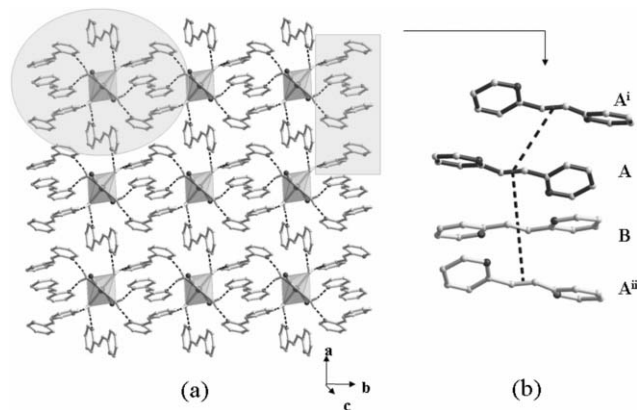


Fig. 2 (a) View of the hydrogen bonded 2D network found in the crystal structures of **2** and **3**. A transparent gray oval shows the building block. (b) Interactions between bpe molecules along the a-axis.

packing a supramolecular isomer of that found for **1**. The building block is also self-assembled by a similar O–H···N hydrogen bonding pattern but it generates a 2D network parallel to the (001) plane (see Fig. 2(a)). In the case of **2** and **3**, the resulting 2D network exhibits a pseudo-square array of metal complex···bpe moieties, with M···M dimensions of 10.13 × 10.68 Å and 10.11 × 10.64 Å for **2** and **3**, respectively.

Accordingly, the bpe···bpe interactions are appreciably different from those observed in the crystal structure of **1**. An analysis of the relative orientations between the double bonds of neighbouring bpe molecules in **2** and **3** reveals two kinds of intermolecular contacts (Fig. 2(b)). In the shorter contact, the centroids of the double bonds are separated by 3.39(3) Å (3.44(2) Å for **3**) (molecules A···B and B···Aⁱⁱ; symmetry code: ii = 1 – x, –y, 1 – z; see Fig. 2(b)). The relative orientations of these double bonds allow an adequate alignment that leads to the formation of the *rtct*-dimer upon irradiation. The next contact is longer, with a distance of 4.32(5) Å (4.21(4) Å for **3**) (see molecules A···Aⁱ; symmetry code: i = 1 – x, y, z), which is slightly above the value proposed by Schmidt (4.2 Å),¹⁶ and would require further shortening to allow photodimerisation. A concerted movement of double bonds due to the reaction of the pairs A···B and B···Aⁱⁱ could permit this approach (*vide infra*).

As expected, the ¹H NMR characterisation of the products obtained after UV irradiation of **1**, **2** and **3** for 7 days confirms the cycloaddition reaction in all cases. The spectrum of the resulting dimer **4**, obtained from the irradiation of **1**, showed a singlet at 4.41 ppm, which is characteristic of the C–H protons of a cyclobutane ring with a *rtct* configuration (Fig. S1a†). The chemical shifts of the remaining signals were consistent with the reported ¹H NMR pattern for such an isomer.¹⁷ The stereochemistry of **4** was confirmed by single crystal X-ray diffraction analysis of a sample of the isolated product obtained by recrystallisation from chloroform.‡ On the other hand, the spectrum of product **5**, isolated after the photoreaction of **2** or **3**, showed a singlet at a lower field (5.13 ppm), corresponding to C–H protons of cyclobutane rings with a *rtct* configuration (Fig. S1b†). The signals corresponding to the starting pyridine were not observed in these spectra (Fig. S1a and Fig. S1b†). The presence in all the spectra of only one signal in the region of the aliphatic methine protons reveals the regio- and stereospecific nature of the

solid state photodimerisation of the starting material into a single cyclobutane product. In addition, the yield of the *rtct*-tpcb (4) was ca. 48%, which is equivalent to a quantitative conversion from topochemically suitable contacts between the bpe molecules in the packing of 1. It is important to note that the *rtct*-tpcb isomer is obtained in very low yields by photoirradiation in solution¹⁷ since it is produced together with a mixture of side products, including the more favoured *rttt*-isomer. On the other hand, dimer *rttt*-tpcb (5), generated from either 2 or 3, was always obtained in ca. 55–60% yields, which is expected given the number of topochemically suitable contacts between the pyridines. These results suggest that the photoreaction has occurred at least partially between all the pairs of bpe contacts mentioned above. All photoproducts obtained are in agreement with the stereochemical control exerted by the crystal packing of their solid precursors.

Optical microscopy analysis of irradiated single crystals of 1, 2 and 3 revealed evident changes in shape. During exposure with UV light, the crystals showed a gradual formation of anisotropic internal cracks on defined faces. These macroscopic features suggest that photoreaction does not proceed *via* single crystal-to-single crystal transformation.¹⁸ Additionally, drastic colour changes were observed when single crystals and/or powder samples of the Co-derivative 3 were irradiated. During UV irradiation, the compound displayed two changes in colour, depending on the wavelength used during the experiment (Fig. S3a–c†). When 3 was irradiated with unfiltered UV light at 302 nm, the crystals changed from pink to blue and finally to green, whereas when a Pyrex filter was used, the colour of the sample changed from pink to blue. Preliminary analysis suggests that these photoinduced changes of colour could be associated with linkage isomerism of the NCS[−] ligand (–NCS or –SCN),¹⁹ such as was observed in the IR spectra after irradiation of the solids. The FT-IR spectrum of a fresh sample of 2 showed the presence of a strong band due to the ν_{NCS} absorption at 2095 cm^{−1} (Fig. S3a†), whereas the IR spectrum of a blue-coloured sample showed a shift of the ν_{NCS} absorption to 2058 cm^{−1}, with a difference ($\Delta\nu$) of 37 cm^{−1} with respect to the fresh sample (Fig. S3b†). The IR spectrum of the green-coloured sample showed a splitting of the absorption band between 2089–2063 cm^{−1} (Fig. S3c†). This band is characteristic of the presence of two coordination modes for the NCS[−] ion.¹⁹ Unlike 3, the Mn-compound 2 does not exhibit changes in the position of the ν_{NCS} absorption after irradiation (Fig. S4†).

In summary, we report an unprecedented example, to the best of our knowledge, of supramolecular isomerism that leads to different solid state reactivity patterns, allowing the regioselective synthesis of tetrakis(2-pyridyl)cyclobutane isomers. This example represents an equivalent supramolecular version of Schmidt *et al.*'s pioneering work demonstrating the formation of different stereoproducts from two polymorphic modifications of *trans*-cinnamic acid.²⁰

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Notes and references

† *Crystal data for 1*: C₅₀H₄₈MnN₁₀O₄S₂, $M_r = 972.04$, monoclinic, space group $P2_1/n$, $a = 13.3756(18)$, $b = 12.0960(14)$, $c = 16.498(2)$ Å, $\beta = 110.314(3)^\circ$, $U = 2503.2(6)$ Å³, $Z = 2$, $\mu(\text{Mo-K}\alpha) = 0.401$ mm^{−1}, $\rho_{\text{calc}} = 1.290$ g cm^{−3}, $R_{\text{int}} = 0.0336$, $R_1 = 0.0670$, $wR_2 = 0.1817$ for 3663 independent reflections ($I > 2\sigma(I)$). CCDC 606784. *Crystal data for 2*: C₅₀H₄₈MnN₁₀O₄S₂, $M_r = 972.04$, monoclinic, space group $P2_1/n$, $a = 10.6800(14)$, $b = 10.1327(13)$, $c = 23.011(3)$ Å, $\beta = 92.672(4)^\circ$,

$U = 2487.4(6)$ Å³, $Z = 2$, $\mu(\text{Mo-K}\alpha) = 0.403$ mm^{−1}, $\rho_{\text{calc}} = 1.298$ g cm^{−3}, $R_{\text{int}} = 0.0353$, $R_1 = 0.0684$, $wR_2 = 0.1934$ for 4752 independent reflections ($I > 2\sigma(I)$). CCDC 606785. *Crystal data for 3*: C₅₀H₄₈CoN₁₀O₄S₂, $M_r = 976.03$, monoclinic, space group $P2_1/n$, $a = 10.6357(10)$, $b = 10.1079(9)$, $c = 22.888(2)$ Å, $\beta = 92.203(3)^\circ$, $U = 2458.7(4)$ Å³, $Z = 2$, $\mu(\text{Mo-K}\alpha) = 0.488$ mm^{−1}, $\rho_{\text{calc}} = 1.318$ g cm^{−3}, $R_{\text{int}} = 0.0400$, $R_1 = 0.0684$, $wR_2 = 0.1938$ for 3538 independent reflections ($I > 2\sigma(I)$) CCDC 606786. *Crystal data for 4*: C₂₄H₂₀N₄, $M_r = 364.44$, tetragonal, space group $P4_2/c$, $a = 15.6498(9)$, $c = 16.1138(9)$ Å, $U = 3946.5(4)$ Å³, $Z = 8$, $\mu(\text{Mo-K}\alpha) = 0.074$ mm^{−1}, $\rho_{\text{calc}} = 1.227$ g cm^{−3}, $R_{\text{int}} = 0.0492$, $R_1 = 0.0594$, $wR_2 = 0.1490$ for 2310 independent reflections ($I > 2\sigma(I)$). CCDC 606787. For crystallographic data in CIF or other electronic format see DOI: 10.1039/b606673a

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