

# Probing atomic level structural transformation in O–H···N heterosynthon crystal†

Mujeeb Khan, Volker Enkelmann and Gunther Brunklaus\*

Received 19th November 2008, Accepted 11th February 2009

First published as an Advance Article on the web 3rd March 2009

DOI: 10.1039/b820732a

Structural changes of resorcinol (res) and *trans*-1,2-bis(4-pyridyl)ethylene (bpe) co-crystals during [2 + 2] photodimerization were monitored by means of single crystal X-ray analysis. The crystals lost their integrity with increasing conversion indicating an interesting case of a *non-ideal* single-crystal-to-single-crystal transformation. The 2(bpe) : 2(res) heterosynthon yielded two different polymorphs upon photodimerization, *i.e.* the dimer obtained via single-crystal-to-single-crystal transformation (as-dimerized dimer) consists of triclinic *P*-1 space group which upon re-crystallization adopted a stable conformation with monoclinic *P*2<sub>1</sub>/*n* space group.

## 1. Introduction

Crystal engineering has been defined as the understanding of inter-molecular interactions in the context of crystal packing and the utilisation of such understanding for the tailored design of new solids with desired physical and/or chemical properties.<sup>1–5</sup> An intriguing feature of the chemistry of organic crystals is that some of the crystals are reactive and others are unreactive, even though the difference of their molecular structure is rather minor.<sup>6</sup> While the reactivity and selectivity in the solid-state is often controlled by the crystal structure, it is still difficult to construct a desired structure. Therefore, fairly simple experimental methods, which compel photoinert crystals to be reactive, will be of great significance. With respect to this, many researchers have been investigating photochemical reactions of two component crystals.<sup>7,8</sup> Such an approach to synthesis can lead to the formation of covalent bonds *at will* in solids facilitating a high yield, solvent free synthesis of molecules that are available either in low yields only, or as part of mixtures, or are not at all accessible in the liquid phase.

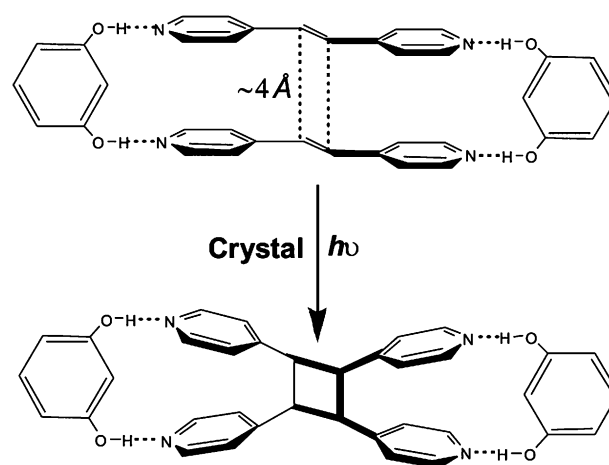
[2 + 2] photodimerizations are among the most extensively studied organic solid-state reactions,<sup>6</sup> and according to Schmidt's topochemical postulates,<sup>9</sup> such reactions commonly occur in solids if two carbon–carbon double bonds are aligned rather parallel to each other and are separated by less than 4 Å.

In pure *trans*-1,2-bis(4-pyridyl)ethylene (bpe) (which crystallizes in a layered structure)<sup>10</sup> olefins of neighbouring layers lie orthogonal and are separated by 6.52 Å, thus rendering bpe photostable.<sup>6</sup> In contrast, 1 : 1 co-crystallization with resorcinol produces a so-called O–D complex (with discrete rings),<sup>11</sup> 2(bpe) : 2(res), where the two C=C bonds are not only oriented parallel but separated by 3.65 Å.

This crystal arrangement indeed complies with topochemical principles<sup>9</sup> and thus, upon broadband UV irradiation, yields the photodimer tetrakis(4-pyridyl)cyclobutane (*cf.* Scheme 1).

In principle, a single-crystal-to-single-crystal transformation<sup>12–14</sup> involves a solvent-free chemical reaction of a single crystal in which the product of the reaction forms within the solid phase of the reactant, so that the integrity of the single crystal (*i.e.* its transparency or shape) remains virtually unchanged as the reactant molecules are converted to the product. This allows for monitoring *in situ* the course of a solid-state reaction *via* X-ray analysis,<sup>12</sup> thus offering valuable insight into the corresponding reaction mechanism and pathways. Since rather intact crystals of intermediate states of the reactions are accessible *via* tail-irradiated SCSC transformation,<sup>13</sup> it is possible to gain an *atomic level* understanding of the structural changes of reactants that occurred during the reaction in the solid state. Such reactions also possess all of the properties considered advantageous for solid state reactions (*e.g.* stereocontrol of reactivity). More importantly, products obtained from such transformations have shown potential applications in technology.<sup>15,16</sup>

In this work, we monitor the single-crystal-to-single-crystal [2 + 2] photodimerization of a 2(bpe) : 2(res) co-crystal upon *tail-irradiation*<sup>13</sup> *via* X-ray analysis to establish both the nature of the reaction mechanism and an atomic level understanding of the structural changes occurring during the reaction. To our best knowledge, such studies have not yet been reported, particularly considering the 2(bpe) : 2(res) supramolecular heterosynthon (*cf.* Scheme 1). Though recently MacGillivray and co-workers reported the SCSC transformation of 4-benzylresorcinol and 1,4-bis(4-pyridylethynyl)benzene



**Scheme 1** Reaction scheme for the [2 + 2] photodimerization of 1 : 1 co-crystal of resorcinol and *trans*-1,2-bis(4-pyridyl)ethylene.<sup>11</sup>

Max-Planck-Institut für Polymerforschung, Postfach 3148, D-55021 Mainz, Germany. E-mail: brunklaus@mpip-mainz.mpg.de

† CCDC reference numbers 710270 and 710271. For crystallographic data in CIF or other electronic format see DOI: 10.1039/b820732a

co-crystals,<sup>17</sup> they have not elucidated the reaction mechanism based on intermediate states of the respective SCSC transformation of the 2(bpe) : 2(res) supramolecular heterosynthon.

## 2. Experimental

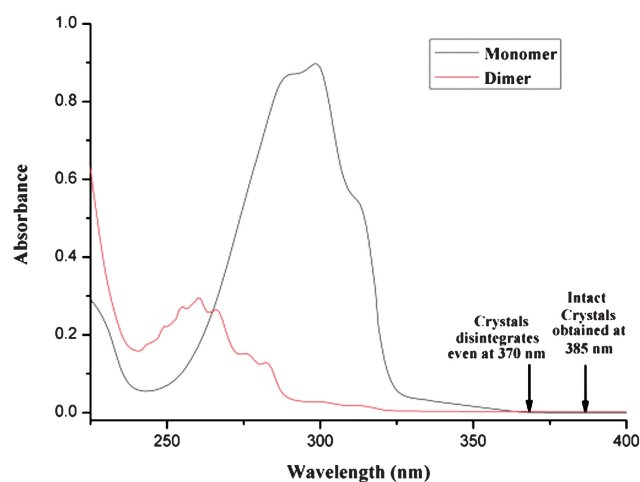
Co-crystals of 2(bpe).2(res) were synthesized as reported.<sup>11</sup> For tail-irradiation, a rather nice and transparent crystal was chosen, and all irradiation and X-ray experiments were performed on the same crystal. The crystal was irradiated in two different steps by an Hg 100 W lamp with an edge filter of 385 nm. The crystal structures were recorded on a Kccd diffractometer with graphite monochromated Mo K $\alpha$  radiation. Lattice parameters were obtained by least-square fits to the scattering angles of reflections observed in several pre-scans. The intensity data collection was performed by  $\phi$  and  $\omega$  scans. The raw data were corrected for Lorentz and polarization effects. The structures were solved by direct methods and refined by full matrix least-squares analyses with anisotropic temperature factors for all atoms except H. In the 14%-converted structure, the positions of the cyclobutane C atoms were determined *via* difference Fourier analysis. The population parameters for the partially occupied sites were determined from a least-squares analysis with common isotropic temperature factors and the boundary condition that the sum of the population parameters is 1. In addition (in the refinement of the 14%-converted structure), the anisotropic temperature factors of the cyclobutane C atoms were constrained to those of the C atoms in the double bond. All positions of the H atoms were first calculated using known molecular geometries and then refined in the riding mode with fixed isotropic temperature factors. Empirical absorption corrections were applied to the data.

## 3. Results and discussions

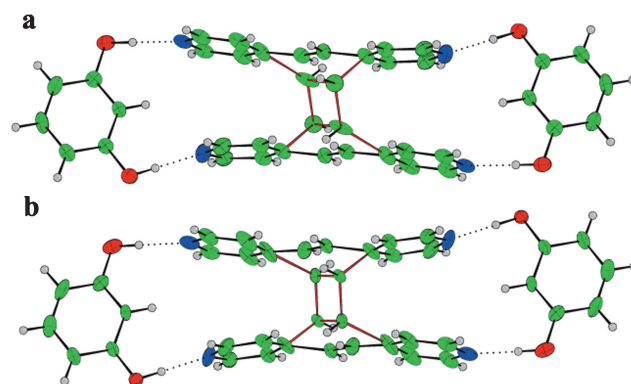
### 3.1. Tailored [2 + 2] photodimerization

The system shown in Scheme 1, undergoes the [2 + 2] photodimerization homogeneously, but through a rare *non-ideal* SCSC transformation. Here, like in the ideal case,<sup>6,9</sup> the transformation takes place homogeneously *i.e.* with the formation of solid solutions of the product and reactant throughout the conversion, but the quality of mixed crystals obtained during the reaction deteriorated drastically into small fragments even under tail irradiation,<sup>13</sup> presumably due to buildup of severe strain in the crystals. This makes it extremely difficult to monitor the complete conversion as both the crystal size and crystal quality (as characterized by the width of the reflections) decreases continuously with conversion so that at a certain level, the crystals were no longer suitable for single crystals X-ray analysis. Upon irradiation at the maximum absorption of the bpe chromophore (300 nm)<sup>18</sup> (*cf.* Fig. 1), a heterogeneous reaction is observed.<sup>19</sup> The surface of the originally yellow crystals is slowly covered with fine powder, while the crystals eventually shatter into microcrystalline particles.

Even when crystals of 2(bpe) : 2(res) are irradiated at 370 nm (70 nm away from the absorption maximum), the crystals quickly start to disintegrate indicating product formation but *not via* an anticipated SCSC transformation. When a filter with the flank of the absorption more than 120 nm longer than the absorption maximum (420 nm) is used, even after hours of irradiation, no indication of product formation was found. Different edge filters were tried between 370 and 420 nm, with crystals either crumbling at an early stage or not



**Fig. 1** Electronic absorption spectrum for bpe monomer and dimer. The splitting of the absorption band is attributed to five different transitions in the bpe monomer.<sup>18</sup> One  $n\text{-}\pi^*$  and other  $\pi\text{-}\pi^*$  transitions.

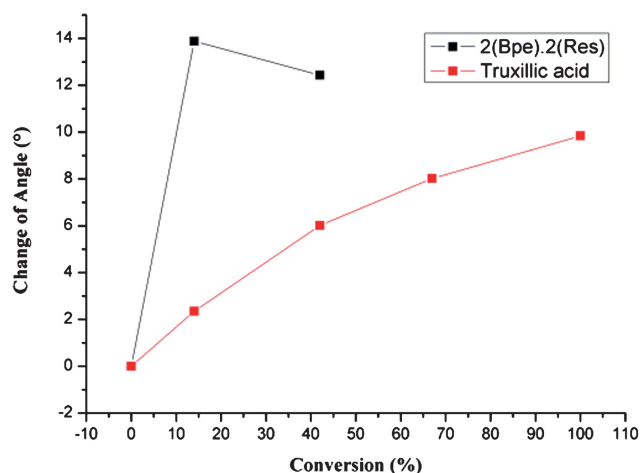


**Fig. 2** Crystal structure projection of (a) 14% and (b) 42% converted mixed crystal of 2(bpe) : 2(res) heterosynthon.

**Table 1** Unit cell parameters obtained during the photodimerization of 2(bpe) : 2(res) heterosynthon. Both, the monomer and mixed crystal have *triclinic* space group whereas the dimer has a *monoclinic* space group. The cell parameters given for the mixed crystals have been transformed to allow for a comparison of the respective angles

Unit cell parameters	2(bpe) : 2(res) monomer <sup>11</sup>	2(bpe) : 2(res) 14% mixed crystal	2(bpe) : 2(res) 42% mixed crystal	2(bpe) : 2(res) dimer <sup>11</sup>
Crystal structure	Triclinic	Triclinic	Triclinic	Monoclinic
Space group	<i>P</i> -1	<i>P</i> -1	<i>P</i> -1	<i>P</i> 2 <sub>1</sub> / <i>n</i>
<i>a</i> /Å	8.070 (1)	7.9360 (4)	7.7682 (4)	11.367 (1)
<i>b</i> /Å	9.832 (1)	9.8340 (5)	9.7938 (5)	9.749 (1)
<i>c</i> /Å	10.876 (1)	10.9160 (5)	11.0478 (5)	14.273 (1)
$\alpha$ /°	73.1190 (1)	86.9300 (12)	85.5507 (12)	90
$\beta$ /°	72.563 (1)	73.8200 (13)	75.1493 (13)	111.668 (3)
$\gamma$ /°	66.184 (1)	68.5050 (13)	68.5050 (13)	90
<i>V</i> /Å <sup>3</sup>	733.868	733.657	742.068	734.965

reacting even after hours of irradiation (checked by X-ray analysis). In contrast, when a 385 nm edge filter was used, the crystal remained intact and transparent even after 2 h of irradiation. X-Ray analysis revealed a ~14% converted mixed crystal, but with increasing conversion, the crystals split into small crystalline fragments that were used in the structure determination. While a crystal of suitable size (~0.2 mm) could be isolated at 42% conversion, the crystal size decreased upon continued irradiation so that no suitable crystals were available for X-ray analysis. Even using an edge filter with a slightly larger value of filtration than a 385 nm filter (389 nm) did not yield fruitful results. The projection of the crystal structure of 14% and 42% converted mixed crystals is given in Fig. 2.



**Fig. 3** The drastic change of angle  $\alpha$  in the unit cell of 14% converted 2(bpe) : 2(res) mixed crystal is compared to that of the gradual changes which occur during the photodimerization of cinnamic acid.<sup>13</sup>

### 3.2. Solid-state reactivity

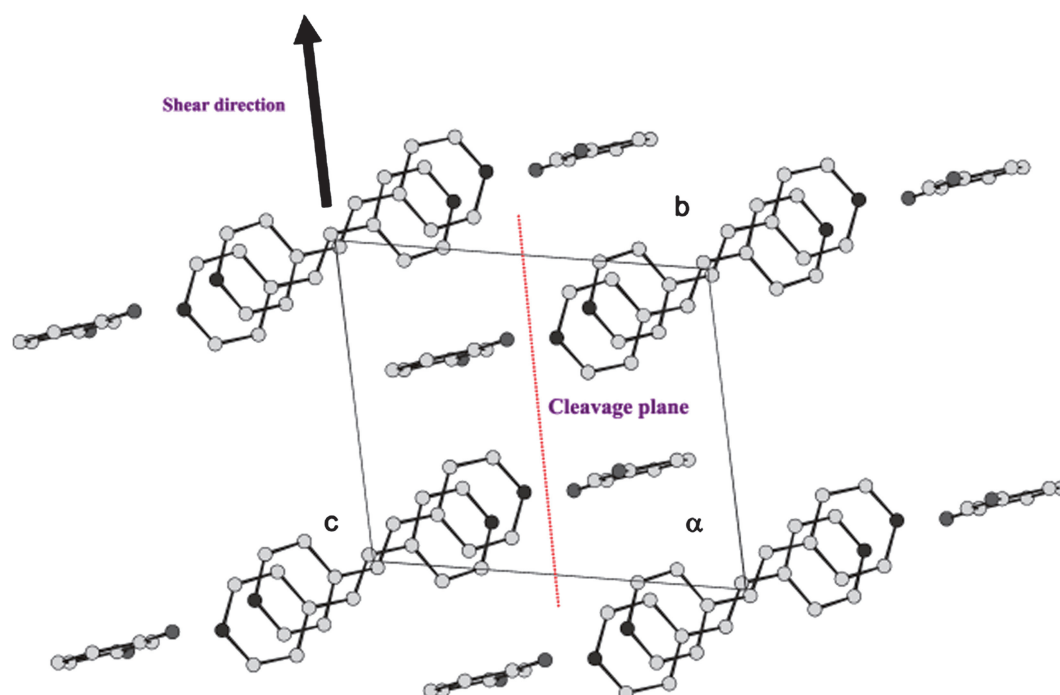
SCSC transformations are governed by the lattice mismatch between reactants and products. At moderate mismatch (cinnamic acid, DSP, styrylpyridium triflate)<sup>13,19,20</sup> the uniform intensity distribution upon tail irradiation leads to high quality as-dimerized crystals. Indeed, in the case of benzylidenecyclopentanone (BBCP),<sup>21</sup> where there is very little lattice mismatch, a SCSC transformation is observed even with broadband irradiation (irradiation at the absorption maximum). Apparently, we deal here with a limiting case with substantial lattice changes during the reaction. The lattice parameters are summarized in Table 1. From the data it is evident that, in particular, one angle of the unit cell (*angle*  $\alpha$ ) changes abruptly by ~14°. (A similar (see Fig. 3) but gradual change has also been observed with  $\alpha$ -*trans*-cinnamic acid).<sup>13</sup>

### 3.3. Changes in lattice parameters

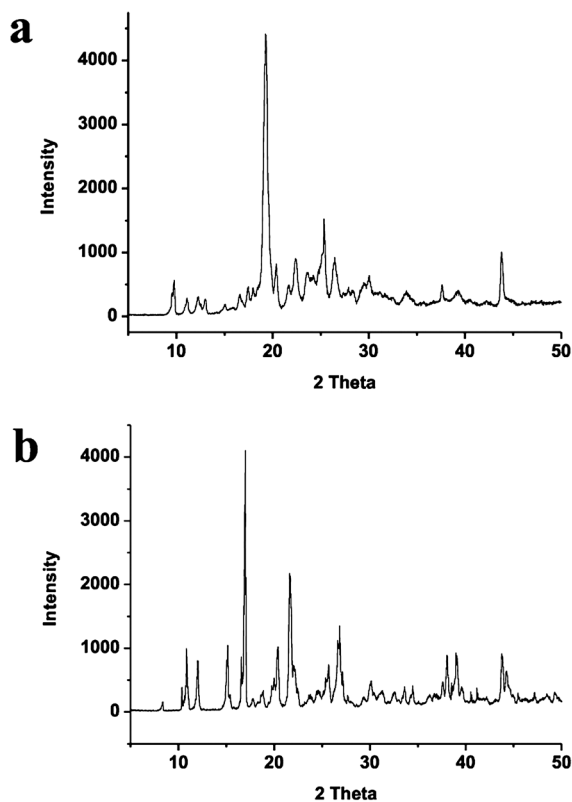
Careful analysis of the lattice changes reveal that in this particular case the change of angle  $\alpha$  is accompanied by a shear movement in the *ab* plane (*cf.* Fig. 4). This plane has been identified as a *rather* prominent cleavage plane; *i.e.* crystals are easily cleaved by outer forces (*e.g.* cut with a razor blade) along this plane. The disintegration of such crystals is therefore a combination of two effects: abrupt change in angle  $\alpha$  and *shear* by large angular changes acting in the direction of the cleavage plane. Table 1 shows that the lattice changes of the other parameters are in the range of (<5%) usually observed in SCSC transformations.

### 3.4. Polymorphism

By powder diffraction experiments (*cf.* Fig. 5) it was checked that the small crystallites at higher conversions retained the triclinic structure. A simulated dimer structure (coordinates of the dimer of the 42% converted structure with an occupancy of 100%) matched the powder



**Fig. 4** Schematic representation of the cleavage plane in the crystals of 2(bpe) : 2(res) heterosynthon that occurs upon photodimerization.



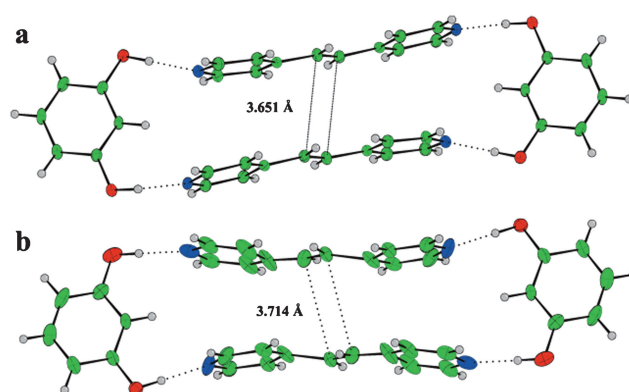
**Fig. 5** Powder diffractograms of (a) 100% converted (*P*-1, triclinic) as-dimerized dimer of 2(bpe) : 2(res); (b) 100% converted recrystallized dimer (monoclinic, *P*<sub>21</sub>/*n*).

diffractogram of the 100% converted as-dimerized dimer (*P*-1 triclinic phase) quantitatively. However when this dimer is recrystallized, another polymorph is produced (monoclinic *P*<sub>21</sub>/*n* phase). The lattice parameters of the stable monoclinic polymorph are included in Table 1.

### 3.5. Analysis of substitutional mixed crystals

In homogeneous topochemical reactions the overall volume change may be low, whereas the change in given lattice parameters can be larger since in certain directions van der Waals contacts are transformed into chemical bonds. This is the case here, where the volume change from monomer to dimer is less than 2%. In contrast, the percent change in cell parameters totals over 10%, particularly affecting the angle  $\alpha$  (larger than 18%), which induces a drastic effect on the quality of the crystal and ultimately forces it to shatter at latter stages of conversion. Therefore, we identify this [2 + 2] photoreaction as a *rare*, but interesting case of a truly homogeneous *non-ideal* SCSC reaction.

Prior to photodimerization, the two substrate (bpe) molecules are related by a center of symmetry and held on top of each other by two resorcinol molecules. The center of symmetry is preserved even after the dimerization.<sup>11</sup> As can be seen in Fig. 6, (2(bpe) : 2(res) crystal structure projection prior to dimerization and after 42% conversion) the position and overall shape of the monomer in a mixed crystal are fairly similar to the position and overall shape of the pair of monomer before irradiation. A major difference is observed in the reacting part of the species, *i.e.* the reacting atoms and their neighbours; the distance between the C=C of the two adjacent molecules has

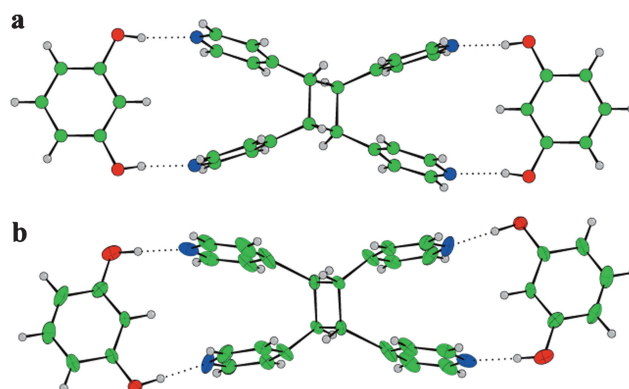


**Fig. 6** Crystal structure projection of monomer molecules (a) prior to photodimerization (triclinic, *P*-1 space group)<sup>11</sup> (b) 6 h irradiated (42% converted) crystal structure with triclinic *P*-1 space group, from the structure atoms belonging to the dimer have been removed for clarity.

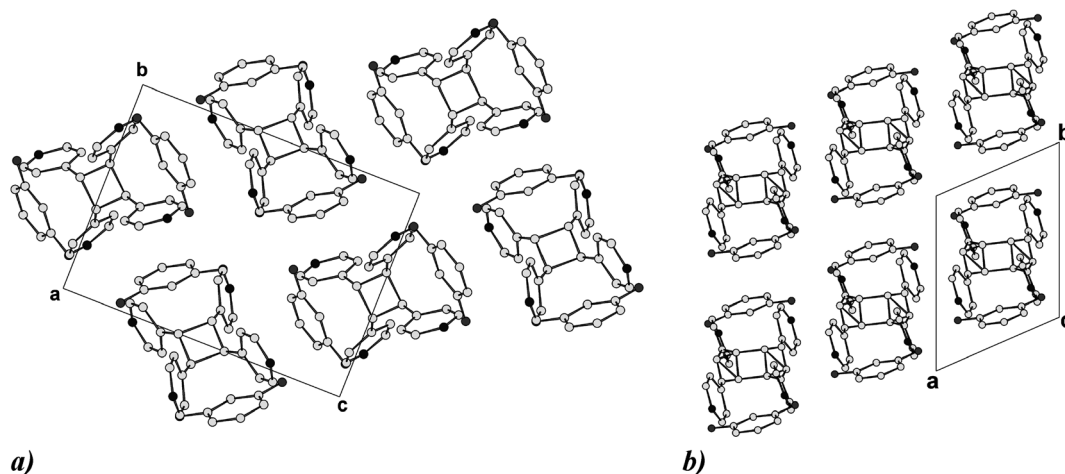
increased from 3.651 to 3.714 Å. Notably, the pyridyl ring occupies the same lattice position whether it is attached to an olefin unit (C=C) or a cyclobutane ring (*cf.* Fig. 2). In crystals at intermediate level of conversion, non-planarity is observed for the bonds from the sp<sup>2</sup> carbon linking the pyridyl ring to the cyclobutane ring or double bond. This deformation is denoted as pyridyl ring tilt (*cf.* Table 2). As

**Table 2** Tilt angles for the substitutional mixed crystals of the 2(res) : 2(bpe) heterosynthons at different conversions

Mixed crystal irradiated by	Tilt angles/ $^{\circ}$		Structure
	A	B	
385 nm Xe lamp 14%	Monomer: 2.87 Dimer: 24.76	7.57 39.61	
385 nm Xe lamp 42%	Monomer: 9.53 Dimer: 20.62	14.86 30.12	



**Fig. 7** Crystal structure projection of dimer molecules a) 100% converted recrystallized dimer with monoclinic *P*<sub>21</sub>/*n* space group;<sup>11</sup> (b) 6 h irradiated (42% converted) as-dimerized dimer with triclinic *P*-1 space group, from this structure atoms belonging to the monomer have been removed for clarity.



**Fig. 8** Packing motif of (a) 100% converted recrystallized dimer with monoclinic  $P21/n$  space group<sup>11</sup> and (b) 6 h irradiated (42% converted) as-dimerized dimer with triclinic  $P-1$  space group. Hydrogen atoms have been removed for clarity.

anticipated, the deformation is less severe for unreacted species at lower conversion, which also increases along with the conversion.

For clarity, the most stable recrystallized dimer is compared with the 42% converted as-dimerized dimer (*cf.* Fig. 7). Two types of conformational changes are observed in the pyridyl rings with respect to the bonds connecting them to the reacting centers: slight rotation along the axis of the bond and the tilt. Upon continuous evolution to the dimer lattice, the pyridyl groups reorient themselves to be increasingly planar with the  $sp^3$  bond off the cyclobutane ring as it increases in concentration. This can be visualized by the decrease in tilt angle with increasing conversion (*cf.* Table 2).

In the stable dimer, however, the tilt angle is almost zero, as the pyridyl rings moved apart from each other and acquired a stable conformation upon recrystallization. This clearly illustrates that the crystal structures of the mixed crystals are a compromise between conformations of the monomer and dimer, respectively, with the anticipated results that the species of higher concentration in the lattice is rather less deformed.

Though the crystal structure projections of the recrystallized and as-dimerized dimer look rather similar, the packing arrangement within the crystal is different (Fig. 8). Indeed, in both cases, the packing unit is comprised of the cyclobutane ring with its four pyridyl rings bracketed by two resorcinols. In the as-dimerized compound, stacks are formed such that two packing units are connected by their long side, while in the recrystallized compound a herringbone-type packing is observed where stacks are formed such that the long side faces the resorcinol of a neighbouring packing unit.

#### 4. Conclusions

The structural changes in the *co-crystal* of 2(bpe) : 2(res) (Scheme 1) obtained upon tail irradiation, are monitored in detail by means of X-ray diffraction. Though the conversion was homogeneous, it occurred *via* a rare *non-ideal* SCSC transformation indicated by significant changes in the lattice dimension at initial stages of the reaction. After the initial large variation of cell constants upon

reaction, further structural changes due to a proceeding reaction were rather gradual. The monomer molecules upon reaction moved from the position adopted in the crystal prior to irradiation, whereas dimers moved towards the position occupied at the final stage. The dimer molecules moved gradually and fluently to the position occupied in the pure as-dimerized dimer crystal that is rather unstable and thus, turned into a stable conformation only after recrystallization. The cell parameters of the monomer, and the mixed crystals, were compared to that of the stable polymorph of the dimer (Table 1).

#### Notes and references

- 1 G. R. Desiraju, *Angew. Chem., Int. Ed.*, 2007, **46**, 8342–8356.
- 2 G. R. Desiraju, *Nature*, 2001, **412**, 397–400.
- 3 D. V. Soldatov and I. S. Terekhova, *J. Struct. Chem.*, 2005, **46**, S1–S8.
- 4 D. Braga, *Chem. Commun.*, 2003, **22**, 2751–2754.
- 5 G. R. Desiraju, *Chem. Commun.*, 1997, **16**, 1474–1482.
- 6 V. Ramamurthy and K. Venkatesan, *Chem. Rev.*, 1987, **87**, 433–481.
- 7 L. R. MacGillivray, *J. Org. Chem.*, 2008, **73**, 3311–3317.
- 8 L. R. MacGillivray, G. S. Papaefstathiou, T. Friscic, T. D. Hamilton, D. K. Bucar, Q. Chu, D. B. Varshney and I. G. Georgiev, *Acc. Chem. Res.*, 2008, **41**, 280–291.
- 9 M. D. Cohen and G. M. J. Schmidt, *J. Chem. Soc.*, 1964, 1996.
- 10 J. Vansant and G. Smets, *J. Org. Chem.*, 1980, **45**, 1557–1565.
- 11 L. R. MacGillivray, J. L. Reid and J. A. Ripmeester, *J. Am. Chem. Soc.*, 2000, **122**, 7817–7818.
- 12 T. Friscic and L. R. MacGillivray, *Z. Kristallogr.*, 2005, **220**, 351–363.
- 13 V. Enkelmann, G. Wegner and K. Novak, *J. Am. Chem. Soc.*, 1993, **115**, 10390–10391.
- 14 M. Khan, G. Brunklaus, V. Enkelmann and H. W. Spiess, *J. Am. Chem. Soc.*, 2008, **130**, 1741–1748.
- 15 D. A. Parthenopoulos and P. M. Rentzeips, *Science*, 1989, **245**, 843–845.
- 16 S. Kawata and Y. Kawata, *Chem. Rev.*, 2000, 1777–1788.
- 17 T. Friscic and L. R. MacGillivray, *Aust. J. Chem.*, 2006, **59**, 613–616.
- 18 R. Abu-Eittah, M. M. Hamed and A. A. Mohamed, *Int. J. Quantum Chem.*, 1991, 211–226.
- 19 V. Enkelmann, *Adv. Polym. Sci.*, 1984, **63**, 92–136.
- 20 K. Novak, V. Enkelmann and G. Wegner, *Angew. Chem., Int. Ed. Engl.*, 1993, **32**, 1614–1616.
- 21 I. Turowska-Tyrk, *Chem.–Eur. J.*, 2001, **7**, 3401–3405.