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We have synthesized the first known cocrystal of 9,10-phenanthrenequinone utilizing both liquid-assisted mechanochemical synthesis and crystallization from a solution.

In the past few years, cocrystallization has become a proven and accepted way of modifying the physical and chemical properties, such as colour,<sup>1</sup> hygroscopicity,<sup>2</sup> UV/Vis absorption,<sup>3</sup> thermal stability and solubility,<sup>4</sup> of solid materials. Cocrystals are usually obtainable by either crystallization from a solution<sup>5</sup> containing the desired reactant and coformer, or, more recently, by mechanochemical methods such as neat grinding (NG) or liquid-assisted grinding (LAG).<sup>6</sup> Of the two methods, mechanochemical synthesis is preferable because it sidesteps having to find a solvent or solvent mixture that can dissolve the reactants equally, is generally much shorter with very high yield, and allows for a much better scale-up without having to significantly increase the amount of solvent used.<sup>7</sup> Both NG and LAG have been established as fast and efficient screening methods for desired crystal forms such as cocrystals, salts, solvates and polymorphs.<sup>8</sup>

The compound we were interested in is 9,10-phenanthrenequinone (**phen**), a polinuclear diketone (Fig. 1) with an intense yellow colour. Up until now, **phen** and derivative structures have mostly been studied and used as chelating agents<sup>9</sup> or as pigments.<sup>10</sup> Generally, the quinones of polycyclic aromatic hydrocarbons are abundant in all burnt organic materials, e.g. automobile exhaust and cigarette smoke.<sup>11</sup> The title compound, **phen**, is a major quinone in diesel exhaust. In the context of biochemistry, many studies have focused on the mutagenicity and metabolic pathways of **phen**.<sup>12</sup> It was

## Mechanochemical and solution-based cocrystallization of 9,10-phenanthrenequinone and thiourea†

Vinko Nemeč, Nikola Škvorc and Dominik Cinčič\*

reported that **phen** causes oxidative protein modification in living cells and accelerates malignant progression of lung cancer cells.<sup>12c</sup> A cursory search in the Cambridge Structural Database<sup>13</sup> (CSD) based on the ability of the cyclic carbonyl oxygen atom (a structural motif present in **phen**) to act as a hydrogen bond acceptor has resulted in 50 000 hits.

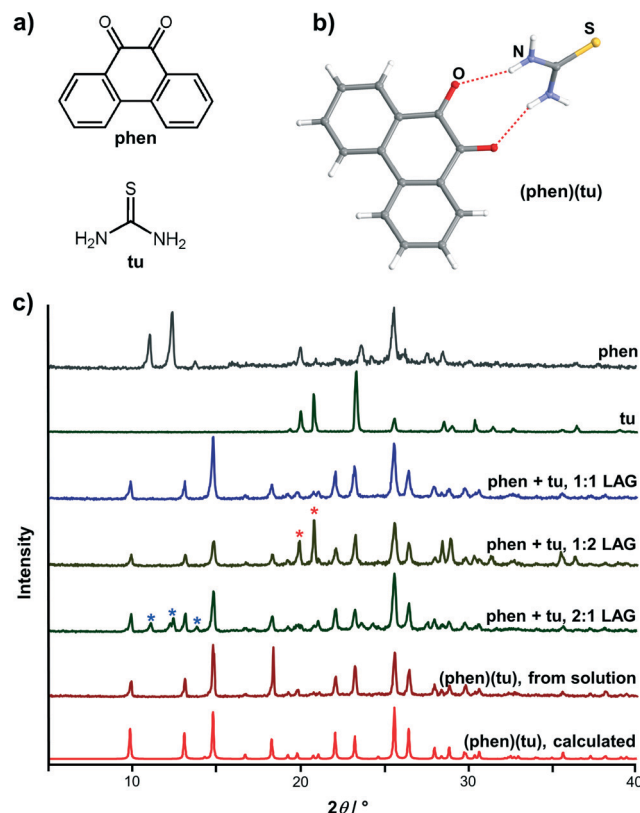


Fig. 1 (a) Structures of 9,10-phenanthrenequinone (**phen**) and thiourea (**tu**), (b) the structure obtained as a result of the single crystal X-ray diffraction experiment, (c) comparison of reactant, mechanochemical product and calculated powder patterns. Residual maxima of the reactants are marked.

Department of Chemistry, Faculty of Science, University of Zagreb, Horvatovac 102a, HR-10000 Zagreb, Croatia. E-mail: dominik@chem.pmf.hr;

Fax: +385 14606341; Tel: +385 14606362

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Restraining the search further to cyclic 1,2-diketones interacting with nitrogen as a hydrogen bond donor has resulted in 928 hits. Of those, 514 structures correspond to cocrystals. In spite of the fact that ketones are a valuable group of synthons in crystal engineering, no cocrystal structures have been published for **phen**, unlike 1,10-phenanthroline-5,6-dione, a compound that is geometrically and chemically mostly analogous to **phen**, and a reported hydrogen and halogen bond acceptor.

Herein we report the cocrystal of **phen** which has been synthesized by liquid-assisted grinding. We were inspired to pursue mechanochemical experiments in our study by a recent report of Bučar and co-workers,<sup>1</sup> who described cocrystals of fluorescein with pyridyl-based cocrystal formers. They presented a proof of principle which states that the optical properties of (poorly soluble) colourants can be altered *via* mechanochemical cocrystallisation, and described the efficiency of mechanochemistry in the screening for and preparation of cocrystals of such materials. In our work, as a good counterpart to **phen** we have selected thiourea (**tu**), a molecule with a significant propensity towards generating hydrogen-bonded structures. To the best of our knowledge, this is the first structurally characterised cocrystal of **phen**. To observe LAG mechanosynthesis, as well as to facilitate the characterisation of the new cocrystal by single-crystal X-ray diffraction, LAG experiments were accompanied by crystallization from the reactant solution. All reactants and products have been characterised by means of powder X-ray diffraction (PXRD), differential scanning calorimetry (DSC) and Fourier-transform infrared spectroscopy (FTIR). As a means to explore the stoichiometric ratio of **phen** and **tu**, we first attempted the mechanochemical synthesis of (**phen**)(**tu**) by LAG of **phen** and **tu** in stoichiometric ratios 1:1, 1:2 and 2:1, respectively, in the presence of a small amount of acetonitrile. Milling was conducted in a Retsch MM200 mill using a stainless steel milling assembly (see the ESI<sup>†</sup>). LAG of **phen** and **tu** in a 1:1 stoichiometric ratio for 30 minutes afforded a powder material with a PXRD pattern identical to that of the crystals prepared by the solution method. In the solution experiment, equimolar amounts of **phen** and **tu** have been dissolved in a hot mixture of ethanol and benzene. The solutions were left at room temperature, and the product crystallized upon cooling. The measured PXRD patterns of (**phen**)(**tu**) obtained by both methods, grinding and from the solution, are in good agreement with those calculated from single crystal data, thus confirming that both products were obtained as a pure single phase (Fig. 1). The powder obtained by grinding and the crystals are orange, markedly different from the intensely yellow **phen** and white **tu** (Fig. 2). The other two out of the three mechanochemical experiments, LAG of **phen** and **tu** in stoichiometric ratios 1:2 and 2:1, resulted in a mixture containing (**phen**)(**tu**) cocrystals and solid reactants, as evidenced by PXRD (Fig. 1).

The (**phen**)(**tu**) cocrystal crystallizes in the orthorhombic system with four formula units per unit cell. The molecular structure of the cocrystal with the atom numbering scheme is

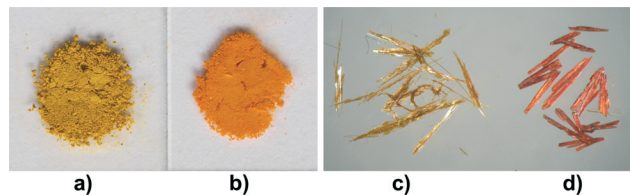


Fig. 2 Photographs of **phen** and cocrystal samples: a) powder of **phen**; b) powder of (**phen**)(**tu**) obtained by LAG; c) crystals of **phen** and d) crystals of (**phen**)(**tu**).

given in Fig. S1 (see the ESI<sup>†</sup>). Each **phen** molecule is associated with a **tu** molecule *via* a N-H...O hydrogen bond (N...O distance: 3.044 Å, N-H...O angle 154°;  $1/2 - x, y - 1/2, z$ ), forming a 1:1 molecular complex through the  $R_2^2(9)$  hydrogen bond motif<sup>14</sup> (Fig. 3). The geometry of **phen** is not consistent with that normally observed for the pure **phen** crystal.<sup>15</sup> The normally planar structure of **phen** gets twisted by about 13 degrees around the least torsionally restricted central ring. The crystal structure of (**phen**)(**tu**) can be described by association of 1:1 molecular complexes with hydrogen-bonded chains, assisted by N-H...S hydrogen bonds (N...S distance: 3.403 Å;  $x, 1 - y, z - 1/2$ ) between **tu** molecules, forming a  $R_2^2(8)$  motif. Also, 1:1 molecular complexes are associated with a 2-dimensional network *via* C-H...S interactions (C...S distance: 3.898 Å and 3.903 Å;  $1 - x, 1 - y, 1 - z$  and  $x + 1/2, y - 1/2, 3/2 - z$ ) between the aromatic carbon atoms of **phen** and sulfur in **tu** (Fig. 3). The overall structure results from the combination of such interactions and it is additionally stabilized by C-H...O hydrogen bonds (C...O distance: 3.439

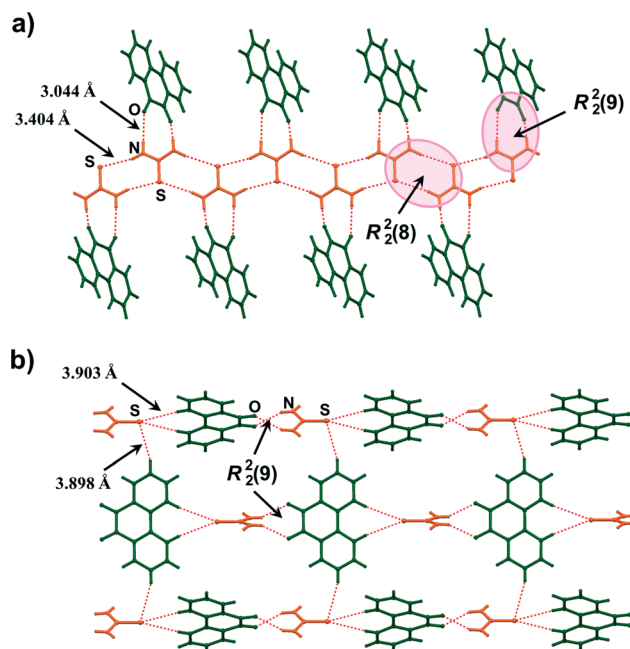


Fig. 3 The crystal structure of (**phen**)(**tu**): (a) chains of hydrogen-bonded molecules *via* N-H...O and N-H...S interactions, and (b) C-H...S interactions and N-H...O hydrogen bond motifs that give rise to the two-dimensional network.



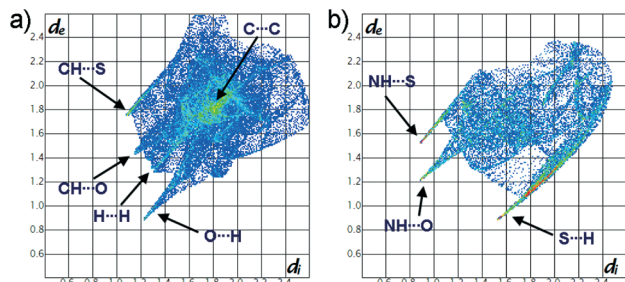


Fig. 4 Two-dimensional fingerprint plot derived from the Hirshfeld surface of the **phen** molecule (a) and **tu** molecule (b) in the (**phen**)/**tu** cocrystal.

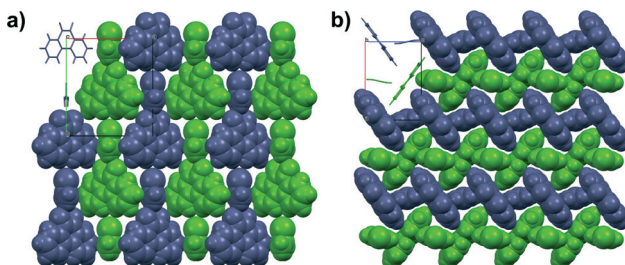


Fig. 5 Assembly of hydrogen-bonded chains of (**phen**)/**tu** into layers viewed along the *c* axis (a) and *b* axis (b). For clarity, adjacent chains are colour-coded blue and green.

Å;  $3/2 - x, y - 1/2, z$ ) (Fig. 5). Also, the described interactions can be observed by a close analysis of the two-dimensional fingerprint plot derived from the Hirshfeld surface<sup>16</sup> of the (**phen**)/**tu** cocrystal components (Fig. 4). The cocrystal as a whole is densely packed (Fig. 5) and a notable detail of the cocrystal structure is the fact that each sulfur is a hexafurcated hydrogen bond acceptor.

To investigate the non-covalent interactions within the cocrystal, the FTIR spectra of pure **phen** and (**phen**)/**tu** were recorded (see the ESI†). Their spectra show strong bands corresponding to the C–O stretching of the **phen** carbonyl group at about  $1670\text{ cm}^{-1}$  ( $1676\text{ cm}^{-1}$  for **phen** and  $1650\text{ cm}^{-1}$  for the cocrystal). The C–O stretching for (**phen**)/**tu** is expectedly at a lower frequency than that for pure **phen** due to the involvement of C–O groups in strong intermolecular hydrogen bonds. The DSC curve of (**phen**)/**tu** shows one endothermic peak at  $175\text{ °C}$  ( $34\text{ kJ mol}^{-1}$ ), which corresponds to the cocrystal melting point (see the ESI†). It is at a lower temperature than that of pure reactants, **phen** ( $206\text{ °C}$ ) and **tu** ( $179\text{ °C}$ ).

In summary, we have presented the first example of a **phen** cocrystal obtained from the reaction of **phen** and **tu** in a 1 : 1 molar ratio by solid-state synthesis. Also, the (**phen**)/**tu** cocrystal has been prepared by crystallization from a solution, despite the low solubility of **phen** in most organic solvents. Single-crystal X-ray analysis of (**phen**)/**tu** revealed an interesting  $R_2^2(9)$  hydrogen bond motif formed between **phen** and **tu** molecules *via* N–H...O hydrogen bonds. Besides exploring synthetic routes, we have also found that the resulting powder material and crystals exhibit an orange

colour, markedly different from the intensely yellow **phen**. Crystal structure analysis demonstrates that the introduction of **tu**, as a cocrystal former, can change the molecular structure of **phen** as well as the geometric arrangement of the chromophore in the cocrystal. A number of recently reported cocrystallizations of organic solid chromophores<sup>1,3</sup> suggest that cocrystallization provides a facile way to develop and design new types of solid organic materials with desirable optical properties, *e.g.* luminescence, emission, colour, and UV/vis absorption. The described results are important in the context of supramolecular synthesis, as well as solid-state and materials chemistry, and could have significant implications for the future design and optimization of colourants, dyes and pigments *via* mechanochemical cocrystallization.

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