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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†

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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.

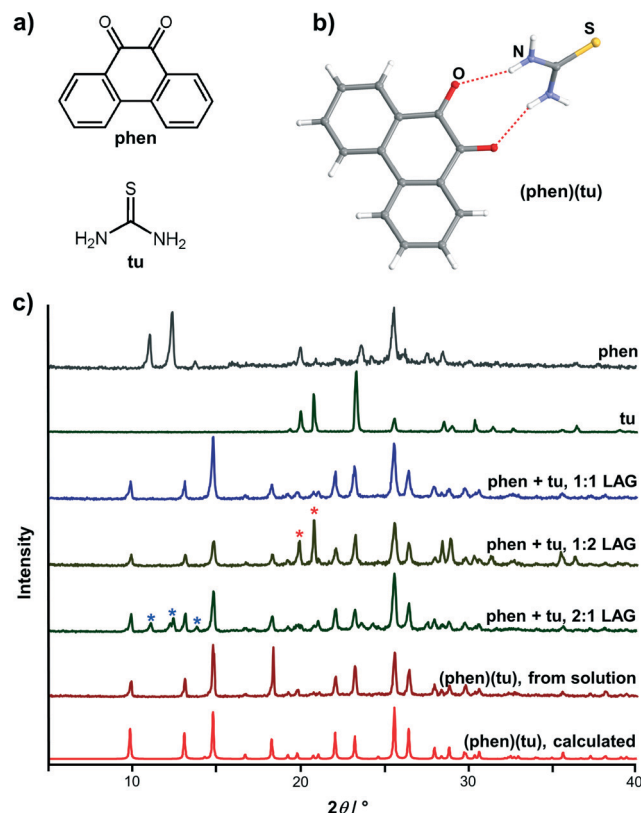


Fig. 1 (a) Structures of 9,10-phenanthrenequinone (**phen**) and thiourea (**tu**), (b) the structure obtained as a result of the single crystal X-ray diffraction experiment, (c) comparison of reactant, mechanochemical product and calculated powder patterns. Residual maxima of the reactants are marked.

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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

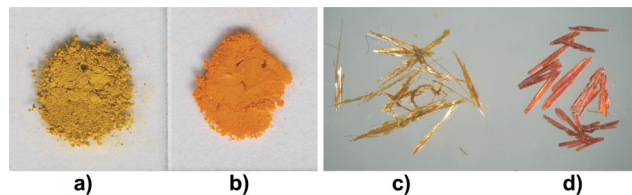


Fig. 2 Photographs of **phen** and cocrystal samples: a) powder of **phen**; b) powder of (**phen**)(**tu**) obtained by LAG; c) crystals of **phen** and d) crystals of (**phen**)(**tu**).

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

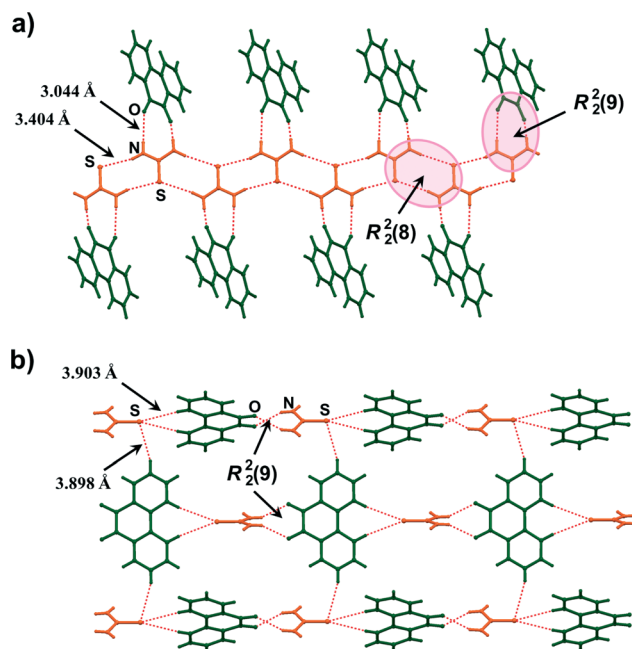


Fig. 3 The crystal structure of (**phen**)(**tu**): (a) chains of hydrogen-bonded molecules *via* N-H...O and N-H...S interactions, and (b) C-H...S interactions and N-H...O hydrogen bond motifs that give rise to the two-dimensional network.



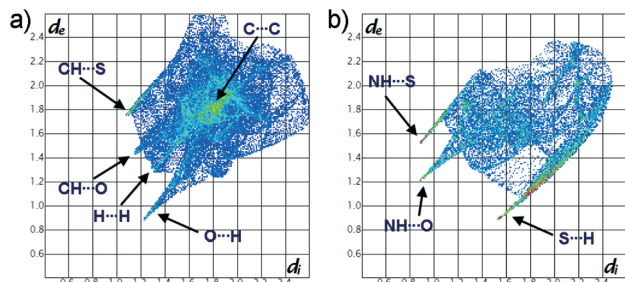


Fig. 4 Two-dimensional fingerprint plot derived from the Hirshfeld surface of the **phen** molecule (a) and **tu** molecule (b) in the (**phen**)/**tu** cocrystal.

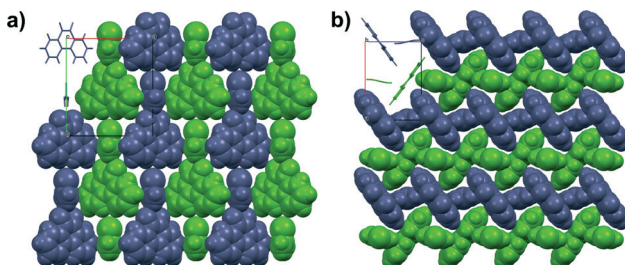


Fig. 5 Assembly of hydrogen-bonded chains of (**phen**)/**tu** into layers viewed along the *c* axis (a) and *b* axis (b). For clarity, adjacent chains are colour-coded blue and green.

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<sup>†</sup>). 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<sup>†</sup>). 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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