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Crystal engineering of urea α-network *via* $\mathrm{I\cdots O_2N}$ synthon and design of SHG active crystal *N*-4-iodophenyl-*N*′-4′-nitrophenylurea

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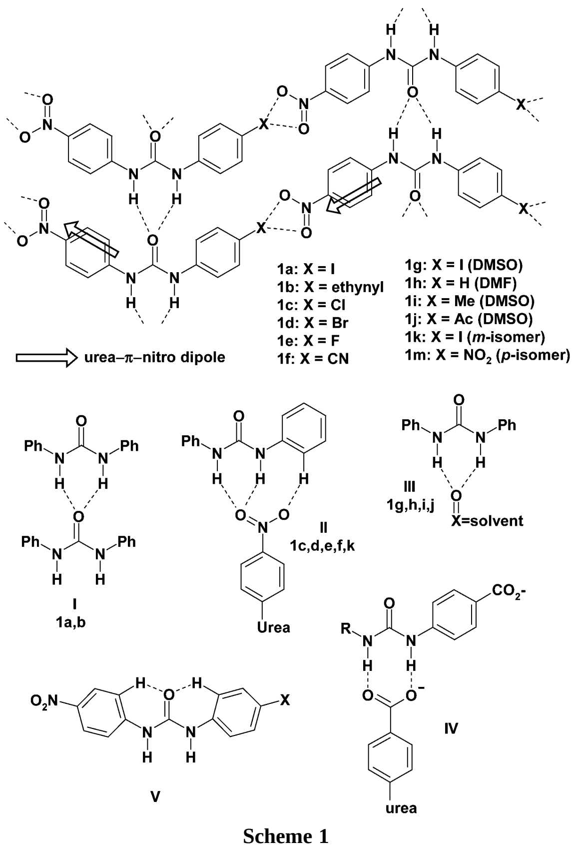
Crystalline nitrodiphenyl ureas adopt the $\mathrm{N{-}H\cdots O}$ tape α-network only when stabilization accrues from the $\mathrm{I\cdots O_2N}$ or $\mathrm{C{\equiv}C{-}H\cdots O_2N}$ synthon, otherwise the urea···nitro motif is preferred; soft, weak interactions can direct polar self-assembly in strong $\mathrm{N{-}H\cdots O}$ hydrogen-bonded crystals.

Urea molecules are well studied in crystal engineering[1] for the rational construction of supramolecular architectures and design of non-linear optical (NLO) materials for second harmonic generation (SHG). The dominant aggregation pattern in *N*,*N*′-disubstituted urea crystal structures is the α-network, a tape of bifurcated $\mathrm{N{-}H\cdots O}$ hydrogen bonds from NH donors to O acceptor. The robust α-network, formed through recognition between strongest-donor and strongest-acceptor, has been shown to persist in the presence of competitive functional groups like COOH and $\mathrm{CONH_2}$.[2] The nitro group is introduced in several organic NLO chromophores because of its ability to produce a strong dipole moment (D–π–A conjugation) and also to favor crystallization in non-centrosymmetric space groups (a necessary condition for SHG).[3] For example, the β-polymorph of *N*-3-nitrophenyl-*N*′-3′-nitrophenylurea (MNPU, space group *C*2)[4] and *N*-4-nitrophenyl-*N*′-4′-nitrophenylurea[5] have powder SHG efficiency of 1.5 and 8.8 times that of urea, respectively. Recently single crystals in polar space group *Fdd*2 have been engineered *via* the $\mathrm{I\cdots O_2N}$ synthon.[6] We report herein a design strategy that incorporates the above structural features in the same system, *e.g.* *N*-4-iodophenyl-*N*′-4′-nitrophenylurea **1a**, leading to crystallization in polar space group *Cc* and a strong SHG response of over 13 times that of urea (= POM[7]). However, several related derivatives of **1** adopt a different crystal packing in a centrosymmetric space group, showing that the soft and weak $\mathrm{I\cdots O_2N}$ interaction is the "discriminator synthon" even in the presence of strong $\mathrm{N{-}H\cdots O}$ hydrogen bonds.

Diaryl ureas **1a–j** were readily synthesized by the cognate condensation of *p*-nitrophenyl isocyanate with the corresponding *p*-X-aniline. Self-assembly of **1** was expected to occur *via* the urea tape $\mathrm{N{-}H\cdots O}$ synthon **I** with $\mathrm{X\cdots O_2N}$ interaction providing auxiliary support in the lateral direction (Scheme 1). From the viewpoint of engineering macroscopic polarity in the crystal, although molecules of **1** are aligned anti-parallel along the carbonyl axis, the inclined, parallel orientation of $\mathrm{NH{-}\pi{-}NO_2}$ chromophores will result in a net dipole moment. The X-ray crystal structure† of 4-iodophenyl-4′-nitrophenylurea confirms that supramolecular organization in **1a** is faithfully reproduced as per the plan. Urea molecules are arranged in a linear array *via* the target $\mathrm{N{-}H\cdots O}$ α-network (2.13, 2.12 Å; 154.9, 155.3°; Fig. 1) and such glide related tapes are connected through the $\mathrm{I\cdots O_2N}$ synthon (3.61, 3.28 Å; 154.3, 169.6°; Fig. 2).‡ There is a twisting of neighboring urea molecules within a tape and also of aryl groups with respect to the urea moiety to achieve efficient close packing of diphenyl groups along the short axis of 4.7 Å. Incidentally, the α-network is not so common in nitrodiphenylureas,[8] so far being reported in only one crystal structure, the metastable β-polymorph of MNPU.[4] Noting that functional group exchange of iodo to ethynyl does not generally disturb crystal packing,[9] the isostructural behavior of **1b**, with $\mathrm{I\cdots O_2N}$ being replaced by $\mathrm{C{\equiv}C{-}H\cdots O_2N}$ interaction, was unambiguously established by its X-ray structure†‡ ($\mathrm{N{-}H\cdots O}$: 2.11, 2.10 Å; 154.6, 156.3°; $\mathrm{C{-}H\cdots O}$: 2.40, 3.05 Å; 167.8, 142.9°). Both **1a** and **1b** have identical powder X-ray diffraction pattern with prominent peaks at $2\theta = 21.4, 22.3°$ (Cu–Kα).

Engineering a non-centrosymmetric crystal structure is a daunting task because only 10–12% of achiral organic molecules crystallize in space groups that lack an inversion center.[10] Next, we



Scheme 1

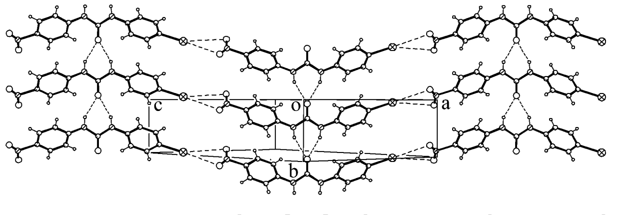


Fig. 1 Urea $\mathrm{N{-}H\cdots O}$ tape along [010] and $\mathrm{I\cdots O_2N}$ synthon in **1a**. The dominant orientation is shown.

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evaluated the robustness of N–H$\cdots$O urea tape synthon in this family of structures to find out if the weak I$\cdots O_2$N (or C≡C–H$\cdots O_2$N) interaction is a mere by-stander in the strong hydrogen bond network or does it indeed play a decisive structural role. X-ray crystal structure† of widely differing molecules—smaller halogens (**1c,d,e**), pseudohalogen (**1f**), halogen–methyl exchange (**1i**), moderately activated Ac donor (**1j**), and finally *para*- to *meta*-iodo isomer (**1k**)—all show the absence of urea tape synthon **I**. Some molecules (**1c,d,e,f**) aggregate *via* urea$\cdots$nitro synthon **II** in which one of the oxygen atoms of NO$_2$ behaves as an acceptor for the strong NH donors and the second O accepts weak C–H$\cdots$O hydrogen bond from *o*-Ph donor (N–H$\cdots$O: 2.10, 2.25 Å; 161.3, 157.0°; C–H$\cdots$O: 2.74 Å, 162.1°; **1d**, Fig. 3); the stronger urea oxygen accepts a (Ph)C–H$\cdots$O interaction (2.97 Å, 164.1°). These four compounds crystallize in centrosymmetric space group $P2_1/n$ with isostructural packing. Crystallization of **1** from solvents with hydrogen bond acceptor groups (*e.g.* C=O, ether O) afforded inclusion complexes through motif **III** (**1g,h,i,j**). To summarize, out of 19 nitrodiphenylurea crystal structures§ 3 adopt urea tape synthon **I**, 7 have urea$\cdots$nitro synthon **II**, and 8 crystallize by inclusion of solvent (often DMSO).¶ The one-dimensional growth of urea network is terminated either by the NO$_2$ group of another molecule or by a solvent molecule during crystallization. Our observation that the urea$\cdots$nitro synthon **II** can tolerate such a wide variation in size and polarity of X group, including *meta*-placement of iodo in **1k**, suggests that **II** is perhaps the more stable recognition motif in this family. Aggregation *via* **II** may be compared with urea$\cdots CO_2^-$ ionic hydrogen bond in motif **IV**.[11] A common feature in structures having the urea$\cdots$nitro synthon is a flat molecular conformation, stabilized by intramolecular C–H$\cdots$O interaction **V**, and the resulting 2D layers are related across an inversion center. Our naïve expectation that moving the NO$_2$ group from *meta*- to *para*-substitution would avoid steric hindrance in urea tape formation and simultaneously activate lateral X$\cdots O_2$N interaction is not borne out in a general sense. The fact that the NO$_2$ group is able to disrupt an otherwise robust synthon, the urea tape α-network, is an all too common problem in crystal engineering. The effect of remote functional group change on supramolecular organization and the subtle role of weak interactions on the final crystal structure are yet to be fully understood.[12]

Desiraju and Harris have highlighted the significance of I$\cdots O_2$N and C≡C–H$\cdots O_2$N synthons in crystal engineering.[6,9] Interestingly, it is these same two functional group synthons that have the necessary specificity and directionality to “turn-on” the target urea tape network and induce crystallization in a polar space group. The energy of the X$\cdots O_2$N interaction is estimated as −6 to −10 kJ mol^{-1} for Cl, Br and I donor groups.[13] The frequent occurrence of urea$\cdots$nitro synthon **II** indicates that urea C=O and nitro O are competitive acceptors for acidic NH donors.‖ In such an enthalpy-balanced crystallization environment, the weak and soft I$\cdots O_2$N and C≡C–H$\cdots O_2$N interaction (energy 2.0–2.5 kcal mol^{-1}) provides the extra stabilization to favor formation of urea tape synthon **I**. Notably, it is the weak interaction that is able to discriminate between the strong N–H$\cdots$O hydrogen-bonded urea$\cdots$urea and urea$\cdots$nitro synthons.[14]

SHG measurement[5] (Nd^{+3}-YAG laser at 1064 nm) on a microcrystalline sample of **1a** gives green signal (530 nm) over 13 times stronger than that of urea, in agreement with possible phase-matching in the polar crystal. In contrast, isostructural solid **1b** is only slightly superior to urea in its SHG efficiency. Full details of crystal packing, synthon energies, and quadratic NLO efficiency will be reported in a full article.

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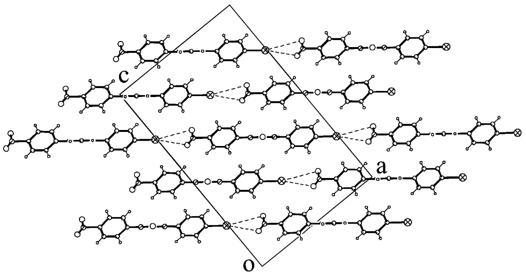

Fig. 2 Perspective view along the *b*-axis showing the polar alignment in **1a** mediated *via* I$\cdots O_2$N synthon to give a very strong SHG effect.

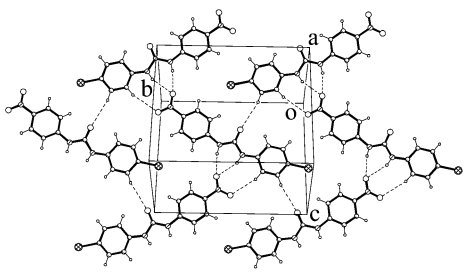

Fig. 3 Urea$\cdots$nitro synthon **II** in **1d**. Urea oxygen is involved in C–H$\cdots$O interaction but the Br atom has no short intermolecular contact.

Notes and references

† Crystal data for **1a**, **1b**, **1c** and **1d** have been deposited with CCDC (Deposit Nos. 231521–231524). See http://www.rsc.org/suppdata/cc/b4/b402050b/ for crystallographic data in .cif or other electronic format.

‡ Partial interchange of iodo and nitro groups leads to disorder (s.o.f. = 0.9, 0.1). The ethynyl structure is fully ordered.

§ 8 structures from refs. 4 and 8, 11 structures in this study.

¶ Attempts to crystallize DNPU **1m** have so far been unsuccessful.

‖ Crystal structures of several nitro benzamides have N–H$\cdots$O=C and N–H$\cdots O_2$N H-bonds from perusal of the CSD. The stable α-form of MNPU (ref. 4) has N–H$\cdots$O=C and N–H$\cdots O_2$N H-bonding.

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