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Co-crystal structures of 4,7-phenanthroline and carboxylic acids: synthon competition and prediction

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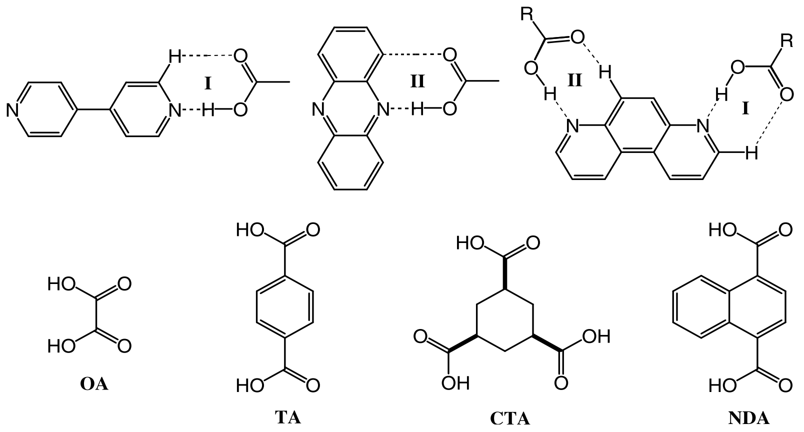
Abstract—Co-crystal formation of 4,7-phenanthroline and various carboxylic acids allows a study of the effect of supramolecular synthon competition. © 2002 Elsevier Science Ltd. All rights reserved.

The ultimate goal of crystal engineering is to pre-design solid-state structures based only on a knowledge of molecular structure.[1,2] The supramolecular synthon approach, in which desired supermolecules are formed and/or assembled using previously identified robust intermolecular interactions, is advantageous in that it offers a considerable simplification in the design of crystal structures.[3] In the co-crystal structures of carboxylic acids with 4,4′-bipyridine and phenazine, for example, O–H···N strong hydrogen bonds and weak C–H···O interactions create synthons **I** and **II**, respectively (Scheme 1).[4] For other bases (building blocks), however, a competition between choices of synthon may arise. In the case of 4,7-phenanthroline (**Ph**),[5] for example, hydrogen atoms on two chemically different sp^2 C atoms can be used to form C–H···O interactions (Scheme 1), giving rise to either synthon **I** or **II**. A search of the Cambridge Structural Database (CSD)[6] reveals that no organic **Ph** co-crystal structure has been reported to date, so that the preference for synthon **I** or **II** in carboxylic acid/**Ph** co-crystals is unknown.

A semi-empirical quantum mechanical calculation to determine the preferred synthon in carboxylic acid/**Ph** co-crystals was therefore undertaken. The AM1 approximation, successfully used elsewhere in studies of hydrogen bond arrangements in organic complexes, was adopted.[7] In order to simplify the calculation, a model structure of oxalic acid (**OA**) and **Ph** (**OA**+**Ph**) was built and geometrically optimised, using the *Cerius*^{2} program.[8] Several restraints were applied: (1) both molecules were constrained to be planar; (2) the H-bond angle of the strong O–H···N interactions was fixed at 180°, with the value of the O···N distances varying between 2.45 and 3.25 Å; (3) the angle between



Scheme 1.

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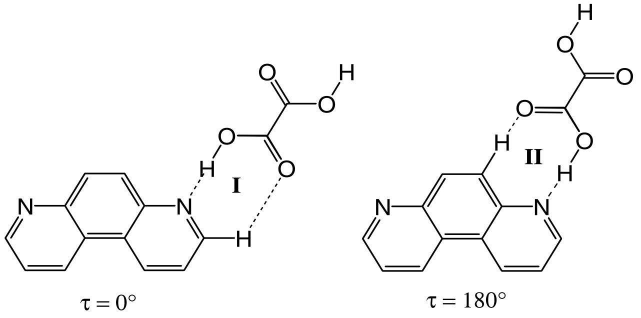
two molecules (τ) was fixed at 0° (synthon **I**), 90 or 180° (synthon **II**), as shown in Scheme 2. Hydrogen-bonding energies (HBE) were calculated for each possible supramolecular entity using the MOPAC interface[9]—details are given in Table 1.[10] For all three values of τ, an increase in the O···N distances results in the HBE values decreasing. Only small HBE differences, for the same O···N distances, are observed between formation of $\tau = 0°$ (synthon **I**) and that of $\tau = 90°$, while the HBE for $\tau = 180°$ (synthon **II**) suggests that this arrangement is significantly less stable. Synthon **I**, therefore, would appear to be thermodynamically preferred over synthon **II** in carboxylic acid/**Ph** co-crystal structures.



Scheme 2.

Table 1. Hydrogen-bonding energies (HBE) of oxalic acid/**Ph** dimers (kcal/mol) (**OA**+**Ph**)

$D_{O\cdots N}$ (Å)	$\Delta_{\text{Heat of formation}}$	$\Delta_{\text{Heat of formation}}$	$\Delta_{\text{Heat of formation}}$
τ	0° (synthon **I**)	90°	180° (synthon **II**)
2.45	8.267	10.137	82.389
2.55	3.616	5.493	58.793
2.65	0.639	2.427	41.377
2.75	−1.079	0.576	28.488
2.85	−1.961	−0.457	18.812
2.95	−2.369	−1.016	11.486
3.05	−2.551	−1.339	6.04
3.15	−2.637	−1.551	2.203
3.25	−2.67	−1.694	−0.287

To compare the theoretical prediction with actual crystal structures, an aliphatic dicarboxylic acid, **OA**, an aromatic dicarboxylic acid, terephthalic acid (**TA**), as well as a tricarboxylic acid, *cis*, *cis*-cyclohexane-1,3,5-tricarboxylic acid (**CTA**), were each separately co-crystallized with **Ph**. The resulting co-crystals, **OA·Ph**, **TA·Ph** (both molar ratio 1:1) and **CTA·2Ph** (molar ratio 1:2), were obtained by slow evaporation at room temperature from a 1:1 acid/**Ph** solution in dimethylsulfoxide (DMSO), tetrahydrofuran (THF) and methanol, respectively (Scheme 1).

In agreement with the HBE calculation, *all* acids and bases interact via synthon **I**. In the structure of **OA·Ph**,[11] zigzag tapes are formed via synthon **I**, involving O–H···N and C–H···O interactions [O···N, H···N, O–H···N: 2.657(4), 1.64 Å, 175.8°; C···O, H···O, C–H···O: 3.259(4), 2.49 Å, 127.3°].[12,13] The torsion angle between carboxylic acid group and aromatic ring is ca. 12.8°. Fig. 1 shows the supramolecular sheets formed by the linkage of adjacent tapes. Zigzag supramolecular tapes formed using synthon **I** also exist in the structure of **TA·Ph** [O···N, H···N, O–H···N (*x*−0.5, *y*, −*z*+0.5): 2.724(2), 1.71 Å, 171°; C···O, H···O, C–H···O (*x*+0.5, *y*, −*z*+0.5): 3.234(3), 2.59 Å, 117°]. In **TA**, the torsion angle between the carboxylic acid group and the aromatic ring (C–O–N–C) is ca. 38.5°, and results in significantly buckled infinite supramolecular sheets, generated by inter-tape C–H···O hydrogen bonds. In the structure of **CTA·2Ph**, the three carboxylic acid groups on the **CTA** molecule interact with three **Ph** molecules using synthon **I**. With the linkage of synthon **I**, a two-acid–four-base unit is produced and adopts a 'chair' conformation (Fig. 2). These supramolecular units pack forming stacks along the *a*-axis in a close packed manner. These three structures, therefore, support the idea that synthon **I** is indeed preferred to synthon **II** in these acid:base co-crystals.

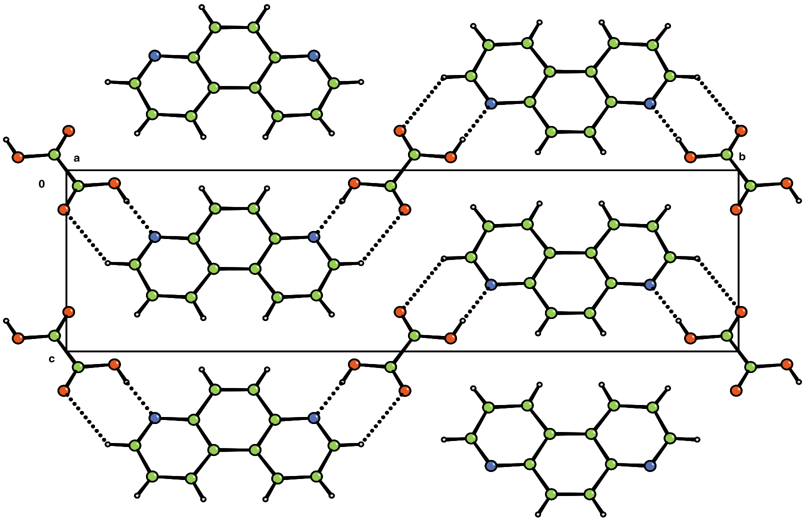


Figure 1. Projection onto (100) showing the supramolecular sheet in the structure of **OA·Ph** involving synthon **I**.

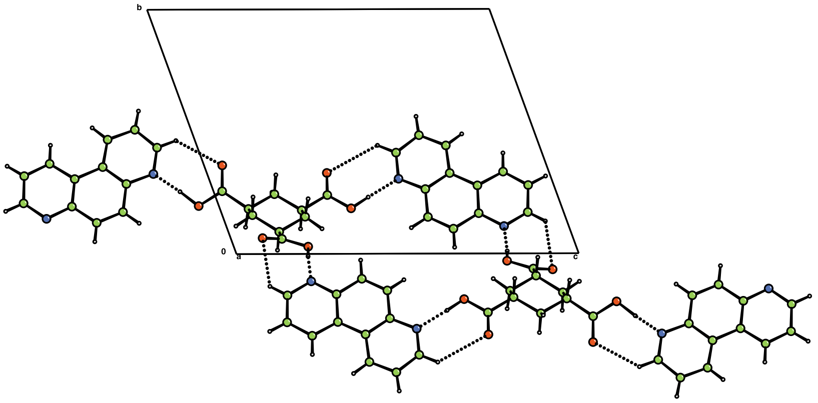


Figure 2. Projection onto (100) showing the two-acid-four-base unit in the structure of **CTA·2Ph**. These units stack along the *a*-axis in a close packed manner.

The crystal structure of **Ph** with 1,4-naphthalenedicarboxylic acid (**NDA**) has also been studied. Interestingly, when co-crystals of **NDA** and **Ph** (**NDA·2Ph**) are obtained by slow evaporation at room temperature from a 1:1 (acid:base) molar ratio solution in *N*,*N*′-dimethylformamide (DMF), synthon **II** is observed with one carboxylic acid group [O···N, H···N, O–H···N: 2.649(2), 1.64 Å, 173°; C···O, H···O, C–H···O: 3.319(2), 2.62 Å, 122°], whilst the other carboxylic acid group adopts synthon **I** [O···N, H···N, O–H···N ($-x$, $-y$+2, $-z$+1): 2.626(2), 1.62 Å, 169°; C···O, H···O, C–H···O ($-x$, $-y$+2, $-z$+1): 3.638(2), 3.21 Å, 105°] (Fig. 3).

In order to rationalise the presence of synthon **II** in **NDA·2Ph**, further AM1 calculations were carried out using models of **TA+Ph**, **CTA+Ph** and **NDA+Ph**, with similar criteria to those used in the case of **OA+Ph**. For **TA** and **CTA** molecular pairs, similar results to that of **OA+Ph** were obtained. In the case of **NDA+Ph**, however, for the same O···N distances, smaller HBE differences are observed in all cases between models of $\tau = 0°$ (synthon **I**) and $\tau = 180°$ (synthon **II**) in **NDA+Ph** (Table 2). This would suggest that, in the case of **NDA·2Ph**, the energy difference between synthon **I** and **II** is likely to be less important during crystallization.

We are not aware of a systematic study having been made of the choice of supramolecular arrangement among two or more possible synthons with the same functional groups, and we describe this as *synthon competition*. In this study, the hydrogen bond arrangements adopted in the majority of carboxylic acid/**Ph** crystal structures, synthon **I**, can be regarded as the result of synthon competition. The actual results of the various competing synthon units determine the specific geometry of supramolecular assemblies in the structures and hence the overall packing arrangements. Our results, furthermore, demonstrate good agreement between experiment and calculation, suggesting that the AM1 approximation can be a practical way to predict the results of synthon competition.

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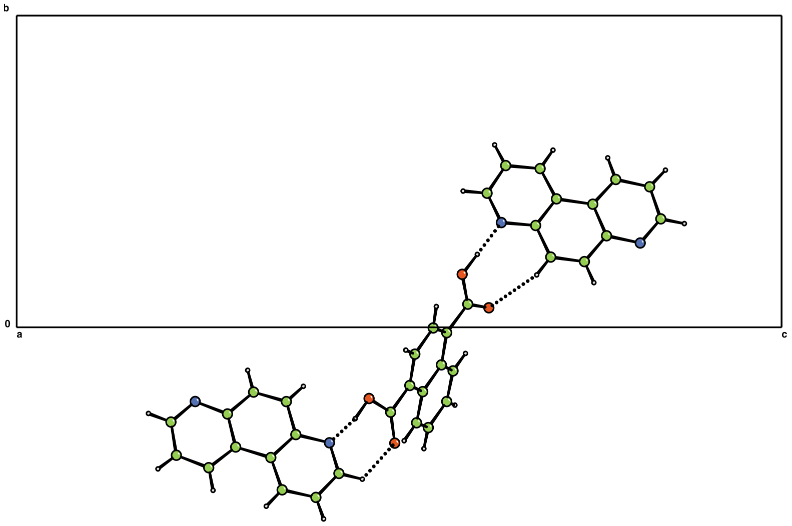
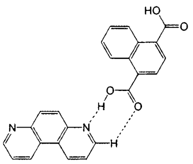
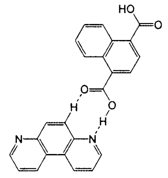
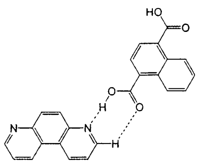
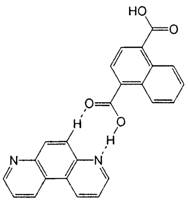


Figure 3. Projection onto (100) of **NDA·2Ph** showing the one-acid-two-base unit formed by synthons **I** and **II**.

Table 2. Hydrogen-bonding energies (HBE) of 1,4-naphthalenedicarboxylic acid/**Ph** pairs (kcal/mol) (**NDA**+**Ph**)[a]

$D_{O\cdots N}$/Å	$\Delta_{\text{Heat of formation}}$	$\Delta_{\text{Heat of formation}}$	$\Delta_{\text{Heat of formation}}$	$\Delta_{\text{Heat of formation}}$	$\Delta_{\text{Heat of formation}}$
τ	0° (synthon **I**)	90°	180° (synthon **II**)	0° (synthon **I**)	180° (synthon **II**)
Scheme					
2.45	10.026	12.347	31.927	9.338	30.877
2.55	5.148	7.101	20.12	4.923	19.005
2.65	1.863	3.5	11.538	2.022	10.37
2.75	-0.187	1.187	5.674	0.278	4.465
2.85	-1.39	-0.235	1.953	-0.691	0.712
2.95	-2.085	-1.113	-0.246	-1.214	-1.509
3.05	-2.504	-1.687	-1.472	-1.514	-2.752
3.15	-2.771	-2.084	-2.125	-1.705	-3.417
3.25	-2.933	-2.356	-2.44	-1.822	-3.741

[a] Note relative positions of naphthalene rings.

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10. HBEs have been calculated by subtracting the heats of formation of the two monomers from that of the pair. Even though a large amount of this energy is due to H-bonding in the pair, the contributions of other types of interactions, e.g. van der Waals interactions and induced and permanent dipole–dipole interactions, can also be significant. Thus, these intermolecular binding energies are collectively termed as the HBE.
11. X-Ray diffraction data (Mo-Kα $\lambda=0.7107$ Å) were collected at 180(2) K using a Nonius Kappa CCD diffractometer equipped with an Oxford Cryosystems system. Data reduction and cell refinement were performed with the programs *DENZO* (University of Texas, Southwestern Medical Center at Dallas, HKL Denzo and Scalepack, USA, 1997) and *COLLECT* (Nonius, B. V. Delft, The Netherlands, 1998) and multi-scan absorption corrections were applied with the program *SORTAV* (Blessing, R. H. *Acta Cryst.* **1995**, *A51*, 33–38). Structures were solved by direct methods using *SHELXS*-97 (University of Göttingen, Germany, 1997) and refined on F^2 against all data using *SHELXL*-97 (University of Göttingen, Germany, 1997). All non-hydrogen atoms were refined with anisotropic displacement parameters. Hydrogen atoms bonded to C or N atoms were placed geometrically and were allowed to ride during subsequent refinement with an isotropic displacement parameter fixed at 1.2 times U_{eq} for the atoms to which they were attached. Hydrogen atoms bonded to O were located in difference Fourier maps and refined isotropically without restraint.

   Crystal data for **OA·Ph**: $C_7H_5NO_2$, $M=135.12$, colourless plate, monoclinic, space group $P2_1/m$, $a=3.7136(7)$, $b=23.455(5)$, $c=6.7199(13)$ Å, $\beta=92.57(3)°$, $V=584.7(2)$ Å^3, $Z=4$, $D_{\text{calcd}}=1.535$ Mg/m^3, $\mu=0.115$ mm^{-1}, $F(000)=280$, crystal size 0.30×0.10×0.04 mm^3, 3477 reflections collected, 1048 independent reflections ($R_{\text{int}}=0.0783$), $R_1=0.0751$, $wR_2=0.2059$ for $I>2\sigma(I)$, $R_1=0.1085$, $wR_2=0.2335$ for all data.

Crystal data for **TA·Ph**: $C_{10}H_7NO_2$, $M=346.33$, colourless block, orthorhombic, space group *Pnma*, $a=13.3988(9)$, $b=30.798(3)$, $c=3.7657(2)$ Å, $V=1553.9(2)$ Å^3, $Z=8$, $D_{\text{calcd}}=1.480$ Mg/m^3, $\mu=0.105$ mm^{-1}, $F(000)=720$, crystal size 0.16×0.10×0.10 mm^3, 5129 reflections collected, 1639 independent reflections ($R_{\text{int}}=0.0596$), $R_1=0.0489$, $wR_2=0.0935$ for $I>2\sigma(I)$, $R_1=0.1038$, $wR_2=0.1103$ for all data.

Crystal data for **CTA·2Ph**: $C_{33}H_{28}N_4O_6$, $M=576.59$, colourless block, triclinic, space group *P*-1, $a=7.2332(4)$, $b=12.3119(9)$, $c=16.4902(13)$ Å, $\alpha=108.891(3)$, $\beta=100.998(4)$, $\gamma=93.412(4)°$, $V=1352.23(16)$ Å^3, $Z=2$, $D_{\text{calcd}}=1.416$ Mg/m^3, $\mu=0.099$ mm^{-1}, $F(000)=604$, Crystal size 0.12×0.12×0.05 mm^3, 11327 reflections collected, 4731 independent reflections ($R_{\text{int}}=0.0851$), $R_1=0.0580$, $wR_2=0.1090$ for $I>2\sigma(I)$, $R_1=0.1344$, $wR_2=0.1364$ for all data.

Crystal data for **NDA·2Ph**: $C_{36}H_{24}N_4O_4$, $M=576.59$, yellow plate, monoclinic, space group $P2_1/c$, $a=7.3810(2)$, $b=12.1035(5)$, $c=30.1798(11)$ Å, $\beta=90.074(2)°$, $V=2696.14(17)$ Å^3, $Z=4$, $D_{\text{calcd}}=1.420$ Mg/m^3, $\mu=0.095$ mm^{-1}, $F(000)=1200$, crystal size 0.40×0.18×0.07 mm^3, 14929 reflections collected, 5527 independent reflections ($R_{\text{int}}=0.0522$), $R_1=0.0500$, $wR_2=0.1032$ for $I>2\sigma(I)$, $R_1=0.0994$, $wR_2=0.1213$ for all data.

Crystallographic data have been deposited with the Cambridge Crystallographic Data Centre as supplementary publication numbers CCDC 190657–190660. Copies of these data can be obtained free of charge on application to CCDC, 12 Union Road, Cambridge, CB2 1EZ, UK (fax: +44(0)1223-336033 or e-mail: deposit@ccdc.cam.ac.uk).

12. Intermolecular bond distances and angles to H atoms were normalised to standard neutron-derived distances along the bond vectors derived from the X-ray results.
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