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Pyrrole-2-carboxylate dimer: a robust supramolecular synthon for crystal engineering

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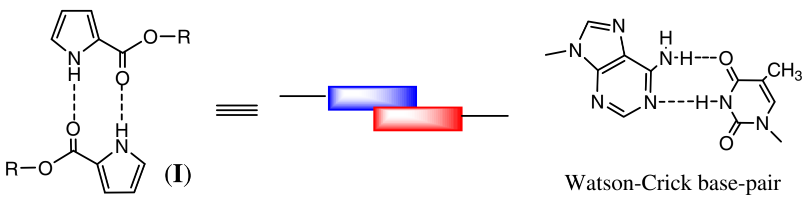
Abstract—Two pyrrole-2-carboxylates, tris[2-(2-pyrryl-carboxy)ethyl]amine (**1**) and tetrakis(2-pyrryl-carboxy-methyl)methane (**2**), were prepared by the treatment of 2-trichloroacetylpyrrole with tri(2-hydroxylethyl)amine and pentaerythritol, respectively. Hexagonal and grid supramolecular structures were obtained from the self-assembly of **1** and **2**, respectively. From the assembly structure, a novel supramolecular synthon of the pyrrole-2-carbonyl dimer has been found. The synthon was demonstrated to be robust by our density functional calculation. It is expected to be useful in the self-assembly of crystal engineering.

Crystal engineering,[1] the design of organic solids, has emerged as an important cross-disciplinary field of chemistry. Identification of novel and robust supramolecular synthons[2] is an important area in this field. Utilization of these synthons can generate the desired supramolecular structure and topology which may lead to new materials that have novel properties.[1,2] Pyrrole based compounds are frequently observed as hosts for neutral molecules[3] and anionic species.[4] Meantime, these compounds can also form higher order self-assembled ensembles in the solid state through hydrogen bonding.[5] Pyrrole-2-carboxylate possesses one hydrogen bond donor (N–H$_{pyrrole}$) and one acceptor (C=O), which favor the pyrrole-2-carboxylate to form centrosymmetric dimers with a pair of N–H···O hydrogen bonds (Scheme 1, **I**). The dimer motif is structurally similar to classic Watson–Crick nucleotide base-pairs (Scheme 1).[5] The calculated hydrogen bond energy for the methyl pyrrole-2-carboxylate is 9.4 kcal/mol at the RHF/6-311+G* level, and its strength is comparable to the hydrogen bond energy found in typical acid dimers.[6] Furthermore, Sessler[7] and co-workers have reported that some ferrocenes based pyrrole-2-carboxylate self-assemble into one-dimensional chain via synthon **I**. Uno et al.[8] also found that [2,2,1]bicyclic and [2,2,2]bicyclic derivatives of pyrrole-2-carboxylate self-assembles into 1-D ribbons via synthon **I**. The recurrence of the dimer motif **I** in the crystal of pyrrole-2-carboxylate based compounds indicates that it would be a robust supramolecular synthon in crystal engineering. However, the use of such synthon to construct supramolecular architecture has not been fully explored. In this letter, we will show a way to use 2-carbonyl pyrrole dimer as a supramolecular connecter to construct



Scheme 1.

Keywords: Pyrrole-2-carboxylates; Self-assembly; Supramolecular synthon.
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hexagonal and grid architecture by changing the spacers.

The crystal may be considered as a network wherein the molecules are the nodes, and the supramolecular synthons are the node connectors.[5] In different node geometry, the same synthon can assemble into various supramolecular structures. For example, the trimesic acid on its own forms a hexagonal network,[9] whereas the terephthalic acid only forms infinite chain.[10] Compounds **1** and **2** were designed with trigonal and cross spacers that are intended to generate hexagonal and grid networks (Scheme 2). As expected, in the crystal structures of both compounds, the desired networks are indeed observed.

Compounds **1** and **2** were prepared by the reaction of 2-(trichloroacetyl)pyrrole with tri(2-hydroxylethyl)-amine and pentaerythritol in the presence of triethylamine in acetonitrile, respectively.[11] Single crystals of **1** and **2** were grown from methanol and chloroform, respectively, and their structures were determined by X-ray crystallography.[12]

The molecular structure of **1** is shown in Figure 1. Although compound **1** is achiral and possesses C_3 symmetry, it crystallizes in a trigonal chiral space group P3. Recently, the generation of chiral crystals from such achiral molecules has been noticed due to its relevance in asymmetry synthesis and the design of non-linear optical materials.[13] Each molecule **1** was connected with three adjacent molecules via synthon **I** ($N\cdots O$ distance 2.904 Å, angle 173.7°) between the 2-carbonyl-pyrrole moieties in the crystal. Thus, six molecules form a hexagon with a 5 Å cavity by synthon **I** (Fig. 2) and the structure of **1** is characterized as a 2-D supramolecular network. The cavity is about 9.7% of the total volume of the crystal as calculated using the program PLATON.[14] The networks stack on but do not eclipse each other. Consequently, this generates a hexagonal tubular architecture. It is worthy to note that no guests were observed in the channels. Sessler and co-workers[5] have reported an amide analog of **1**, compound **3**, in which the synthon **I** was also found, indicating that the dimer motif **I** is robust. However, the hydrogen bonds between amide NHs and carbonyl groups deform the C_3 symmetry of the compound and perturb it to self-assemble as compound **1**.

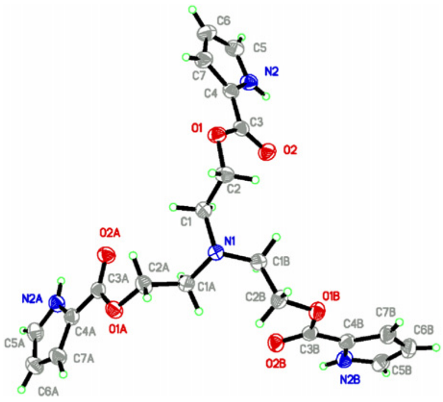
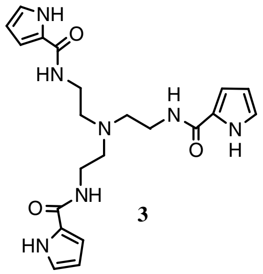


Figure 1. ORTEP view of compound **1** showing 30% probability displacement ellipsoids with atom numbering.



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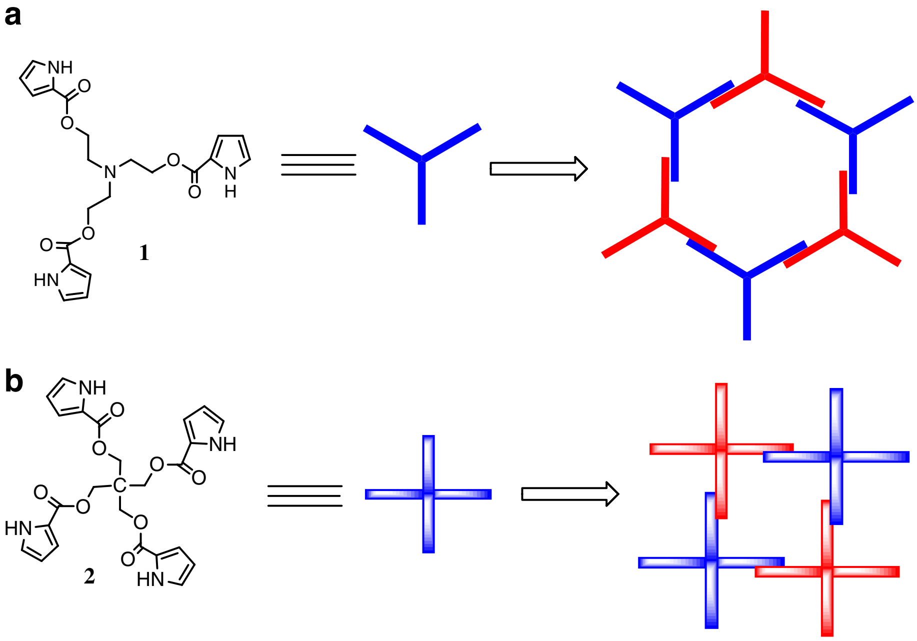

Scheme 2. (a) Hexagonal network formed by the self-assembly of **1**. (b) Grid network formed by the self-assembly of **2**.

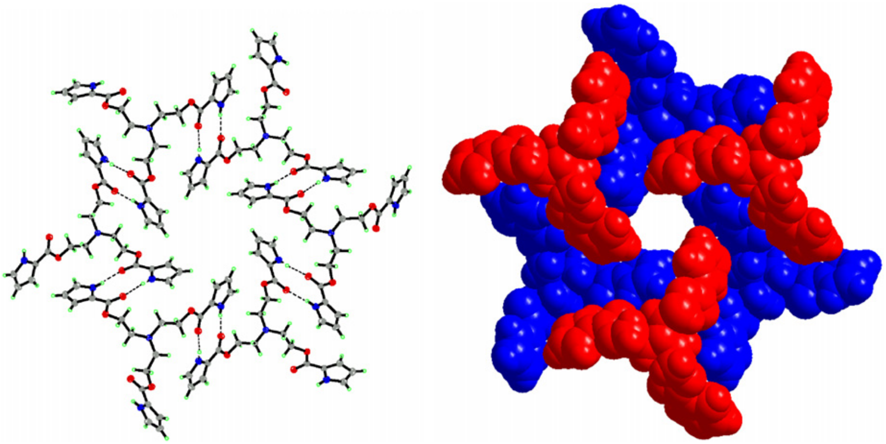

Figure 2. Hexagonal self-assembly of compound **1** via hydrogen bonds. Left: ORTEP perspective. Right: space-filling view.

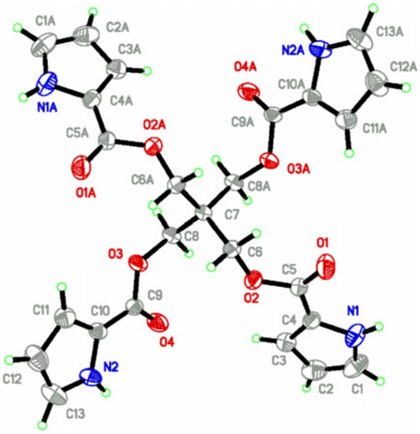

Figure 3. ORTEP view of compound **2** showing 30% probability displacement ellipsoids with atom numbering.

As shown in Figure 3, the structure of **2** has C_2 symmetry. The four carbonyl groups are all in the same side of the pyrrole NH, and so the pyrrole-carbonyl dimer can be formed. Each molecule **2** was connected with its four adjacent molecules via two type synthon **I** [N1–H1···O1$^{\text{i}}$, N···O distance 2.994 Å, angle 168.6°, symmetry code: (i) $-x+2$, y, $-z+1/2$; N2–H2···O4$^{\text{ii}}$, N···O distance 2.889 Å, angle 154.9°, symmetry code: (ii) $-x+1$, $-y$, $-z+1$] to form a 2-D structure. If **2** is visualized as a cross, its assembly structure can be characterized as a grid with the molecule as the node (Fig. 4). There is no cavity in this structure.

To investigate the thermal stabilities of crystals of **1** and **2**, thermogravimetric (TG) experiments were performed. The TG curves show a consecutive weight loss, up to 95.5% from 280 to 340 °C (peak at 310 °C) for **1**, but to 97.8% from 394 to 500 °C (peak at 474 °C) for **2**. This result indicates that both compounds are indeed thermally stable.

In order to evaluate the strength of synthon **I**, the hydrogen bond energy of synthon **I** observed in crystal

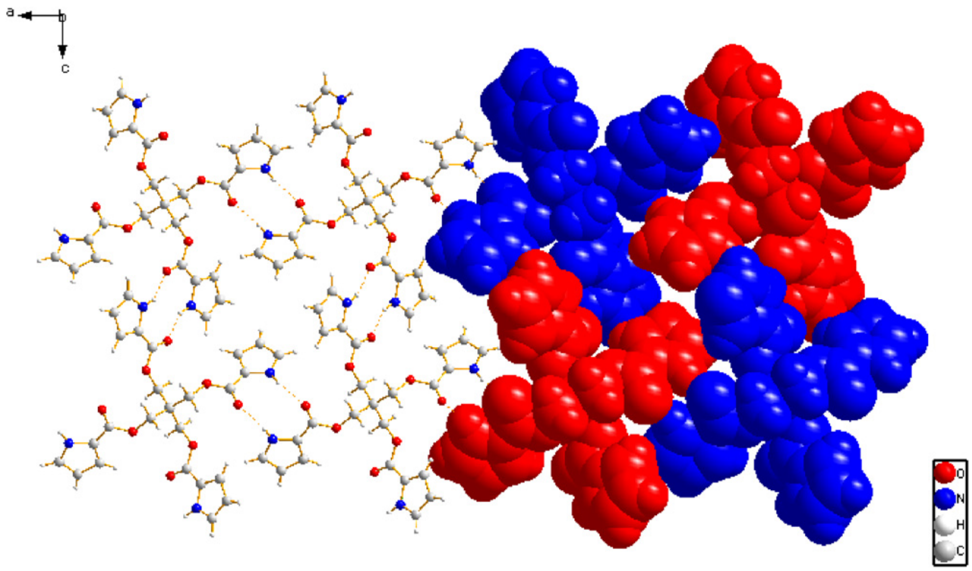

Figure 4. Grid self-assembly of **2** via hydrogen bonds (ORTEP and space-filling view of the structure were drawn in one picture).

structures **1** and **2** were evaluated using density functional calculations. The **1** monomer, **1**·**1** dimer, **2** monomer and **2**·**2** dimer units were cut out as the calculation models for the assembly structure from the crystals of compound **1** and compound **2**, respectively. At the B3LYP/6-31G* level, the Mulliken population analysis has been carried out on the geometries of monomer and dimer units using the Gaussian 03 program.[15] Stabilization energies resulting from hydrogen bonding interactions between monomers were computed as the difference in the energy between the dimer and its two isolated monomers.[16] The calculated energy of synthon **I** observed in the crystal of **1** is 12.1 kcal/mol, whereas the energies in the crystal of **2** are 11.3 and 10.6 kcal/mol, respectively. This is consistent with the calculated hydrogen bond energy for the methyl pyrrole-2-carboxylate in the literature (9.4 kcal/mol at RHF/6-311+G* level).[6] These results indicate that synthon **I** formed by pyrrole-2-carbonyl dimer is robust, and so it can be used as a supramolecular synthon in crystal engineering.

In conclusion, a novel supramolecular synthon of a pyrrole-2-carbonyl dimer has been successfully used to design organic crystals. The hexagonal and grid supramolecular self-assemblies were obtained by using appropriate spacers. Both experimental and calculated results demonstrate that the synthon is robust enough to be useful in crystal engineering. However, probably due to the small size spacers, both crystals have only small cavities, which may limit their application. The preparation of pyrrole-2-carboxylate with larger spacers is under way in our laboratory.

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11. Spectroscopic data for **1**: mp = 110 °C, ^{1}H NMR (300 MHz, DMSO-d_6); δ 2.92 (t, $J = 3$ Hz, 6H, –CH$_2$–), 4.21 (t, $J = 3$ Hz, 6H, –CH$_2$–), 6.10 (s, 3H, Py CH), 6.72 (s, 3H, Py CH), 6.97 (s, 3H, Py CH), 11.77 (s, 3H, Py NH); ^{13}C NMR (75 MHz, DMSO-d_6): δ 53.5, 62.7, 110.2, 115.7, 122.3, 124.6, 161.1; FAB-MS: 428.5 (M^{+}); Elemental analysis: $C_{21}H_{24}N_4O_6$: Calcd: C, 59.72; H, 5.92; N, 12.66. Found: C, 59.50; H, 5.97; N, 12.64. For **2**: mp = 225 °C, ^{1}H NMR (300 MHz, DMSO-d_6); δ 4.52 (s, 8H, –CH$_2$–), 6.19 (s, 4H, Py CH), 6.84 (s, 4H, Py CH), 7.06 (s, 4H, Py CH), 11.87 (s, 4H, Py NH); ^{13}C NMR (75 MHz, DMSO-d_6): δ 42.9, 62.6, 110.4, 116.4, 122.1, 124.9, 160.6; FAB-MS: 509.6 (M+1); Elemental analysis: $C_{25}H_{24}N_4O_8$: Calcd: C, 59.05; H, 4.76; N, 11.02. Found: C, 58.87; H, 4.38; N, 11.15.
12. X-ray single-crystal diffraction data for **1** and **2** complexes were collected on a Bruker Apex II CCD diffractometer at room temperature using a fine-focus molybdenum Kα tube ($\lambda = 0.71073$ Å). There was no evidence of crystal decay during data collection. A semiempirical absorption correction was applied (SADABS), and the program SAINT was used for integration of the diffraction profiles.[17] All structures were solved by direct methods with SHELXS and refined by full-matrix least-squares on F^2 with the SHELXL program of the SHELXTL package.[18] The H atoms were first found in difference electron density maps, and then placed in the calculated sites and included in the final refinement with fixed thermal factors. Crystal data for **1**: $C_{21}H_{24}N_4O_6$, $M_r = 428.44$, $T = 293(2)$ K, trigonal, space group P-3, $a = 15.589(5)$ Å, $b = 15.589(5)$ Å, $c = 5.387(4)$ Å, $\alpha = 90$, $\beta = 90$, $\gamma = 120$, $V = 1133.7(9)$ Å^3, $Z = 2$, $\rho_{\text{calc}} = 1.255$ g cm^{-3}, $\mu = 0.093$ mm^{-1}, $F(000)$: 452, reflections collected: 6229, independent reflections: 1354 ($R_{\text{int}} = 0.0242$), final R indices [$I > 2\sigma(I)$]: $R_1 = 0.0499$, $wR_2 = 0.2188$, R indices (all data): $R_1 = 0.0649$, $wR_2 = 0.2300$. CCDC 608191. Crystal data for **2**: $C_{25}H_{24}N_4O_8$, $M_r = 508.48$, $T = 293(2)$ K, orthorhombic, space group Pbcn, $a = 11.1701(10)$ Å, $b = 9.9616(8)$ Å, $c = 22.4848(19)$ Å, $\alpha = 90$, $\beta = 90$, $\gamma = 90$, $V = 2501.9(4)$ Å^3, $Z = 4$, $\rho_{\text{calc}} = 1.350$ g cm^{-3}, $\mu = 0.102$ mm^{-1}, $F(000)$: 1064, reflections collected: 12694, independent reflections: 2208 ($R_{\text{int}} = 0.0327$), final R indices [$I > 2\sigma(I)$]: $R_1 = 0.0364$, $wR_2 = 0.0896$, R indices (all data): $R_1 = 0.0624$, $wR_2 = 0.1036$. CCDC 608192.

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