Hydrogen-bonding Control of Molecular Aggregation: Self-complementary Subunits lead to Rod-shaped Structures in the Solid State

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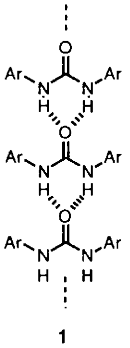
Simple cyclohexane-1,3,5-triamide derivatives are shown to form linear, rod-shaped structures in the solid state; a triple hydrogen-bonding interaction directs formation of the aggregate and leads to non-centrosymmetric packing arrangement with modest non-linear optical properties.

There is enormous current interest in the design of molecular building blocks that can assemble into structures of nanometre scale dimensions.[1] An important goal in this developing field has been the identification of molecular subunits that allow the controlled formation of different two- and three-dimensional shapes. Some success has been achieved by us and others in the directed self assembly of such structures as sheets,[2] ribbons,[3] spheres,[4] helices[5] and tubes.[6] A particularly interesting strategy to this end involves the design of self-complementary molecules in which binding groups on one part of the structure fit precisely with complementary groups on a different region of an adjacent molecule.[4] The orientation of the interacting groups will determine the nature and size of the aggregate. A simple example is seen with the dialkylureas **1**, which pack in hydrogen-bonded linear arrays with all the carbonyl dipoles aligned in the same direction.[7] Both urea-NH groups are directed to the same carbonyl-O and are well positioned to interact with the lone-pair electron density. A similar non-linear positioning of the NH donor and carbonyl-O acceptor groups is also seen in the crystal structures of several diamides, such as glutaramide **2**, in which the two carbonyl groups insert into the space between the two amide-NHs.[8]

We sought to extend these essentially planar aggregates into three-dimensional structures. With the urea hydrogen bonding motif this can be envisioned by using disc-shaped molecules with three or more carboxamide groups on the periphery, as in **3**. Molecular modelling studies suggested that *cis,cis*-cyclohexane-1,3,5-tricarboxamide derivatives (*e.g.* **4**) could be candidates for the central core since the three equatorial carbonyl groups can readily direct themselves parallel to each other and perpendicular to the ring. The resulting conformation will possess three carbonyl oxygens on one surface of the molecule ideally positioned to hydrogen bond with the three amide-NH on the opposite surface of an adjacent molecule, as in **5**. Furthermore, the use of appropriate aromatic amides should allow π–π interactions between adjacent subunits to further stabilize the aggregate.



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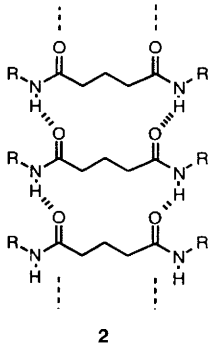

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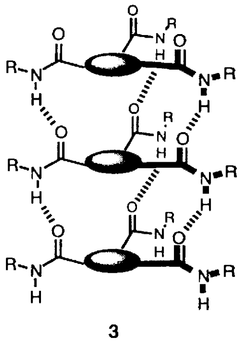

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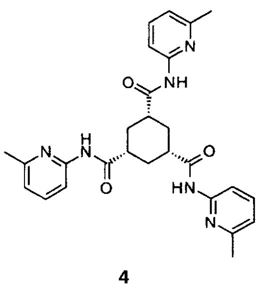

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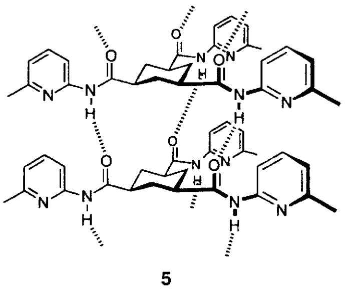
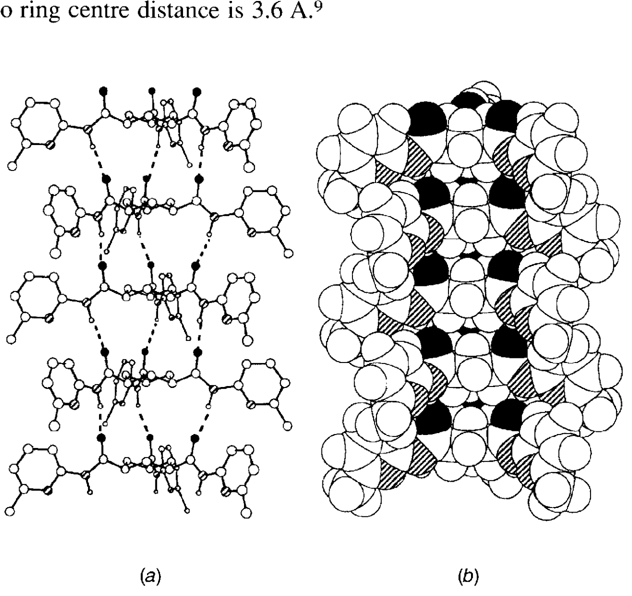


5

The simple tris-anilide of cyclohexane-1,3,5-tricarboxylic acid was found to be insoluble in all organic solvents. However, the corresponding 6-picoline derivative **4** (prepared from the tris-acid chloride and 2-amino-6-methylpyridine) readily dissolved in chlorocarbons and was used for this study. Crystallization of **4** (5×10^{-2} mol dm^{-3}) from a 1 : 1 mixture of MeOH–CH_2Cl_2 resulted in large rod-shaped crystals, measuring as much as 1 cm in length. X-Ray diffraction analysis† showed a compact packing arrangement in which the triamide monomers form an extended column structure stabilized by three intermolecular hydrogen bonds between each monomer (Fig. 1). The compound crystallizes in a trigonal space group (*R*3*c*) with the molecule residing on a crystallographic threefold axis. The equatorial position of the carboxamide substituents allows almost linear hydrogen bonds to be formed (NH···O angle 162.7°) with an H···O bond length of 2.19 Å. The overall structure corresponds closely to that shown schematically in **5**, except that close interaction between the pyridine rings leads to two distinct monomers (related by *c*-glide symmetry) in the unit cell (HN-Pyr torsion angle, 10.1 and −10.1°). This π–π stacking appears to play an important role in the formation of the aggregates. The picoline groups on adjacent stacked cyclohexane rings take up an alternating, interlocked arrangement with the 3- and 4-protons of one pyridine projecting into the π-face of its neighbour [as seen in Fig. 1(*b*)]. The interplane angle between the aromatic rings is 40–45° and the closest CH to ring centre distance is 3.6 Å.[9]



(*a*) (*b*)

Fig. 1 Crystal structure of **4**, shown (*a*) in ball and stick (most hydrogen atoms removed for simplicity) and (*b*) in space-filling representations

In addition to stabilizing the stacked structure, this type of edge-to-face interaction is also important in controlling the interactions among the hydrogen bonded rods. A top view of the structure (Fig. 2) shows that the hydrogen-bonded rods take up a parallel packing arrangement with a compact interleaving of the amide side arms. Each picoline group projects into the cleft formed by the side arms of an adjacent rod with a close positioning (*ca.* 4.0 Å) of the pyridine CH_3 to the plane of the pyridine on the adjacent rod. It is also evident from Fig. 2 that the packed rods are parallel (rather than anti-parallel) to each other with all of the amide dipoles pointing in the same direction and consistent with the hexagonal setting of the crystal's chiral space group (*R*3*c*).

The crystal packing of **4** is qualitatively similar to that of urea, the classic organic second-order nonlinear-optical material,[10] and of its derivatives. This fact, and the obvious electronic analogy between urea and **4**, prompted us to investigate the nonlinear-optical properties of the latter. In accord with expectation, second-harmonic generation (SHG) is observed from powdered samples of **4**, although the efficiency is modest (0.06 *vs.* urea; Kurtz–Perry method, λ_{ex} = 1064 nm, pulsed Nd:YAG laser, power = 9 mJ/pulse). This efficiency is consistent with observations for other derivatives of urea, which exhibit SHG efficiencies that are typically within one order of magnitude of that of urea.[11]

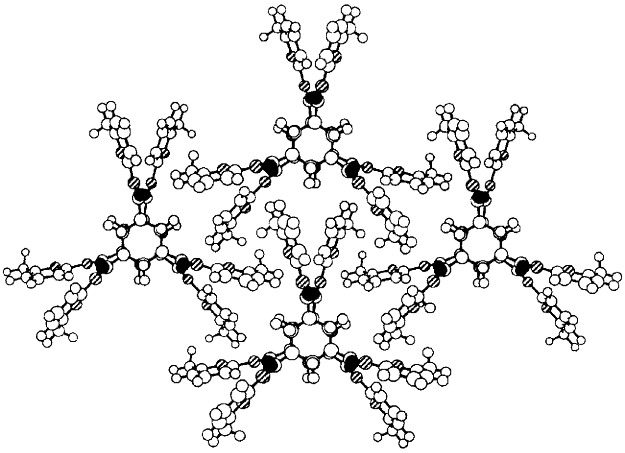


Fig. 2 Top view of the crystal structure of **4**

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Footnote

† *Crystal data* for $C_{27}H_{30}N_6O_3$: trigonal, *R*3*c*; *a* = 21.960(3), *c* = 9.702(2) Å, *V* = 4051.9(11) Å^3, *Z* = 6, D_c = 1.196 g cm^{-3}, 296 K. A Siemens P3 diffractometer was used to collect 5373 data points of which 3414 data with [$F > 9.0\sigma(F)$] were used in the solution and refinement. X-Ray data were corrected for absorption [λ(Mo-Kα) = 0.71073 Å]. Structure was solved by direct methods which located all non-hydrogen atoms. Hydrogen atom positions were calculated [*d*(C–H) = 0.96 Å]. Structure refined to R_F = 0.0504 and R_{WF} = 0.0711; GOF = 1.57, highest final difference peak, 1.05 e Å^{-3}. Atomic coordinates, bond lengths and angles, and thermal parameters have been deposited at the Cambridge Crystallographic Data Centre. See Information for Authors, Issue No. 1.

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