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Molecular Recognition and Self-Assembly by "Weak" Hydrogen Bonding: Unprecedented Supramolecular Helicate Structures from Diamine/Diol Motifs

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There is an increasing interest in the development of solid-state structures able to exhibit new physical and chemical properties.[1] The engineering of such solids often requires the establishment of mutually complementary interactions among discrete chemical entities capable of self-assembling into an organized molecular framework.[2,3] Supramolecular architecture has largely capitalized on noncovalent interactions, and particularly on hydrogen bonding involving amidic-type NH and carbonyl-type O atoms,[4,5] mimicking a tool widely used by nature for this purpose.[6] To the best of our knowledge, molecular recognition through weaker hydrogen bonding, such as that intervening between alcohols and amines, has not been employed for the construction of supramolecular systems, although it has been invoked to explain chiral discrimination utilizing chromatographic and NMR techniques.[7] In the present communication, we report unprecedented examples of well-defined supramolecular structures, generated by molecular recognition between a C_2-symmetrical diol and complementary C_2-symmetrical diamines, that spontaneously self-assemble through a unique network of hydrogen bonds. The resulting 3-dimensional assemblages possess a tertiary triple-stranded helicate structure, whose helicity is controlled by the chirality of the diamine. The superstructures reported herein constitute remarkable examples of metal-free[8,9] helicates self-assembled by *simple hydrogen bonding between amine and alcohol groups.*

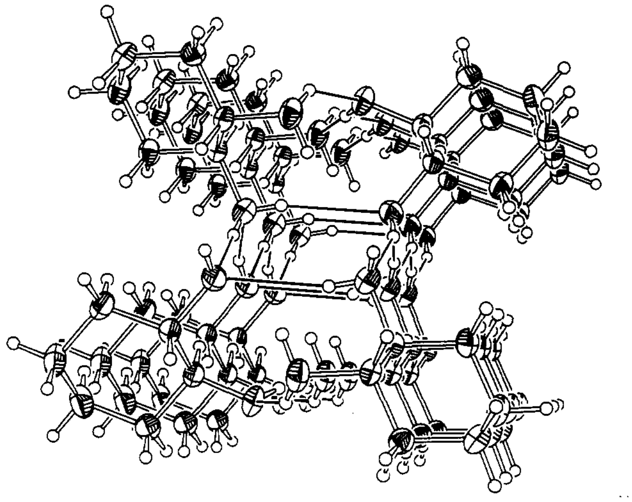
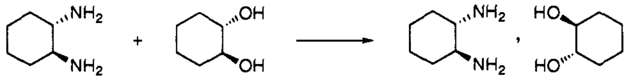


Figure 1. ORTEP view of the crystal assembly of homochiral complex **3a** along the axis of the network.[11] *R* value, 0.033.

Scheme 1



1a (*S*,*S*) **2** (*S*,*S*) **3a** homochiral (*S*,*S*/*S*,*S*)

1b (*R*,*R*) **3b** heterochiral (*R*,*R*/*S*,*S*)

When equimolar amounts of enantiomerically pure *trans*-1,2-diaminocyclohexanes (**1a** and **1b**) and (1*S*,2*S*)-*trans*-1,2-cyclohexanediol (**2**) were melted together and crystallized, products **3a** [needles from benzene, mp 78–79 °C, $[\alpha]_D^{21}$ + 38.2° (*c* 1, $CDCl_3$)] and **3b** [needles from benzene, mp 63–65 °C, $[\alpha]_D^{21}$ –0.9° (*c* 1, $CDCl_3$)] were obtained quantitatively (Scheme 1). Enantiomeric enrichment of selected racemic 1,2-diols had been reported by Kawashima and co-workers,[10] determined using a similar crystallization procedure. The X-ray structure analysis of adducts **3a** and **3b** unambiguously showed the formation of a 1:1 complex between one molecule of diol and one of diamine, linked by a pair of interactions well within the distance of a definite hydrogen bond.[6,11] Slight differences in the hydrogen-bonding distances and angles account for the different melting points and solubilities exhibited by the two diastereomeric complexes, which in turn account for the enantiomeric enrichment previously reported.[10] Furthermore, adducts **3a** and **3b** both form well-defined and extremely ordered supramolecular structures (Figure 1).[11] A peculiar self-assembly of discrete complex units develops, in which the cyclohexane rings of both reagents are stacked into four vertical columns with the polar groups facing inwards. A pleated sheetlike central core is formed as a staircase by eight-membered, square-planar, hydrogen-bonded units, featuring fully tetracoordinated heteroatoms and involving one functional group from each molecule. Remaining functional groups are engaged in two symmetrical side rows of hydrogen bonds, which flank the staircase and join diols to diamines through tricoordinated heteroatoms.[11] The entire set of hydrogen bond distances ranges from 1.87 to 2.37 Å for **3a** and from 1.88 to 2.42 Å for **3b**. Except for one of the four hydrogens on nitrogen of the diamine, which remains buried inside the superstructure and is not accessible for coordination, *all* other hydrogens are engaged in a fully hydrogen-bonded assembly. Extensive hydrogen bonding is indeed shown by IR spectra (KBr) of **3a** and **3b** with respect to those of **1** and **2**.[11] The full tetracoordination of *both* oxygen and nitrogen atoms in the core is unusual and is not shared by the diamine nor the

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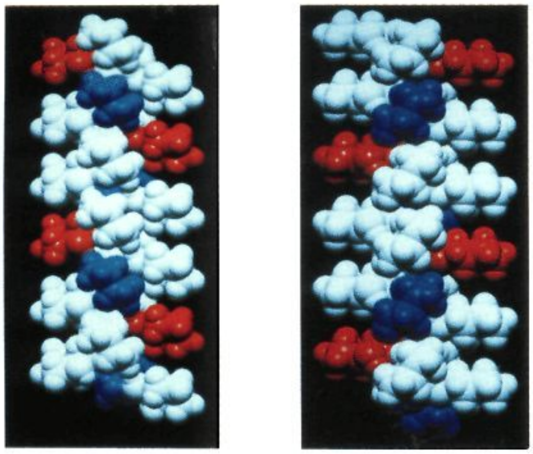

Figure 2. Space-filling representation of the crystal assembly of (left) homochiral complex **3a** and (right) heterochiral complex **3b**, showing the triple-stranded helicate tertiary structures (side view). One strand is represented in colors, blue (diamine **1**) and red (diol **2**), showing the left-handed (**3a**) and right-handed (**3b**) helicity of the assembly.

diol progenitors.[11] Filling the coordination vacancies might provide the assembly an extra stabilization energy and account for the preference of the partners for cocrystallization. Although examples of hydrogen bonding between amino and hydroxy groups, such as that occurring between glycosidic hydroxyls and nucleic acid amino groups, are frequent,[6] none exhibit this peculiar staircase-like assembly, nor do they utilize the full coordination capabilities of both heteroatoms. Both homo- and heterochiral complexes **3a** and **3b** form very similar chiral structures that differ merely in the opposite sense of twisting of the hydrogen-bonded sides; notably, identical staircase-like cores self-assemble regardless of the chirality of the paired components. The hydrogen-bonding donor direction runs in one sense in the core and in the opposite sense in the side rows, with the same sense of donation in the two rows within each set, irrespective of the nature of the heteroatom. Apparently, as remarked by Lehn in a different context,[3] *the diamine/diol motif consists of mutually complementary partners possessing encoded stereochemical and functional information that is read by the recognition process.* This results in the observed highly organized supramolecular architecture.

The molecular assemblies of **3a** and **3b** possess a tertiary structure in which the cyclohexane rings of the diamine/diol motif wrap around the core in a triple-stranded helicate (Figure 2).[11] A full turn comprises four units, involving a pair each of alternating diols and diamines, held together by four hydrogen bonds in a 16-atom strand. Three strands run parallel in the helicate at a fixed distance, so that the groove of the helix is one-third of the pitch. The strands are held together by alternate hydrogen bonds of the staircase and of the side rows along the network axis. Remaining alternate hydrogen bonds of the core and of the side rows constitute the strands themselves, while the perpendicular hydrogen bonds of the staircase fix the gauge of the helix, so that the helicate is completely rigid.[12] Interestingly, the chirality sense of the helicate is governed by the chirality of the diamine for both the homo- and the heterochiral complexes. Thus, where the *S,S* enantiomer gives a left-handed helix, the *R,R* gives the opposite, *irrespective of the chirality sense of the diol* (Figure 2). Also, in **3a** hydrogen bonds constituting the strands are homogeneously formed between *oxygen donors* and *nitrogen acceptors*, while the reverse is true for **3b**, so that diastereomeric arrays are distinguished not only by the chirality sense of the helix but also by the donating/accepting role of the hydrogen-bonded partners (Figure 2).[11,13]

The interchangeable donor–acceptor interaction observed in the solid state is also confirmed by ^{1}H NMR spectroscopy in benzene or toluene solution. A downfield shift is observed for *both* the C*H*OH and the C*H*NH$_2$ signals which might be related to average charge densities on respective heteroatoms. In solvents of low polarity, **3a** and **3b** show time-averaged ^{1}H and ^{13}C NMR spectra in the range from −40 to +25 °C due to fast exchange of molecules within kinetically labile adducts.[14] Nevertheless, chiral discrimination is clearly evident in the ^{13}C NMR spectra of adducts of nonenantiopure diols, since diol signals are split and their intensities are proportional to the mole ratio of enantiomers.[7b,11]

The self-assembling complementarity of the diamine/diol motifs **3a** and **3b** provides convincing evidence that the engineering of highly organized supramolecular structures based on molecular recognition can now be extended to include "weak" hydrogen-bonding interactions. It is also noteworthy that adducts **3a** and **3b** can be *sublimed cleanly as undissociated complexes* (45 °C, 1.5 Torr), thus demonstrating their remarkable physical stability. Preliminary results with other C_2-symmetrical diols utilizing **1a** and **1b** as the "assembler" units suggest that such finely tuned molecular recognition phenomena of the type described herein are prevalent. Further investigations are in progress and will be reported in due course.

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Supplementary Material Available: Full details of the X-ray structures of **1b**, **2**, **3a**, and **3b**, as well as selected NMR and FTIR spectra and subsidiary ORTEP and space-filling views of the crystal structures (65 pages); observed and calculated structure factors (37 pages). This material is contained in many libraries on microfiche, immediately follows this article in the microfilm version of the journal, and can be ordered from the ACS; see any current masthead page for ordering information.

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(12) The pitch of the helix is 15.724 (**3a**) and 15.048 Å (**3b**); the groove is 5.241 (**3a**) and 5.016 Å (**3b**); the outer gauge is 13.219 (**3a**) and 13.251 Å (**3b**) between diamine residues and 13.738 (**3a**) and 14.287 Å (**3b**) between diol residues. Thus, the left-handed helix of the homochiral complex is longer and narrower than the right-handed helix of its diastereomeric counterpart.

(13) Hydrogen bonds of the strands are characterized by N···O distances of 2.787 and 2.985 Å for **3a** and 3.203 and 3.280 Å for **3b**, which lie in the range of typical hydrogen bonding (see ref 6). Hydrogen bonds are shorter for **3a** (N···H, 1.928 and 2.128 Å) than for **3b** (O···H, 2.425 and 2.426 Å). Whether this is a consequence of the architecture of the two diastereomers or of the different donor–acceptor ability of oxygen and nitrogen cannot be ascertained.

(14) Precipitation of the aggregate occurred at lower temperature before slow exchange could be observed.