Hydrogen-bonded Layers of Hydrogentartrate Anions: Two-dimensional Building Blocks for Crystal Engineering

Christer B. Aakeröy,*[a]† and Peter B. Hitchcock[b]
[a] *Department of Chemistry, University of Minnesota, 207 Pleasant St. S.E., Minneapolis, MN 55455, USA*
[b] *School of Chemistry and Molecular Sciences, University of Sussex, Falmer, Brighton, UK BN1 9QJ*

An investigation of hydrogen-bond patterns in a family of ionic crystals has established the use of hydrogen bonding as a potential design strategy for crystal engineering of ionic materials. In 11 out of 12 crystal structures of anhydrous hydrogentartrate salts (data extracted from the Cambridge Structural Database), the anions were found to generate infinite two-dimensional sheets created by relatively short O—H···O hydrogen bonds. The regular occurrence of the infinite layer, even in the presence of widely differing cations, demonstrates the selectivity, strength and directionality of hydrogen bonds between ions in the solid state. The two-dimensional sheet was subsequently employed as a building block ('scaffolding') in the synthesis of a material with a three-dimensional hydrogen-bond network, 1*H*-imidazolium hydrogen L-tartrate (the X-ray single-crystal structure is reported), where the cation provides the anticipated cross-link between adjacent anionic layers. Each anionic network was also described using a notation based upon graph theory which simplifies the process of recognizing and communicating complex structural information.

Keywords: *Hydrogen bonding*; *Crystal engineering*; *Graph set*; *Hydrogentartrate*; *Crystal structure*

Ever since Pasteur carried out the first reported separation of crystalline enantiomers,[1] tartaric acid has held a firm place in the archives of ground-breaking chemical discoveries. 145 years later, it is possible that hydrogentartrate salts may play a key role in inspiring further development in one of the most exciting and challenging of current scientific disciplines: crystal engineering.[2]

Many elegant studies have illustrated that hydrogen bonding can be used as a versatile tool, with which molecular subunits can be joined together in a relatively predetermined way.[3–6] However, hydrogen bonding is also known to be energetically strong enough to have a profound effect on the spatial arrangement of ions in the solid state,[7] and it would therefore seem reasonable to use the strength and directionality of the hydrogen bond as an interionic synthetic route towards specific ionic aggregates and materials.[8,9]

Earlier work on some organic hydrogentartrates (the materials were prepared and investigated for their non-linear optical properties)[10] showed that their crystal structures incorporated a highly ordered, infinite layer of hydrogentartrate anions linked together by relatively short O—H···O interactions. This paper presents an extensive analysis of 12 crystal structures of hydrogentartrate salts with the purpose of establishing whether an infinite 2D anionic layer is a regular feature of these salts. Such aggregates could be used as structural building blocks (molecular 'scaffolding'), provided that they can be shown to possess structural and spatial consistency in the presence of chemically different counterions. This survey focuses on the anionic networks, since they form a point of reference throughout these materials and they are also expected to generate the most distinctive patterns, due to the availability of several hydrogen-bond donors and acceptors on each anion.

Potential applications for the design of novel materials with predictable structural features and properties can be found in almost every commercial and academic area concerned with macroscopic structure–property considerations, *e.g.* non-linear optics, shape-selective catalysis and pharmaceutical drug design.

Encoding Hydrogen-bond Patterns

An important aspect of crystal engineering pertains to the manner in which hydrogen-bond patterns are described. Etter *et al.* have developed a methodology[11] for classifying hydrogen-bond networks in, primarily, molecular solids. However, since the existing graph-set language is not always adequate for examining multi-dimensional aggregates with a high hydrogen-bond density (a consequence of the inherent difficulties with translating 3D information into scalar quantities), an additional descriptor,‡ based upon the terminology of Etter *et al.*, has been utilized as a means of specifically representing 2D hydrogen-bonded networks.

The original encoding[11] comprises a classification of patterns generated by specific hydrogen-bond types and by combinations of hydrogen bonds. Most patterns in organic molecular solids can be adequately described in terms of four principal motifs; chains (*C*), dimers (*D*), rings (*R*) and intramolecular hydrogen bonds (*S*).¶ Although this notation may not

† Permanent address: University of Sussex, School of Chemistry and Molecular Sciences, Falmer, Brighton, UK BN1 9QJ.

‡ The 2D descriptor utilized in this paper is employed as a means of facilitating a comparison and analysis of specific aggregate-types. The descriptor may have general applicability to a range of 2D structural types and this is currently being investigated. In the course of this investigation, certain modifications to the 2D descriptor may become necessary.

¶ A graph set is specified using the pattern designator (G), its degree (n) and the number of donors (d) and acceptors (a); $G_d^a(n)$. G, the descriptor referring to the pattern of hydrogen bonding, can be either S (intramolecular bond), C (infinite chain), R (intermolecular ring) or D (acyclic dimers and other finite structures) and the parameter n refers to the number of atoms in a ring, or the repeat unit of a chain. The set of ions/molecules to be analysed is called an array. Graph sets are assigned initially to motifs (patterns constructed by only one type of hydrogen bond), and then to the first-level network (a sequential listing of every motif). For example, if the array contains four different hydrogen-bond types, then the first-level graph set is a combination of four motifs. Higher-level networks are assigned by listing patterns generated by combinations of different hydrogen-bond types.

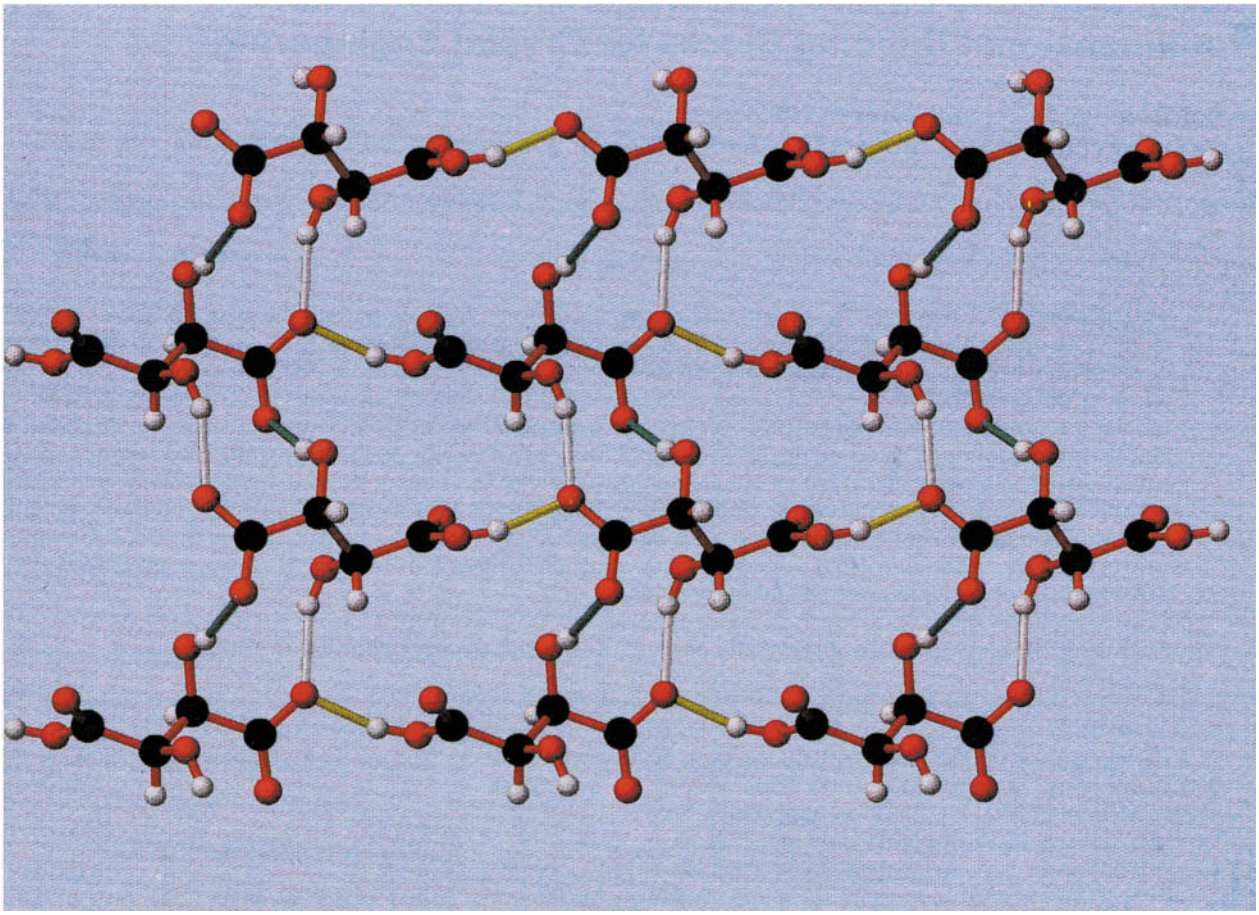


Plate 1 Anionic network of caesium hydrogen-L-tartrate; $N_{2D}=L\{R_2^2(11)R_4^3(17)\}$.[19] Covalent bonds, red; hydrogen bonds, yellow, green and white.

Table 1 Aggregate types and a graph-set description for the anionic networks in hydrogentartrate salts[a]

salt	aggregate type	graph set	r(O···O)/Å[b]	∠(O—H···O)/degrees
1	double chain	$N_1=C_1^1(6)C_1^1(6)C_1^1(7)$	2.49	177
2	buckled layer	$N_{2D}=L\{R_2^2(11)R_4^3(17)\}$	2.559	178
3	buckled layer	$N_{2D}=L\{R_2^2(11)R_4^4(19)\}$	2.55	161
4	buckled layer	$N_{2D}=L\{R_2^2(7)R_4^4(21)\}$	2.51	174
5	buckled layer	$N_{2D}=L\{R_4^4(22)\}$	2.50	167
6	buckled layer	$N_{2D}=L\{R_4^4(22)\}$	2.49	179
7	flat layer	$N_{2D}=L\{R_3^3(12)R_3^3(16)\}$	2.438	163
8	buckled layer	$N_{2D}=L\{R_2^2(11)R_4^3(17)\}$	2.57	165
9	buckled layer	$N_{2D}=L\{R_2^2(11)R_4^4(19)\}$	2.54	168
10	flat layer	$N_{2D}=L\{R_4^4(22)\}$	2.498	168
11	buckled layer	$N_{2D}=L\{R_4^4(21)\}$	2.48	174
12	buckled layer	$N_{2D}=L\{R_2^2(11)R_4^3(17)\}$	2.558	173
13	flat layer	$N_{2D}=L\{R_3^3(12)R_3^3(16)\}$	2.50	167

[a]The search yielded structural data for (*a*) hydrogen-L-tartrates with the following cations; (–)-3-benzoyl-3-ethyl-1-methylpiperidinium (**1**),[13] rubidium (**2**),[14] *S*-(+)-*N*-methylamphetammonium (**3**),[15] 3-methylene-4-(prop-2-enyl)pyrrolidinium (**4**),[16] (–)-adrenalinium (**6**),[17] 3-hydroxypyridinium (**7**),[18] caesium (**8**),[19] *R*-(–)-*N*-methylamphetammonium (**9**),[15] (–)-1-phenylethylammonium (**10**),[20] piperazinium(2+) (**11**),[9] (*b*) ammonium hydrogen-D-tartrate (**12**),[21] and (*c*) (–)-1-phenylethylammonium hydrogen-*meso*-tartrate **13**.[22] [b]The hydrogen-bond interaction responsible for the head-to-tail linking of adjacent anions.

provide an unambiguous assignment of every structural arrangement, it is flexible enough to facilitate a systematic description of a wide range of hydrogen-bonded solids.[12]

The presence of hydrogen-bonded, infinite, 2D aggregates (sheets or layers) in crystal structures is not a unique phenomenon. Although a hydrogen-bonded sheet can be generated by the interconnection of very different (chemically and geometrically) building blocks, certain structural aspects of a sheet are amenable to a compact, yet informative, notation. One way of describing the topology of a hydrogen-bonded sheet is to identify the size, and the number, of unique hydrogen-bonded rings within the sheet. This paper will employ the following notation for characterizing such aggregates:

$$N_{2D}=L\{R_d^a(n)'R_d^a(n)''R_d^a(n)\ldots\}$$

where N_{2D} indicates a 2D network, L specifies it to be of a layered, or sheet-like, type, and the remaining variables are the same as those defined previously.

Plate 1 shows an example of how this notation is applied. Note that N_{2D} does not include intramolecular hydrogen bonds since such bonds are not instrumental in connecting adjacent molecules/ions into aggregates. Furthermore, only rings that do not contain smaller hydrogen-bonded rings as part of their structure are listed in this 2D descriptor.

Results and Discussion

Table 1 summarizes the observed aggregate types and a graph-set description for each structure, and it also contains infor-

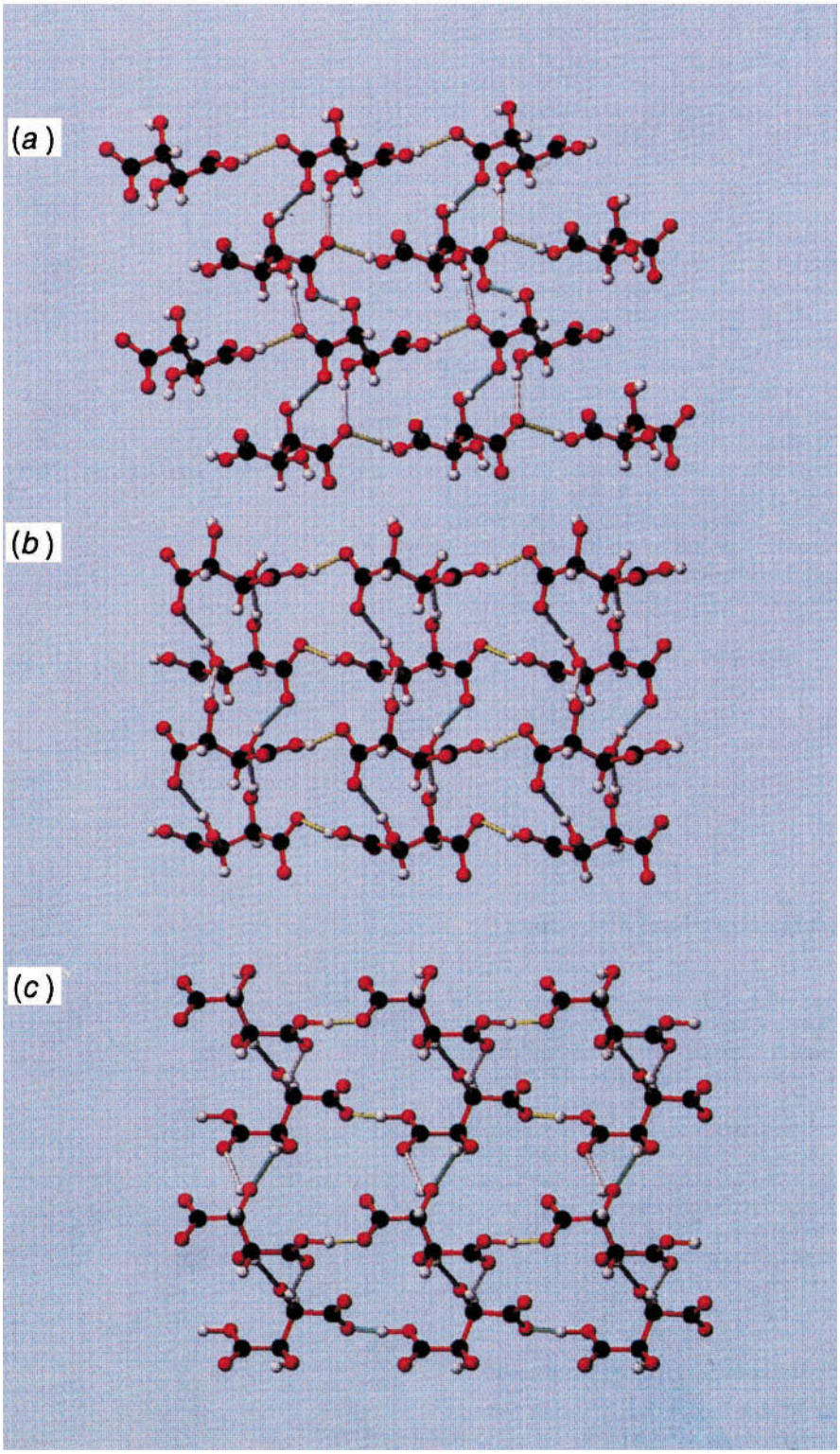


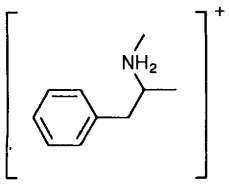
Plate 2 Anionic networks of (*a*) **2**,[14] (*b*) **3**,[15] and (*c*) **4**.[16] The relevant graph sets are listed in Table 1. Covalent bonds, red; hydrogen bonds yellow, green and white.

mation about the geometry of the O—H···O hydrogen bond (coloured yellow in Plate 1) which is responsible for the head-to-tail linking of adjacent anions into infinite chains. This interaction is present in every hydrogentartrate structure included in this survey.

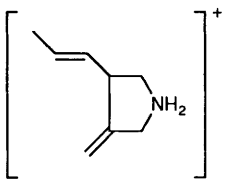
The most commonly occurring hydrogen-bonded aggregate in these salts is an infinite 2D anionic sheet; a structural feature exhibited by 11 of the 12 structures in this family. The sheet is generated by crosslinking of neighbouring chains and each chain is created by a O—H···O hydrogen bond linking anions in a 'head-to-tail' fashion. Adjacent chains are then cross-linked either by one O—H···O hydrogen bond, creating a network with a $N_{2D}=L\{R_d^a(n)\}$ graph set, or by two O—H···O hydrogen bonds, generating a network with a $N_{2D}=L\{R_d^a(n)'R_d^a(n)\}$ graph set. The average O···O distance for the 'head-to-tail' hydrogen bond is 2.51(4) Å with an average O—H···O bond angle of 170(6)°, indicating the presence of a strong, almost linear, hydrogen bond.

The anionic sheet is absent in only one crystal structure, (–)-3-benzoyl-3-ethyl-1-methylpiperidinium hydrogen-L-tartrate (**1**).[13] There does not seem to be a simple explanation for the observed structure of this compound; salts containing similar cations are currently being prepared with a view to establishing whether this is a structurally unique material.

The remarkable consistency of the infinite hydrogen-bonded sheet is illustrated by the fact that hydrogen-L-tartrate salts with very different (both chemically and geometrically) cations *e.g.* rubidium, *S*-(+)-*N*-methylamphetaminium and 3-methylene-4-(prop-2-enyl)pyrrolidinium, (in **2**,[14] **3**[15] and **4**[16]) display very similar anionic configurations, Plate 2. The cations of **3** and **4** are shown below. Consequently, hydrogentartrate anions may be employed as a means of incorporating a specific structural 2D feature into a crystalline material whilst, at the same time, imposing severe restrictions on the positional freedom of the cation.



cation of **3**



cation of **4**

Design of Novel Hydrogen-bonded Structures

Hypothesis

Having established that most of the materials in this diverse series are dominated by rigid, structurally consistent, anionic networks, a new hydrogentartrate salt 1*H*-imidazolium hydrogen-L-tartrate (**5**) was synthesized. The cation, 1*H*-imidazolium, was chosen in a deliberate attempt to provide a specific cross-link between adjacent sheets. The combination of hydrogen-bond donors at opposite ends of a small, rigid spacer, and a lack of hydrogen-bond acceptors (which could disrupt the anionic network), suggested that this cation would provide a cross-link for the anionic scaffolding, thereby creating a three-dimensional network. This hypothesis was tested by the subsequent preparation and crystallographic characterization of 1*H*-imidazolium hydrogen-L-tartrate.

Crystal Structure of 1H-Imidazolium Hydrogen-L-tartrate†

The cation and anion do not exhibit any unusual features (Fig. 1), with the anion displaying the expected zig-zag con-

† Fractional coordinates are listed in Table 2 and selected bond lengths and angles in Table 3.

Table 2 Final fractional coordinates ($\times10^4$ for C, N, O; $\times10^3$ for H) and equivalent isotropic thermal factors for **5** with e.s.d.s in parentheses

	x	*y*	*z*	U_{eq}
O(1)	3609(2)	871(0)	8234(2)	37(1)
O(2)	2680(2)	−290(4)	5900(2)	42(1)
O(3)	−487(2)	−1436(4)	6469(2)	45(1)
O(4)	−482(2)	2684(3)	6592(2)	42(1)
O(5)	−1990(2)	305(4)	9624(2)	42(1)
O(6)	−3466(2)	1544(3)	7439(2)	38(1)
N(1)	5582(3)	581(4)	4076(3)	45(1)
N(2)	5986(3)	639(4)	1798(2)	42(1)
C(1)	2435(3)	68(4)	7155(2)	26(1)
C(2)	648(3)	−370(4)	7616(3)	29(1)
C(3)	−265(3)	1509(4)	7904(3)	28(1)
C(4)	−2054(3)	1083(4)	8378(3)	27(1)
C(5)	6739(3)	193(5)	3198(3)	42(1)
C(6)	4057(3)	1301(5)	3198(3)	40(1)
C(7)	4307(4)	1338(5)	1775(3)	43(1)
H(O1)	501(5)	118(8)	803(5)	
H(N1)	607(5)	57(8)	533(5)	
H(2)	90(5)	−116(8)	861(4)	
H(N2)	651(5)	57(8)	94(4)	
H(O3)	21(5)	−162(8)	584(5)	
H(3)	57(5)	223(9)	876(4)	
H(O4)	−146(5)	298(7)	648(4)	
H(5)	804(5)	−48(8)	362(5)	
H(6)	318(5)	176(7)	357(5)	
H(7)	358(5)	173(8)	90(5)	

U_{eq} is defined as one third of the trace of the orthogonalised U_{ij} tensor.

Table 3 Selected bond lengths (/Å) and angles (/degrees) for **5** with e.s.d.s in parentheses

bond lengths/Å			
O(1)–C(1)	1.303(2)	O(1)–H(O1)	1.13(4)
O(2)–C(1)	1.206(2)	O(3)–C(2)	1.413(3)
O(3)–H(O3)	1.86(4)	O(4)–C(3)	1.417(3)
O(4)–H(O4)	0.176(4)	O(5)–C(4)	1.236(3)
O(6)–C(4)	1.264(3)	N(1)–C(5)	1.319(4)
N(1)–C(6)	1.357(3)	N(1)–H(N1)	1.12(4)
N(2)–C(5)	1.311(3)	N(2)–C(7)	1.357(4)
N(2)–H(N2)	0.94(4)	C(1)–C(2)	1.522(3)
C(2)–C(3)	1.525(4)	C(2)–H(2)	1.03(4)
C(3)–C(4)	1.528(3)	C(3)–H(3)	1.02(4)
C(5)–H(5)	1.09(4)	C(6)–C(7)	1.331(4)
C(6)–H(6)	0.86(4)	C(7)–H(7)	0.91(4)
bond angles/degrees			
C(1)–O(1)–H(O1)	119(2)	C(2)–O(3)–H(O3)	101(3)
C(3)–O(4)–H(O4)	103(3)	C(5)–N(1)–C(6)	108.5(2)
C(5)–N(1)–H(N1)	119(2)	C(6)–N(1)–H(N1)	131(2)
C(5)–N(2)–C(7)	109.0(2)	C(2)–C(3)–C(4)	109.8(2)
C(7)–N(2)–H(N2)	124(2)	C(5)–N(2)–H(N2)	127(2)
O(1)–C(1)–C(2)	113.2(2)	O(1)–C(1)–O(2)	125.1(2)
O(3)–C(2)–C(1)	110.5(2)	O(2)–C(1)–C(2)	121.7(2)
O(3)–C(2)–H(2)	109(3)	O(3)–C(2)–C(3)	110.1(2)
C(1)–C(2)–H(2)	109(2)	C(1)–C(2)–C(3)	109.4(2)
O(4)–C(3)–C(2)	109.5(2)	C(3)–C(2)–H(2)	109(3)
O(4)–C(3)–H(3)	107(3)	O(4)–C(3)–C(4)	112.5(2)
C(2)–C(3)–H(3)	108(3)	C(4)–C(3)–H(3)	110(2)
O(5)–C(4)–O(6)	126.3(2)	O(5)–C(4)–C(3)	117.5(2)
O(6)–C(4)–C(3)	116.2(2)	N(1)–C(5)–N(2)	108.2(2)
N(1)–C(5)–H(5)	123(2)	N(2)–C(5)–H(5)	129(3)
N(1)–C(6)–C(7)	107.4(2)	N(1)–C(6)–H(6)	123(3)
C(7)–C(6)–H(6)	130(3)	N(2)–C(7)–C(6)	106.9(2)
N(2)–C(7)–H(7)	122(3)	C(6)–C(7)–H(7)	131(3)

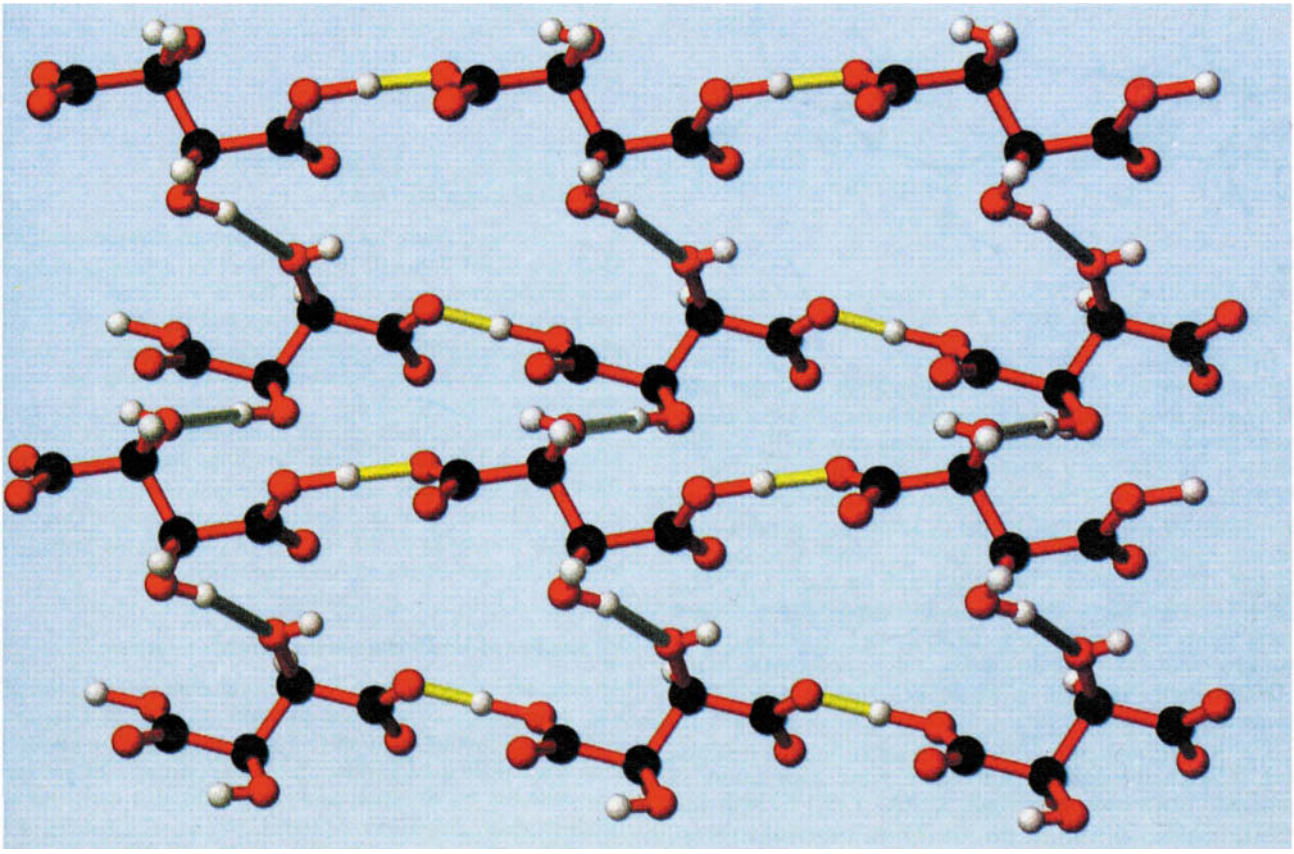


Plate 3 Infinite 2D sheet of anions, parallel to the *a*–*b* plane, in **5**. Covalent bonds, red; hydrogen bonds, yellow and green.

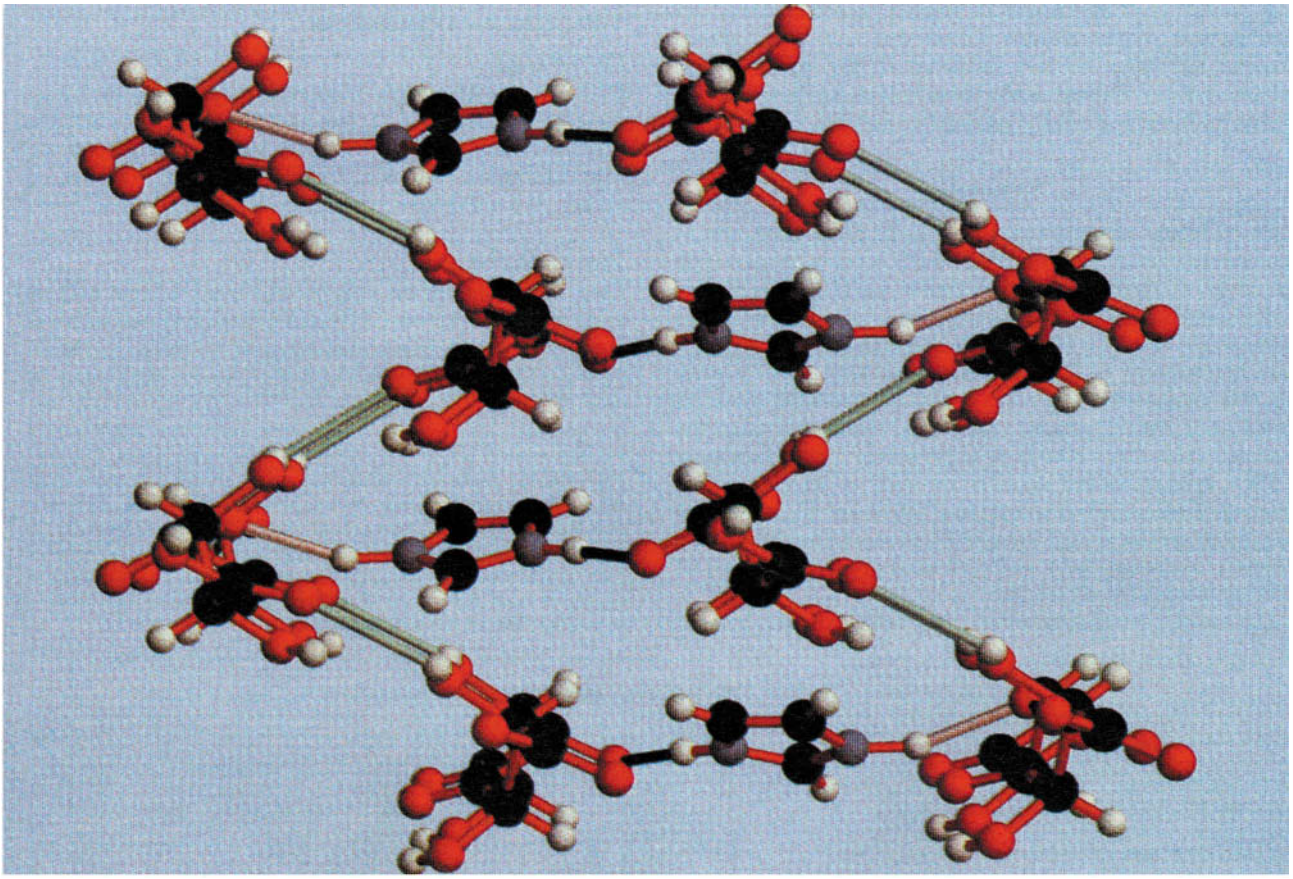


Plate 4 Cross-linking of adjacent anionic sheets by the 1*H*-imidazolium cation in **5**. Cation/anion layer parallel to the *a*–*c* plane. Covalent bonds, red; hydrogen bonds, green, pink and black.

DOCKET ALARM

Explore Litigation Insights

Docket Alarm provides insights to develop a more informed litigation strategy and the peace of mind of knowing you're on top of things.

Real-Time Litigation Alerts

Keep your litigation team up-to-date with **real-time alerts** and advanced team management tools built for the enterprise, all while greatly reducing PACER spend.

Our comprehensive service means we can handle Federal, State, and Administrative courts across the country.

Advanced Docket Research

With over 230 million records, Docket Alarm's cloud-native docket research platform finds what other services can't. Coverage includes Federal, State, plus PTAB, TTAB, ITC and NLRB decisions, all in one place.

Identify arguments that have been successful in the past with full text, pinpoint searching. Link to case law cited within any court document via Fastcase.

Analytics At Your Fingertips

Learn what happened the last time a particular judge, opposing counsel or company faced cases similar to yours.

Advanced out-of-the-box PTAB and TTAB analytics are always at your fingertips.

API

Docket Alarm offers a powerful API (application programming interface) to developers that want to integrate case filings into their apps.

LAW FIRMS
Build custom dashboards for your attorneys and clients with live data direct from the court.

Automate many repetitive legal tasks like conflict checks, document management, and marketing.

FINANCIAL INSTITUTIONS
Litigation and bankruptcy checks for companies and debtors.

E-DISCOVERY AND LEGAL VENDORS
Sync your system to PACER to automate legal marketing.