8702 J. Am. Chem. Soc. **1998,** *120,* 8702−8710

C−H···F Interactions in the Crystal Structures of Some Fluorobenzenes

Venkat R. Thalladi,[†] Hans-Christoph Weiss,[‡] Dieter Bläser,[‡] Roland Boese,*,[‡] Ashwini Nangia,*,[†] and Gautam R. Desiraju*,[†]

Contribution from the School of Chemistry, University of Hyderabad, Hyderabad 500 046, India, and Institut für Anorganische Chemie, FB 8, Universität-GH Essen, Universitätsstrasse 5-7, D-45177 Essen, Germany

Received April 9, 1998

Abstract: The existence and nature of C−H···F−C interactions in crystalline fluorobenzenes **1**−**3** and **7**−**10** are discussed. These compounds were chosen because they contain only C, H, and F atoms; this is necessary in the evaluation of the weak acceptor capabilities of the C−F group. All of these compounds are liquids at room temperature, and single crystals for X-ray diffraction were grown in situ. The analysis of the C−H···F interactions that are found in all of these crystal structures takes the form of comparisons with related C−H···O/C−H···N analogues. Fluorobenzene, **1**, bears a close relationship to pyridinium fluoride, pyridine 1-oxide, and benzonitrile at the level of individual interactions, showing that the character of the structure-determining intermolecular interactions in these four crystal structures are the same. Similarly, 1,4-difluorobenzene, **3**, and 1,4-benzoquinone are related, the C−H···F interactions in the former playing the same structural role as the C−H···O interactions in the latter. A comparison of **3** with the unsymmetrical 1,4-dihalogenated benzenes, **4**−**6** indicates the importance of C−H···F interactions in these structures. With an increase in the F content of the molecules, the C−H acidity also increases and the C−H···F interactions in 1,3,5-trifluorobenzene, **7**, and 1,2,4,5-tetrafluorobenzene, **8**, become stronger and more important. Compounds **7** and **8** are structurally very similar to 1,3,5-triazine and 1,2,4,5-tetrazine, and this similarity further strengthens the argument that C−H···F interactions resemble C−H···N interactions and provides evidence for their description as weak hydrogen bonds. 1,2,3,4-Tetrafluorobenzene, **9**, is polymorphic but the role of the C−H···F interactions in the two forms is similar. A comparison of the C−H···F geometries in compounds **1**−**10** with other C-, H-, and F-containing compounds in the Cambridge Structural Database reveals that the hydrogen bond properties are more pronounced in **1**−**10**. It is concluded that only when the carbon acidity is enhanced to the levels of the compounds in the present study, is the hydrogen-bond nature of the C−H···F interaction even revealed. This study also demonstrates that the C−F group prefers to form C−H···F interactions rather than F···F contacts. The behavior of organic fluorine in crystal packing is therefore quite different from the heavier halogens.

Introduction

Hydrogen bonding, the master-key of molecular recognition, is the most reliable design element in crystal engineering.[1] Hydrogen bonds of the O−H···O═C, O−H···O−C, N−H···O═C, N−H···O−C, N−H···O−H, and O−H···N−H type have been extensively studied and employed in the synthesis of supramolecular assemblies.[2] In contrast, little is known about hydrogen bonds of the O−H···F−C and N−H···F−C type. Pauling's definition of the hydrogen bond[3] would imply that F, as the most electronegative atom, should be a stronger hydrogen-bond acceptor than O and N atoms. While the F^- ion is indeed one of the best acceptors and the strength of the hydrogen bond formed by the HF_2^- anion approximates a covalent bond,[4] it is the C−F group, the so-called "organic fluorine", that does not form hydrogen bonds commensurate with electronegativity considerations, as do the C−O and C−N groups. Glusker and co-workers have been in the forefront of studying intermolecular interactions of the C−F group[5] and have commented upon its hydrogen-bond acceptor capability.[6] Based on Cambridge Structural Database (CSD) studies, these authors concluded that the C−F group is unable to compete favorably with O and N atom acceptors. Recently, Howard et al.[7] and Dunitz and Taylor[8] have undertaken database and computational studies to assess the acceptor capabilities of the C−F group with −OH and −NH donors. These studies are in general agreement with those of Glusker and show that the C−F group is a very poor

---

[†] University of Hyderabad.

[‡] Universität-GH Essen.

(1) For selected reviews that describe the use of hydrogen bonding in crystal engineering, see: (a) Subramanian, S.; Zaworotko, M. J. *Coord. Chem. Rev.* **1994**, *137*, 357. (b) Aakeröy, C. B.; Seddon, K. R. *Chem. Soc. Rev.* **1993**, *22*, 397. (c) Desiraju, G. R. *Crystal Engineering: The Design of Organic Solids*; Elsevier: Amsterdam, The Netherlands, 1989; pp 115−173.

(2) (a) Philp, D.; Stoddart, J. F. *Angew. Chem., Int. Ed. Engl.* **1996**, *35*, 1154. (b) Lehn, J.-M. *Supramolecular Chemistry*; VCH: Weinheim, 1995. (c) Whitesides, G. M.; Simanek, E. E.; Mathias, J. P.; Seto, C. T.; Chin, D. N.; Mammen, M.; Gordon, D. M. *Acc. Chem. Res.* **1995**, *28*, 37. (d) Lawrence, D. S.; Jiang, T.; Levett, M. *Chem. Rev.* **1995**, *95*, 2229.

(3) Pauling, L. *The Nature of the Chemical Bond*; Cornell University Press: Ithaca, NY, 1960.

(4) Harrell, S. A.; McDaniel, D. H. *J. Am. Chem. Soc.* **1964**, *86*, 4497.

(5) (a) Murray-Rust, P.; Stallings, W. C.; Monti, C. T.; Preston, R. K.; Glusker, J. P. *J. Am. Chem. Soc.* **1983**, *105*, 3206. (b) Shimoni, L.; Carrell, H. L.; Glusker, J. P.; Coombs, M. M. *J. Am. Chem. Soc.* **1994**, *116*, 8162.

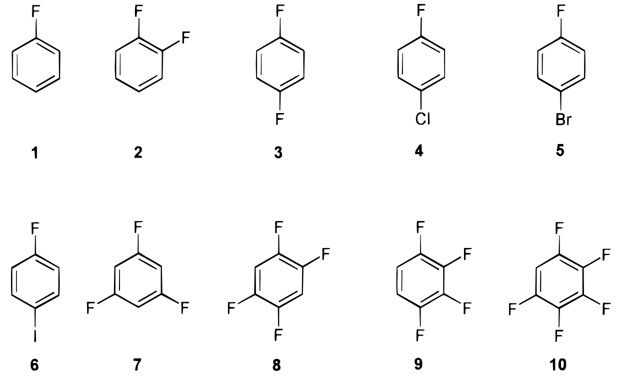
(6) Shimoni, L.; Glusker, J. P. *Struct. Chem.* **1994**, *5*, 383.

(7) Howard, J. A. K.; Hoy, V. J.; O'Hagan, D.; Smith, G. T. *Tetrahedron* **1996**, *52*, 12613.

(8) Dunitz, J. D.; Taylor, R. *Chem. Eur. J.* **1997**, *3*, 89.

S0002-7863(98)01198-6 CCC: $15.00

Scheme 1



acceptor, hardly ever forming hydrogen bonds. However, it should be noted that in these studies of O(N)−H···F−C hydrogen bonds, there is the unavoidable competition from N and O acceptor atoms.[5a]

Weaker hydrogen bonds of the C−H···X−C type have also been increasingly implicated in the stabilization of crystal structures. The C−H group is known to be a hydrogen-bond donor, and C−H···O, C−H···N, and C−H···Cl hydrogen bonds have been used in crystal engineering.[9] This raises the question as to the existence and nature of the C−H···F−C (hereafter C−H···F) hydrogen bond. This is the subject of the present paper. It has been stated that the poor competition of the C−F group with O and N atom acceptors extends to C−H donors.[6] Therefore, in the evaluation of the acceptor capabilities of the C−F group, C−H···F geometries in compounds containing *only* C, H, and F atoms are better candidates. This indeed was the approach adopted by Shimoni and Glusker who concluded from their CSD study[6] that, though C−H···F interactions are weak, they make a contribution to crystal packing. Yet, Howard et al.[7] state that “the predominant C−F···H−C contacts in the Database appear to have very little significance in energy terms and are essentially van der Waals complexes”. The present study is another attempt to characterize the C−H···F interaction: (1) Is it a specific “hydrogen bond” type of interaction or does it merely provide van der Waals stabilization? (2) Can this weak interaction be made a part of a useful supramolecular synthon that is an operative fusing element in crystal architecture? (3) What are the prospects for this interaction in systematic crystal structure design?

Given the elusive nature of the C−H···F interaction, it was clear at the outset that compounds where it might, if at all, be manifested would have to be chosen with care. As stated above, only compounds containing C, H, and F atoms (and no other) are appropriate. Further, the dependence of the strength of the C−H···X interaction on C−H group acidity[9] meant that the selected compounds should have as large a number of acidic C−H groups as possible.[10] Thus, we were led to compounds **1**−**3** and **7**−**10** (Scheme 1). Additionally, compounds **4**−**6** were identified as being closely related to **3**. Fluorobenzenes **1**−**10** are advantageous from several viewpoints. They form a chemically homogeneous set, and all of them contain just a single type of C−H group. Because of the presence of the F substituents on the benzene rings, the acidity of the C−H groups is enhanced. Arguably, the acceptor ability of C(sp^2)−F is not as good as that of C(sp^3)−F.[7] Still, the ease of obtaining compounds **1**−**10** (Aldrich) and the fact that the strength of any hydrogen bond depends more on donor acidity than on acceptor basicity led us to believe that these compounds were worthy of further structural study.

More specifically, the objective of the present work is to rigorously evaluate the role of C−H···F interactions in the crystal structures of compounds **1**−**10**. This study is also important from the viewpoint of establishing the function of the C−F group in crystal packing in that it might help in the understanding of the binding of a fluorinated substrate to a macromolecular receptor.[11] Another aim of this work was to ascertain the importance, if any, of the F···F interaction. It appears, on the basis of CSD and computational studies, that the C−F group does not favor the formation of F···F contacts as do the C−Cl, C−Br, and C−I groups.[12] This difference between F and the other halogens has been noted in several other studies.[10,13] In this paper, evidence is presented for the strongly contrasting behavior of F vis-à-vis the other halogens.

Experimental Section

General Procedure for Crystal Growth. All fluorobenzenes reported in this study were commercially available (Aldrich) and were used for crystal growth as received. Since all of these compounds are liquids, a special crystal growth technique described below was followed.[14] The experimental setup consists of an X-ray diffractometer with an attached low-temperature device for cooling the sample. An IR laser source is set up in such a way that the sample can be heated with the focused laser. The intensity and the position of the laser focus are computer controlled. The liquid sample was loaded into a thin-walled glass capillary (approximately 0.3 mm diameter), and the capillary was then sealed. After placing the capillary on the goniometer, the sample was cooled slowly until it just solidified. The cooling had to be done carefully so as to ensure that the liquid becomes polycrystalline and not glassy, since if this happens, obtaining a single crystal by this procedure is most unlikely. The IR laser was then applied with such an intensity sufficient to partially melt the polycrystalline compound. The laser beam was applied on a very tiny portion (0.1−0.2 mm) of the capillary and then scanned along the length of the capillary *very* slowly (approximately 1 mm/h or less) while the temperature was kept constant. The rate of scanning depends on the nature of the sample and can only be assessed during the experiment. After a few cycles of scanning, the polycrystalline sample transforms into a cylindrical single crystal. Warming of the polycrystalline sample to just below the melting point ensures that the sample is close to the temperature of the maximum crystallization speed. At this stage the quality of the crystal was checked at different positions by X-ray rotation photographs, and the laser experiment was repeated with varying intensities and scan speeds until an X-ray quality single crystal was obtained.

Collecting the data just below the melting point of the sample was obviously difficult and once the single crystals suitable for X-ray data collection were obtained, the temperature was gradually lowered. The data were then collected (Table 1). The integrity of the crystal was checked at regular intervals during the cooling with standard X-ray methods. It must be mentioned that in several instances getting a single

---

[9] For selected reviews that describe the use of weak hydrogen bonding in crystal engineering, see: (a) Desiraju, G. R. *Acc. Chem. Res.* **1991**, *24*, 290. (b) Desiraju, G. R. *Acc. Chem. Res.* **1996**, *29*, 441. (c) Steiner, T. *Cryst. Rev.* **1996**, *6*, 1. (d) Desiraju, G. R. *Science* **1997**, *278*, 404. (e) Desiraju, G. R. *Chem. Commun.* **1997**, 1475.

[10] An interesting recent case of a C−H···F hydrogen bond arising from enhanced C−H acidity is provided by 4-ethynylfluorobenzene. See: Weiss, H.-C.; Boese, R.; Smith, H. L.; Haley, M. M. *Chem. Commun.* **1997**, 2403.

[11] (a) Evans, T. A.; Seddon, K. R. *Chem. Commun.* **1997**, 2023. (b) O’Hagan, D.; Rzepa, H. S. *Chem. Commun.* **1997**, 645 and references therein. (c) Glusker, J. P. *Acta Crystallogr.* **1995**, *D51*, 418.

[12] (a) Desiraju, G. R.; Parthasarathy, R. *J. Am. Chem. Soc.* **1989**, *111*, 8725. (b) Fernández-Castaño, C.; Foces-Foces, C.; Cano, F. H.; Claramunt, R. M.; Escolástico, C.; Fruchier, A.; Elguero, J. *New. J. Chem.* **1997**, *21*, 195.

[13] Brock, C. P.; Kuo, M.; Levy, H. A. *Acta Crystallogr.* **1978**, *B34*, 981.

[14] Nussbaumer, M.; Boese, R. In *Correlations, Transformations, and Interactions in Organic Crystal Chemistry, IUCr Crystallographic Symposia, Vol. 7*; Jones, D. W., Katrusiak, A., Eds.; Oxford University Press: Oxford, 1994; pp 20−37.

Table 1. Crystallographic Data for the Compounds in This Study

	1	**2**	**3**	**7**	**8**	**9a**	**9b**[e]	**10**
emp. form.	C_6H_5F	$C_6H_4F_2$	$C_6H_4F_2$	$C_6H_3F_3$	$C_6H_2F_4$	$C_6H_2F_4$	$C_6H_2F_4$	C_6HF_5
form. wt.	96.10	114.09	114.09	132.08	150.08	150.08	150.08	168.07
mp (K)	231	239	260	267.5	277	231	231	225
T (K)[a]	123(2)	123(2)	215(2)	130(2)	135(2)	123 (2)	153	200(2)
cryst. syst.	tetragonal	monoclinic	monoclinic	monoclinic	monoclinic	monoclinic	monoclinic	monoclinic
space group	$P4_32_12$ (No. 96)	$P2_1/n$ (No. 14)	$P2_1/c$ (No. 14)	$I2/a$ (No. 15)	$P2_1/c$ (No. 14)	$C2/c$ (No. 15)	$P2_1/n$ (No. 14)	$P2_1/c$ (No. 14)
a (Å)	5.799(2)	7.4806(11)	5.809(2)	6.160(2)	4.4719(11)	19.171(3)	6.6955(6)	12.380(3)
b (Å)	5.799(2)	5.9608(9)	6.530(2)	11.909(3)	10.285(2)	6.9496(12)	7.5618(6)	9.910(2)
c (Å)	14.530(7)	11.725(2)	7.190(2)	7.504(2)	6.342(2)	9.207(2)	11.1058(8)	9.880(2)
α (deg)	90	90	90	90	90	90	90	90
β (deg)	90	103.815(11)	101.89(2)	95.47(2)	107.97(2)	116.187(13)	92.818(6)	102.50(3)
γ (deg)	90	90	90	90	90	90	90	90
Z	4	4	2	4	2	8	4	8
V (Å^3)	488.6(4)	507.68(13)	266.88(14)	548.0(3)	277.46(13)	1100.7(4)	561.61(8)	1183.4(4)
D_{calc} (Mg/m^3)	1.306	1.493	1.420	1.601	1.796	1.811	1.775	1.887
F (000)	200	232	116	264	204	592	592	656
2θ range	3.78−30.04	2.94−30.01	3.58−25.03	3.22−27.46	3.92−29.92	2.37−30.12		1.68−27.43
index ranges	$-8 \leq h \leq 0$	$-10 \leq h \leq 4$	$-6 \leq h \leq 6$	$-1 \leq h \leq 7$	$-5 \leq h \leq 5$	$-26 \leq h \leq 25$		$-13 \leq h \leq 13$
	$0 \leq k \leq 8$	$-8 \leq k \leq 8$	$-7 \leq k \leq 7$	$-15 \leq k \leq 15$	$-14 \leq k \leq 14$	$0 \leq k \leq 9$		$0 \leq k \leq 10$
	$0 \leq l \leq 20$	$0 \leq l \leq 16$	$-8 \leq l \leq 5$	$-9 \leq l \leq 9$	$-8 \leq l \leq 0$	$-1 \leq l \leq 12$		$-12 \leq l \leq 0$
R1	0.0407	0.0344	0.0443	0.0419	0.0424	0.0433		0.0344
wR2	0.1056	0.1051	0.1139	0.1092	0.1112	0.1241		0.0912
GOF	1.060	1.055	1.144	1.055	1.085	1.070		1.055
N-total[b]	858	2395	1614	1422	1567	1872		1467
N-indep.[c]	718	1231	476	628	761	1608		1409
N-obsd.[d]	637	1119	378	538	692	1336		1099
variables	44	90	45	49	51	99		208

[a] Temperature of the data collection. [b] *N*-total is the total number of reflections collected. [c] *N*-indep. is the number of independent reflections. [d] *N*-obsd. is the number observed reflections based on the criteria $I > 2\sigma_I$. [e] Data for **9b** is given for comparison.

crystal itself was difficult. Sometimes innumerable attempts were necessary before a suitable crystal was obtained. Maintaining the integrity of the crystal during cooling was equally difficult (probably due to the different expansion factors of glass and the sample which produces mechanical stress in the crystal); this is the reason the data for **1**−**10** were collected at different temperatures. In each instance the data were collected at the best (or only) possible temperature.

X-ray Crystallography. The X-ray data were collected on a Nicolet R3 diffractometer using Mo $K\alpha$ radiation, corrected for the cylindrical shape of the crystal, and the structure solution and refinement were carried out using the SHELXS-86[15a] and SHELXL-93[15b] programs. In all structures reported in this paper (**1**−**3** and **7**−**10**), the H atoms were located from difference Fourier maps and were refined isotropically. Table 1 gives the salient details of crystallographic results, and further details are provided in the Supporting Information.

Retrieval of C−H···F Geometries. The October 1997 release of the CSD,[16] consisting of 175 093 entries, was used to retrieve C−H···F interactions. A database subset was made for error and disorder free structures consisting only of the elements C, H, and F with *R* 0.10 and for which the atom coordinates field is present (screens 32, 35, 88, and 153). Duplicate entries with higher *R* values were removed. Subsequent searches were made on these database subset. The C−H bond lengths were normalized to the standard neutron distance. All H···F distances 3.0 Å were retrieved in a C−H···F angle range of 100−180°.

Results and Discussion

General Considerations. Repeated reference has been made in the literature to the presence of C−H···F interactions with only limited descriptions as to what these interactions really are.[17] A working hypothesis here is that if the C−H···F interaction is of the hydrogen-bond type, its structural consequences should be similar to those of C−H···O and C−H···N interactions, the archetypes of the weak hydrogen bond.[18] An analysis of the similarities and differences between C−H···F and C−H···O/C−H···N situations will therefore be found throughout this paper. Comparisons have been made between the structures of fluorobenzenes **1**−**10** and topologically similar structures stabilized by C−H···O and C−H···N hydrogen bonds. Such comparisons are simplified by the identification of supramolecular synthons **I**−**IV** (Scheme 2).[19] These synthons, based on C−H···F interactions, are topologically similar to well-known C−H···O- and C−H···N-based synthons. Their structural significance will become apparent in the course of the discussion.

Fluorobenzene, 1, and Its Close Relationship to Pyridinium Fluoride, Pyridine 1-Oxide, and Benzonitrile. In crystalline fluorobenzene, **1**, ($P4_32_12$) molecules are bisected by the 2-fold axis along [001] (Figure 1a) and the symmetry-related *o*-H atoms are involved in C−H···F interactions (2.47 Å, Table 2). The C−F group acts as a bifurcated acceptor. In effect, each molecule is linked to four neighbors via mutually perpendicular C−H···F-mediated helices along [100] and [010]. The *m*-H atoms form C−H···π interactions[20] (C···π, H···π, C−H···π; 3.57 Å, 2.73 Å, 134.5°; π is the centroid of the

---

[15] (a) Sheldrick, G. M. *Acta Crystallogr.* **1990**, *A46*, 467. (b) Sheldrick, G. M. *SHELXL-93 Program for the Refinement of Crystal Structures*; University of Göttingen, Germany.

[16] Allen, F. H.; Davies, J. E.; Galloy, J. J.; Johnson, O.; Kennard, O.; Macrae, C. F.; Mitchell, E. M.; Mitchell, G. F.; Smith, J. M.; Watson, D. G. *J. Chem. Inf. Comput. Sci.* **1991**, *31*, 187.

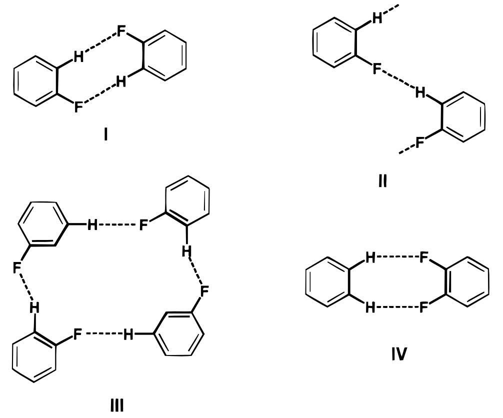
[17] (a) Swift, J. A.; Pal, R.; McBride, J. M. *J. Am. Chem. Soc.* **1998**, *120*, 96. (b) Helmle, O.; Csöregh, I.; Weber, E.; Hens, T. *J. Phys. Org. Chem.* **1997**, *10*, 76. (c) Fei, X.; Hui, Y.-Z.; Rüdiger, V.; Schneider, H.-J. *J. Phys. Org. Chem.* **1997**, *10*, 305. (d) Corey, E. J.; Rohde, J. J.; Fischer, A.; Azimioara, M. D. *J. Am. Chem. Soc.* **1997**, *38*, 333. (e) Schwiebert, K. E.; Chin, D. N.; MacDonald, J. C.; Whitesides, G. M. *J. Am. Chem. Soc.* **1996**, *118*, 4018. (f) Kumar, V. A.; Begum, N. S.; Venkatesan, K. *J. Chem. Soc., Perkin. Trans. 2* **1993**, 463. (g) Kumar, V. A.; Venkatesan, K. *J. Chem. Soc., Perkin. Trans. 2* **1993**, 2429. (h) Williams, J. F.; Cockcroft, J. K.; Fitch, A. N. *Angew. Chem., Int. Ed. Engl.* **1992**, *31*, 1655.

[18] Such a comparison, in which the donor is always the same whereas the acceptor groups (O, N, and F) are varied, is expected to be important in validating the acceptor properties of the C−F group.

[19] Desiraju, G. R. *Angew. Chem., Int. Ed. Engl.* **1995**, *34*, 2311.

[20] (a) Madhavi, N. N. L.; Katz, A. K.; Carrell, H. L.; Nangia, A.; Desiraju, G. R. *Chem. Commun.* **1997**, 1953. (b) Weiss, H.-C.; Bläser, D.; Boese, R.; Doughan, B. M.; Haley, M. M. *Chem. Commun.* **1997**, 1703.

Scheme 2



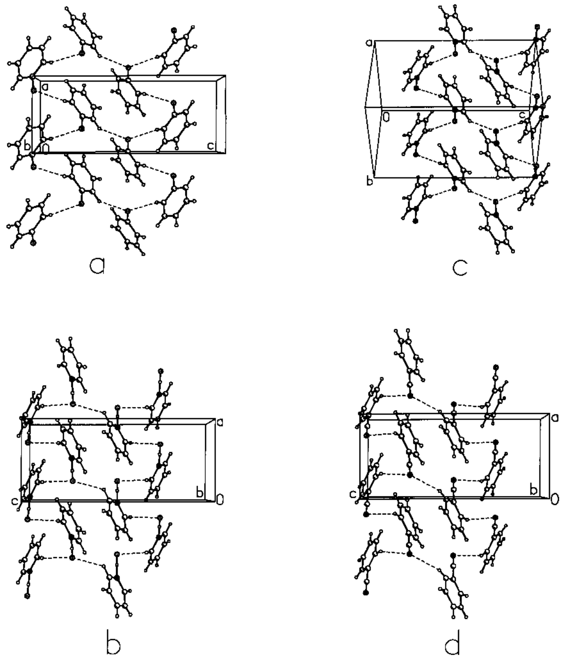


Figure 1. Structural similarity between **1** and PyHF, PyNO, and PhCN. (a) C−H···F-mediated helices in the crystal structure of **1**. Helices along [100] are shown horizontal. Helices along [010] are reduced to a single interaction for clarity; thus, only three of the four near neighbors are shown. (b−d) C−H···F⁻-, C−H···O-, and C−H···N-mediated helices in PyHF, PyNO, and PhCN, respectively. Notice the similarity between all structures.

Table 2. C−H···F Interactions in the Crystal Structures of **1**−**10**[a]

compd	interaction	H···F (Å)	C···F (Å)	C−H···F (deg)
1	C2−H2···F1	2.47	3.38	140.3
2	C4−H4···F2	2.64	3.34	122.0
	C5−H5···F1	2.58	3.52	145.0
3	C2−H2···F1	2.68	3.57	139.2
	C3−H3···F1	2.49	3.46	148.4
4	C13−H13···F11	2.44	3.46	156.5
	C23−H23···F33	2.50	3.53	159.1
	C33−H33···F22	2.41	3.37	148.3
5	C31−H31···F12	2.50	3.54	161.3
	C32−H32···F11	2.42	3.41	151.9
6	C3−H3···F1	2.56	3.41	134.5
7	C2−H2···F1	2.62	3.40	127.8
	C2−H2···F3	2.45	3.44	151.3
	C4−H4···F3	2.50	3.42	142.7
8	C2−H2···F3	2.36	3.38	156.8
9a	C5−H5···F3	2.57	3.64	173.5
	C6−H6···F2	2.58	3.35	127.1
	C6−H6···F1	2.49	3.52	159.6
9b	C5−H1···F3	2.65	3.51	136.2
	C6−H2···F2	2.64	3.40	127.1
	C6−H2···F4	2.50	3.56	164.5
10	C6−H1···F12	2.63	3.64	155.5
	C6−H1···F15	2.86	3.57	122.7
	C6−H1···F11	2.78	3.46	120.4
	C16−H11···F4	2.64	3.57	143.5
	C16−H11···F1	2.60	3.32	123.4
	C16−H11···F2	2.73	3.65	143.4

[a] All C−H bond lengths are normalized to 1.08 Å.

aromatic ring) that link adjacent C−H···F helices. No short C···F or F···F interactions are found (shortest C···F and F···F distances are 3.37 and 4.73 Å).

In **1**, the possible intermolecular contacts are C···C (stacking), C···H (herringbone), C···F (dipole···dipole), H···F (hydrogen bond), and F···F (close-packing or polarization). In reality, the only short intermolecular contacts found are the C−H···F interactions. Do these influence the crystal packing? In this context it is relevant to compare the structure of **1** with those of pyridinium fluoride (PyHF),[21] pyridine 1-oxide (PyNO),[22] and benzonitrile (PhCN).[23] These structures (Figures 1b−d) are constructed respectively with C−H···F⁻, C−H···O, and C−H···N hydrogen bonds and bear a close similarity to **1**.

PyHF (Figure 1b) belongs to space group $P4_12_12$ which is enantiomorphous to $P4_32_12$. Here, too, molecules are bisected by the 2-fold axis and both *o*-H atoms act as hydrogen bond donors, now in C−H···F⁻ (2.52 Å) interactions[24] forming interconnected and perpendicular helices along [100] and [010]. Indeed, PyHF and **1** are isostructural (except for the difference in handedness). PyNO (Figure 1c) has been described in the space group $C222_1$ with two symmetry-independent molecules, each bisected by a distinct 2-fold axis. Here again, all *o*-H atoms are involved in the formation of C−H···O hydrogen bonds with perpendicular and interlinked C−H···O-mediated helices. An inspection of Figure 1(a and c) will show that PyNO and **1** are structurally very similar. Finally, PhCN (Figure 1d) belongs to space group $P4_12_12$ and is isostructural to **1** (except for the handedness). Here, C−H···N hydrogen bonds substitute for the C−H···F interactions.

The structural similarity at this very fine level, that is, at the level of individual interactions, between **1** on one hand and PyHF, PyNO, and PhCN on the other, indicates that the nature and character of the structure-determining intermolecular interactions in these four structures *are identical*. There is no argument that inorganic fluoride is one of the best hydrogen-bond acceptors. So the C−H···F⁻ interaction in PyHF is an attractive and significant hydrogen bond.[24] The nature and strength of C−H···O and C−H···N hydrogen bonds are well-documented, and these interactions are shown to control the crystal packing in many instances.[25] Their respective roles in the structures of PyNO and PhCN parallel that of C−H···F⁻ in PyHF. It may be adduced thus that the C−H···F interaction,

---

[21] Boenigk, D.; Mootz, D. *J. Am. Chem. Soc.* **1988**, *110*, 2135.

[22] Ulku, D.; Huddle, B. P.; Morrow, J. C. *Acta Crystallogr.* **1971**, *B27*, 432. The H atoms were not located in the reported structure and have been inserted by us in calculated positions. Though this structure has been reported in the orthorhombic space group $C222_1$, we found that it can be represented better in the tetragonal system.

[23] Fauvet, G.; Massaux, M.; Chevalier, R. *Acta Crystallogr.* **1978**, *B34*, 1376.

[24] (a) Grepioni, F.; Cojazzi, G.; Draper, S. M.; Scully, N.; Braga, D. *Organometallics* **1998**, *17*, 296. (b) Ashton, P. R.; Fyfe, M. C. T.; Glink, P. T.; Menzer, S.; Stoddart, J. F.; White, A. J. P.; Williams, D. J. *J. Am. Chem. Soc.* **1998**, *120*, 12514. (c) Kiplinger, J. L.; Arif, A. M.; Richmond, T. G. *Inorg. Chem.* **1995**, *34*, 399. (d) Kiplinger, J. L.; Richmond, T. G.; Arif, A. M.; Dücker-Benfer, C.; van Eldik, R. *Organometallics* **1996**, *15*, 1545.

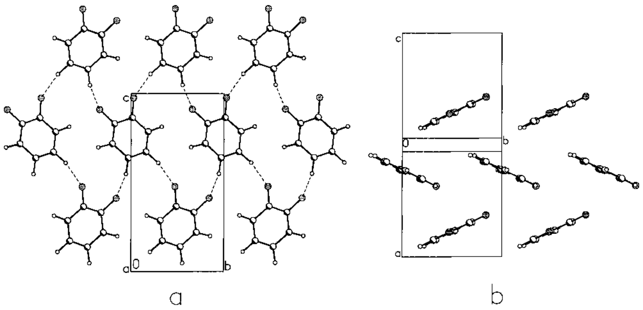


Figure 2. Crystal structure of **2**. (a) C−H···F catemer structure. Alternating molecules provide C−H and C−F groups. (b) Herringbone arrangement of molecules in **2** similar to that found in benzene.

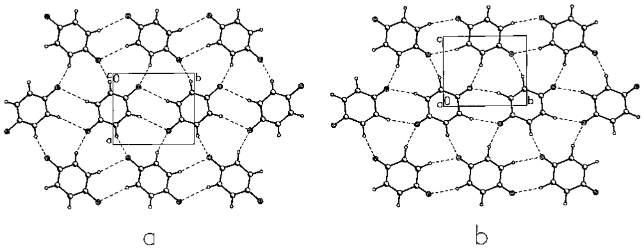


Figure 3. Structural similarity between **3** and BQ. (a) Corrugated layer structure parallel to (10$\bar{2}$) in **3**. Notice synthons **I** and **II**. (b) Flat layers stabilized by C−H···O hydrogen bonds in the crystal structure of BQ. Notice the C−H···O dimers and catemers.

albeit probably weaker, in **1** is likewise important in the adoption of the observed crystal structure.

It is now instructive to compare the crystal structures of **1** and chlorobenzene. These packings are completely different, suggesting the differing behavior of C−F and C−Cl groups. In chlorobenzene, Cl···Cl and herringbone interactions contribute to the major stabilization.

Herringbone Packing in the Crystal Structure of 1,2-Difluorobenzene, 2. The space group is $P2_1/n$. Screw-related molecules are connected by C−H···F interactions (2.58 and 2.64 Å, Table 2) giving catemeric chains along [010] as shown in Figure 2a. The structure is replete with many other weak C−H···F interactions but herringbone interactions predominate, and the overall packing (Figure 2b) is similar to that of benzene, in the manner of 2-aminophenol, another *o*-disubstituted benzene that some of us have discussed recently elsewhere.[26]

Similarity between 1,4-Difluorobenzene, 3, and 1,4-Benzoquinone and Its Relationship to Other Symmetrical and Unsymmetrical 1,4-Dihalogenated Benzenes, 4−6. All H atoms in **3** are involved in C−H···F interactions (2.68 and 2.49 Å, Table 2, Figure 3a) that generate dimer and catemer synthons **I** and **II** (Scheme 2). Molecules translated along [010] are linked by synthon **I** and form linear tapes. Adjacent screw axis related tapes (space group $P2_1/c$, $Z = 2$) are connected by synthon **II** to generate a corrugated layer structure parallel to (10$\bar{2}$). These corrugated layers are held together by weak herringbone interactions along [001] to complete the three-dimensional structure.

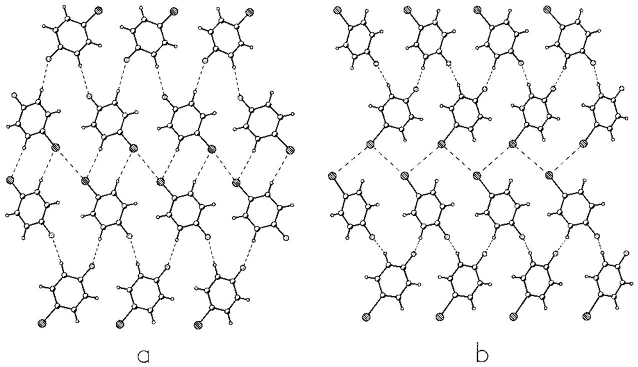


Figure 4. Crystal structures of **4** and **6**. (a) Layer structure in **4**. Two such symmetry independent layers are observed in the structure. A similar layer structure is also found in **5**. (b) Alternating C−H···F catemer synthons **II**, and type II I···I interactions in the corrugated layer structure in **6**.

A comparison of the crystal structures of **3** and 1,4-benzoquinone (BQ)[27] is revealing. BQ adopts space group $P2_1/a$ ($Z = 2$), and C−H···O-mediated dimers and catemers topologically similar to **I** and **II** may be identified. C−H···O dimer mediated tapes are linked by C−H···O catemers to produce a perfectly flat layer structure (Figure 3b). It is evident from Figure 3(a and b) that C−H···F interactions and C−H···O hydrogen bonds produce similar supramolecular synthons which lead to similar supramolecular structures (tapes and layers) in **3** and BQ.

The structure of **3** may be contrasted with those of other 1,4-dihalobenzenes.[28] 1,4-Dichlorobenzene exists in triclinic (β-form) and monoclinic (α- and γ-forms) modifications that are in part stabilized by type-I and type-II Cl···Cl interactions, respectively.[29] The cell dimensions and symmetry of 1,4-dibromobenzene are similar to and several forms of 1,4-diiodobenzene are closely related to the α- and γ-forms of 1,4-dichlorobenzene. All of these structures are distinct from **3**, which is stabilized by C−H···F interactions. While the structures of the other 1,4-dihalobenzenes show X···X (hereafter, X = Cl, Br, or I) interactions, significant F···F interactions are not favored in **3**. With its ability to form attractive C−H···F interactions, **3** resembles BQ rather than the other 1,4-dihalobenzenes.

An interesting structural excursion is provided by a comparison of the structure of **3** with those of 4-chlorofluorobenzene, **4**, 4-bromofluorobenzene, **5**, and 4-iodofluorobenzene, **6**.[30] The C−H···F catemer synthon **II** is present in all three crystal structures and is identical to that observed in **3**. Figure 4(a and b) show that this catemer synthon is well-insulated from other X···X patterns, characteristic only of the heavier halogens. So, while type-II I···I interactions are found in **6** (Figure 4b), both type-I and type-II Cl···Cl and Br···Br interactions are found in **4** and **5** respectively (Figure 4a shows only the type-I interac-

---

(25) (a) Thalladi, V. R.; Panneerselvam, K.; Carrell, C. J.; Carrell, H. L.; Desiraju, G. R. *J. Chem. Soc., Chem. Commun.* **1995**, 341. (b) Reddy, D. S.; Goud, B. S.; Panneerselvam, K.; Desiraju, G. R. *J. Chem. Soc., Chem. Commun.* **1993**, 663. (c) Thalladi, V. R.; Brasselet, S.; Bläser, D.; Zyss, J.; Boese, R.; Nangia, A.; Desiraju, G. R. *Chem. Commun.* **1997**, 1841.

(26) Allen, F. H.; Hoy, V. J.; Howard, J. A. K.; Thalladi, V. R.; Desiraju, G. R.; Wilson, C. C.; McIntyre, G. J. *J. Am. Chem. Soc.* **1997**, *119*, 3477.

(27) Trotter, J. *Acta Crystallogr.* **1960**, *13*, 86.

(28) Britton, D. *Acta Crystallogr.* **1976**, *B32*, 976.

(29) A halogen···halogen contact C−X···X−C is defined as type I if the C−X···X angle θ_1 is equal or nearly equal to the X···X−C angle θ_2. If $\theta_1 \approx 180°$ and $\theta_2 \approx 90°$, the contact is defined as type II. See: Ramasubbu, N.; Parthasarathy, R.; Murray-Rust, P. *J. Am. Chem. Soc.* **1986**, *108*, 4308.

(30) The structures of **4**, **5**, and **6** have three, two, and one molecules in the asymmetric unit, and a detailed structural description based on various kinds of intermolecular interactions is outside the scope of this paper and will be presented elsewhere (Kirchner, M.; Weiss, H.-C.; Boese, R. Unpublished results). These structures are considered in this paper to the extent that they contain C−H···F interactions. Salient crystallographic details are as follows. For **4**: monoclinic, $P2_1/n$ (No. 14), $a = 14.182(8)$, $b = 5.978(4)$, and $c = 20.271(13)$ Å, $\beta = 101.09(5)°$, $Z = 12$, $T = 125$ K. For **5**: monoclinic, $P2_1/c$ (No. 14), $a = 8.772(4)$, $b = 6.044(5)$, and $c = 22.149(7)$ Å, $\beta = 93.61(3)°$, $Z = 8$, $T = 125$ K. For **6**: monoclinic, $P2_1$ (No. 4), $a = 4.2000(8)$, $b = 5.6800(11)$, and $c = 13.590(3)$ Å, $\beta = 98.67(3)°$, $Z = 2$, $T = 120$ K.

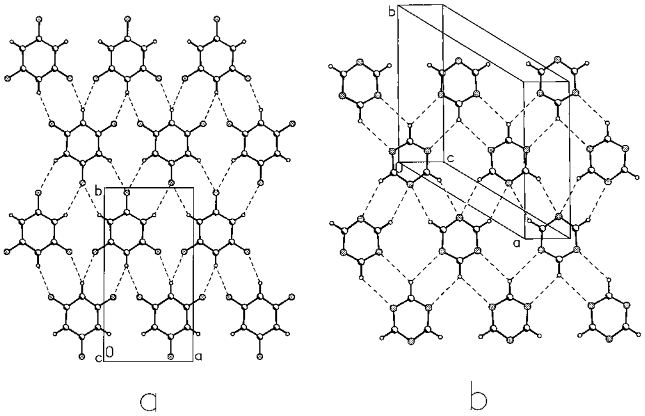


Figure 5. Structural similarity between **7** and 1,3,5-triazine. (a) Two cross-linked synthon **I** mediated tapes in the crystal structure of **7**. The third tape is not shown for clarity. Notice the bifurcation at H and F atoms. (b) C−H···N dimer mediated cross-linked tapes in the structure of triazine. Notice the similarity between the two structures.

tions). Notably, no short F···F contacts are observed in any of the three structures and the shortest F···F distances in **4**, **5** and **6** are 3.34, 3.38, and 3.41 Å, respectively. An alternation of synthon **II** with these halogen···halogen interactions and C−H···Cl/C−H···Br dimers in **4**/**5** results in a layer structure and the three-dimensional structure is completed by appropriate stacking and herringbone arrangements.

Despite other variations in structures **4**−**6**, the C−H···F-based synthon **II** remains intact. This synthon is, in effect, sufficiently robust in the presence of the well-known type-I and type-II Cl···Cl, Br···Br, and I···I interactions. It, therefore, either gives rise to the dominant pattern in these structures or, at least, is immune to the interference from the X···X interactions and the putative F···F interaction that is not seen at all. Indeed, one of the conclusions of this work is that such an F···F interaction is not a realistic structural possibility in a general sense.[31] Compounds **3**−**6** offer ample scope for such an interaction to manifest itself, and its absence shows that it is unable to compete with the C−H···F interaction. In that such a viability of the C−H···F interaction is demonstrated, one could infer that there are specific, electrostatic reasons for this. Hints along these lines were obtained a decade ago by one of us,[12a] but the present study offers direct experimental evidence for the importance of the C−H···F interaction and of synthons based on this interaction.

1,3,5-Trifluorobenzene, 7, and 1,3,5-Triazine and the Identical Role of C−H···F Interactions and C−H···N Hydrogen Bonds in These Crystal Structures. The molecule of 1,3,5-trifluorobenzene, **7**, (*I*2/*a*) is bisected by the 2-fold axis. Each H and F atom is involved in the formation of two C−H···F interactions, or in other words, bifurcation occurs at every atom. Each molecule is connected to six neighbors through synthon **I**. This extends to three cross-linked, synthon **I** mediated tapes, two of which are shown in Figure 5a. In effect, the three-dimensional structure is extensively stabilized by C−H···F interactions (2.45, 2.50, and 2.62 Å, Table 2).[32] The reader will note that as one moves along the series **1**−**10** toward the more F-rich molecules, the relative importance of C−H···F interactions increases, and in **7**, for instance, this is mostly the only interaction of significance. The structure of **7** is clearly understood then as a result of the enhanced C−H acidity brought about by increasing the number of F-substituents and of the availability of a matching number of C−F acceptors. In this light, it is not at all difficult to appreciate the close similarity between **7** and the classical structure of 1,3,5-triazine[33] ($R\bar{3}$, $Z = 3$; Figure 5b) wherein each molecule is linked to six neighbors through C−H···N dimers. Here too, three cross-linked, now C−H···N dimer mediated, tapes may be identified. Specifically, the following similarities may be noted between **7** and *sym*-triazine: (i) both have similar molecular features in terms of the number and relative disposition of hydrogen-bond donor and acceptor groups; (ii) these groups are utilized in the same manner and 12 short hydrogen-bond type interactions (C−H···F, C−H···N) per molecule are observed in both cases; (iii) each molecule is connected to six neighbors through topologically similar supramolecular synthons and in an identical manner; (iv) antiparallel stacking of molecules is seen in both structures. This close similarity between **7** and *sym*-triazine indicates that the C−H···F interactions in **7** and the C−H···N hydrogen bonds in *sym*-triazine play a very similar role in supramolecular assembly in the respective cases. In a very early review on weak hydrogen bonding, Bernstein, Cohen, and Leiserowitz[34] emphasized (prophetically) that, for such interactions, it is the repetitiveness of a certain pattern that is more significant than the geometrical attributes. With the hindsight of many examples over the last two decades, this repetitiveness has been extended to include similarities in topology and network structure using concepts such as supramolecular synthons,[19] graph sets,[35] and other models, and it is in this context that one is able to discern more clearly the hydrogen bond like properties of the C−H···F interaction.

Near Similarity of 1,2,4,5-Tetrafluorobenzene, 8, and 1,2,4,5-Tetrazine. The molecule of **8** lies on an inversion center ($P2_1/c$, $Z = 2$), and the two symmetry-related H atoms form short C−H···F interactions (2.36 Å, Table 2). Each molecule is thus connected to four neighbors as shown in Figure 6a. This defines synthon **III** that mediates in the formation of corrugated layers roughly parallel to $(10\bar{2})$.[36] The close-packing of these layers leads then to the three-dimensional structure. As was observed for **7** and 1,3,5-triazine, the structures of **8** and 1,2,4,5-tetrazine[37] (Figure 6b) are indeed very similar. Corrugated layers based on C−H···N interactions are seen in the tetrazine and are topologically similar to those found in the structure of **8**.[38] This similarity further strengthens the argument that C−H···F interactions determine crystal packing as do C−H···N interactions and, in this respect, provides additional evidence for their description as weak hydrogen bonds. Along these lines, it should be noted that the C−H···F interaction in the structure of **8** is the shortest among those found in this study.

---

[31] We are stating here that even when a short type-I F···F geometry is seen, it is only as a result of close-packing or it may even be repulsive. Such a conclusion is further strengthened by the fact that type-II F···F contacts are rarely seen, if at all (see: Thalladi, V. R.; Weiss, H.-C.; Boese, R.; Nangia, A.; Desiraju, G. R. To be submitted).

[32] The other *sym*-trihalobenzenes are isostructural but quite different from **7**. These structures are fully stabilized by type-II X···X interactions showing again the distinctive behaviour of F vis-à-vis the heavier halogens. (a) For 1,3,5-trichlorobenzene and 1,3,5-tribromobenzene, see: Milledge, H. J.; Pant, L. M. *Acta Crystallogr.* **1960**, *13*, 285. (b) For 1,3,5-triiodobenzene, see: Thalladi, V. R.; Hoy, V. J.; Howard, J. A. K.; Allen, F. H.; Desiraju, G. R. Unpublished results.

[33] Coppens, P. *Science* **1967**, *158*, 1577.

[34] Bernstein, J.; Cohen, M. D.; Leiserowitz, L. In *The Chemistry of Quinonoid Compounds*; Patai, S., Ed.; Interscience: New York, 1974; p 37.

[35] Bernstein, J.; Davis, R. E.; Shimoni, L.; Chang, N.-L. *Angew. Chem., Int. Ed. Engl.* **1995**, *34*, 1555.

[36] It is interesting to note that the tetramer synthon **III** is also observed in the structure of **3**, a molecule that contains the complementary number and location of hydrogen-bond donors and acceptors.

[37] Bertinotti, F.; Giacomello, G.; Liquori, A. M. *Acta Crystallogr.* **1956**, *9*, 510.

[38] Unsurprisingly, these structures do not resemble those of 1,2,4,5-tetrachloro- or -tetrabromobenzene.

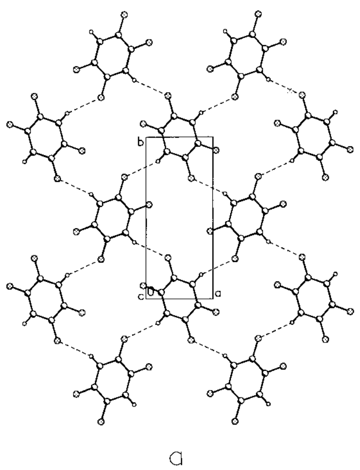


Figure 6. Structural similarity between **8** and 1,2,4,5-tetrazine. (a) Corrugated layer structure formed by synthon **III** in **8**. (b) Similar structure formed by topologically similar C−H···N synthons in tetrazine.

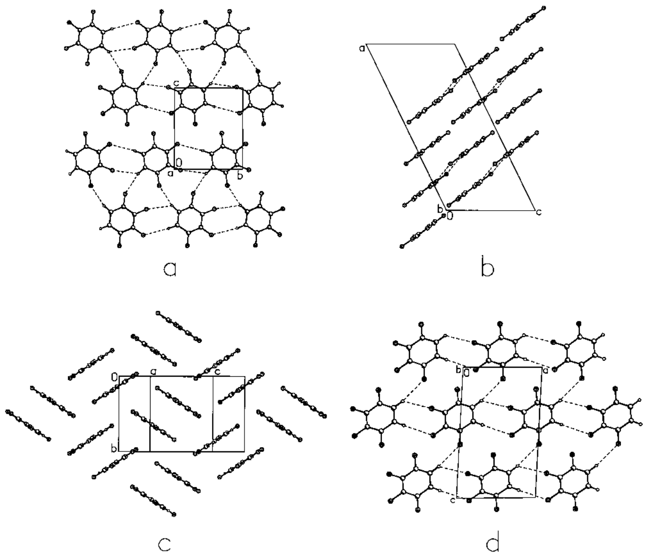


Figure 7. Polymorphism in 1,2,3,4-tetrafluorobenzene, **9**. (a) Experimental $C2/c$ structure (this study) to show tape and layer structures. Notice synthons **II** and **IV**. (b) Experimental $C2/c$ structure to show stacking of layers. (c) Experimental $P2_1/n$ structure[39] to show the sandwich herringbone arrangement. (d) Experimental $P2_1/n$ structure to show the tape arrangements. Notice the similarity to a.

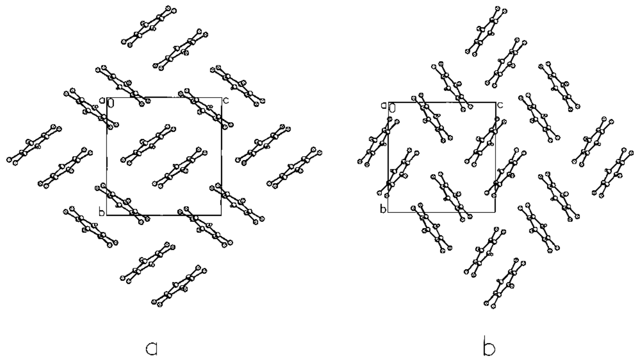


Figure 8. Crystal structure of **10** showing sandwich herringbone packing of molecules. Symmetry independent molecules form alternating independent layers at different heights along [100]. The layers shown in a and b are present at (100) and (200), respectively.

This is as might have been expected if the strength of a C−H···F interaction increases with increasing acidity and hardness of the H atom. In general, C−H···O and C−H···N hydrogen bonds are considered to arise from the interactions between a soft donor (C−H) and a soft acceptor (O or N). The F atom in the C−F group is, however, a hard acceptor, and this could be one of the reasons why it does not form very effective C−H···F hydrogen bonds. The hardness of the H atoms in compounds **1**−**10** (in addition to their acidity) could well promote the formation of short C−H···F hydrogen bonds in this structural family.

Polymorphism in 1,2,3,4-Tetrafluorobenzene, 9. Crystals grown from the pure liquid and as described in the Experimental Section were found to belong to space group $C2/c$ ($Z = 8$). This form is labeled **9a**, and X-ray data were collected at 123 K. We noted later that another form, **9b**, ($P2_1/n$, $Z = 4$) had been obtained by others from 1:3 toluene−pentane at 195 K, and the crystal structure was determined at 153 K.[39] Interestingly, C−H···F interactions are important in both polymorphs. Layers parallel to $(30\bar{1})$ are observed in **9a** (Figure 7a). Both H atoms in the molecule, one of them bifurcated, participate in C−H···F interactions (2.49, 2.57, and 2.58 Å, Table 2). Molecules translated along [010] are connected by synthon **IV** to form tapes. Adjacent glide related tapes are held together in pairs by synthon **II**. Successive pairs of tapes are inversion related (but not connected with C−H···F interactions) to generate the layer. Stacking along [100] gives the three-dimensional structure (Figure 7b). In **9b**, antiparallel stacking of molecules leads to stacked centrosymmetric diads. The packing of these diads in a sandwich herringbone fashion (pyrene structure) also produces a layer (Figure 7c).[40] However, in this case the planes of the molecules are nearly perpendicular to the layer. The interlayer packing is governed by C−H···F interactions (Figure 7d) with both the H atoms involved and with one of them being bifurcated (2.50, 2.64, and 2.65 Å, Table 2). Successive screw axis related synthon **IV** based tapes are linked with additional C−H···F interactions.

Synthon **IV** is identified in both forms and linear tapes based on this synthon constitute a significant portion of the respective structures. Though the packing of these tapes is different in the two forms, it is the C−H···F interactions that are utilized for this purpose. All in all, the C−H···F interactions seem to play an important and similar role, similar in that the same synthons are seen in both cases (compare Figure 7(a and d)), though the final structures are different (contrast Figure 7(b and c)).

To further gauge the significance of these structures, as concerned as we were that one or both of them might be kinetically locked in, ab initio predictions were attempted with the Polymorph Predictor module in the Cerius^2 program.[41,42] The prediction was carried out in each of the observed space groups, and in each case, a structure was obtained that closely matched the experimental structure. Both of the predicted

---

(39) Kottke, T.; Sung, K.; Lagow, R. J. *Angew. Chem., Int. Ed. Engl.* **1995**, *34*, 1517.

(40) Note that such packing is similar to that observed in the crystal structure of pyrene. See: Desiraju, G. R.; Gavezzotti, A. *J. Chem. Soc., Chem. Commun.* **1989**, 621.

(41) (a) Cerius^2 Program, Molecular Simulations, 9685 Scranton Road, San Diego, CA 92121-3752, and 240/250 The Quorum, Barnwell Road, Cambridge CB5 8RE, UK. (b) For a description of the polymorph prediction sequence used by the program, see: Gdanitz, R. J. In *Theoretical Aspects and Computer Modeling of the Molecular Solid State*; Gavezzotti, A., Ed.; Wiley: Chichester, 1997; pp 185−202.

(42) Molecular minimizations were performed with the AM1 Hamiltonian in Mopac 6.0 and ESP charges were assigned. The Dreiding 2.21 force field was used for all calculations involved in the prediction. The prediction sequence was repeated twice to check its reproducibility.

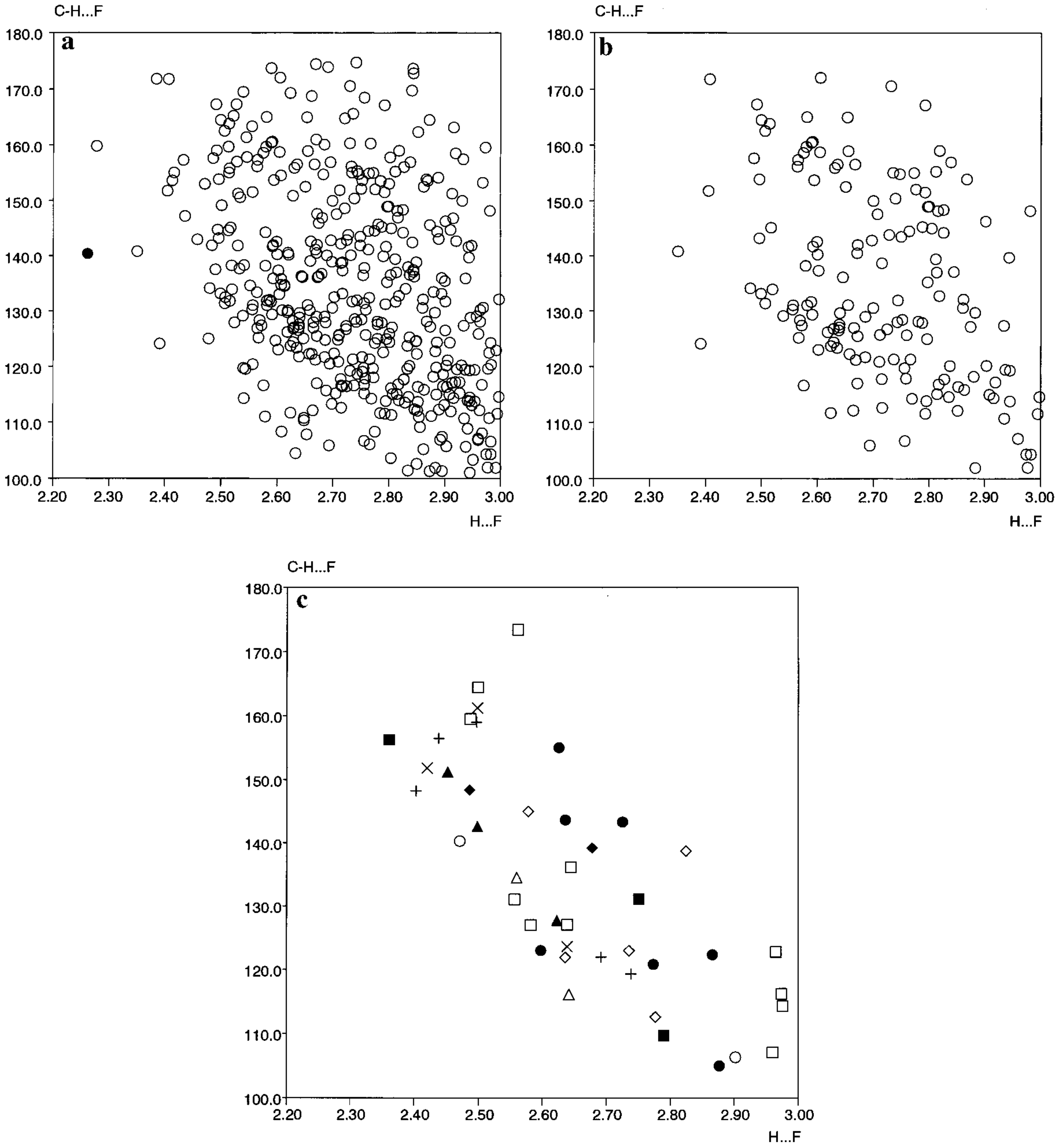


Figure 9. Scatterplots of H···F distances versus C−H···F angles for C−H···F interactions. (a) Interactions between any C−H and any C−F group in the CSD (433 observations). The ≡C−H···F interaction in 4-fluoroethynylbenzene[10] is marked as ●. (b) Interactions between C(sp^2)−H and C(sp^2)−F groups in the CSD (155 observations). (c) Interactions found in the present study (○, **1**; ◇, **2**; ◆, **3**; △, **4**; ×, **5**; +, **6**; ▲, **7**; ■, **8**; □, **9a**, **9b**; ●, **10**). Notice the contrast between the wide scatter of points in a and b and the narrow band in c. Table 2 contains only some of the interactions shown here.

structures contain synthon **IV** mediated tapes.[43] That polymorphism is obtained in this system could have to do with the fact that the temperature of crystal growth is different in the two cases.

Sandwich Herringbone Packing in the Crystal Structure of Pentafluorobenzene, 10. In this F-rich molecule, the C−H group is trifurcated between three C−F groups. There are two symmetry-independent molecules ($P2_1/c$, $Z = 8$), and each forms a stacked centrosymmetric diad as in **9b** (Figure 8). The assembly of 2_1-related diads in a sandwich herringbone fashion leads to alternating, symmetry-independent layers parallel to (100). Interlayer packing is stabilized by C−H···F interactions (2.60−2.86 Å, Table 2). In hindsight, **9b** and **10** seem to adopt the same crystal structure because their large dipole moments favor the antiparallel diad as the primary structural motif.

Hydrogen-Bond Nature of the C−H···F Interactions in Fluorobenzenes 1−10. As mentioned at the outset, the C−H···F interaction is generally weak and does not play a significant structural role in crystal packing because of the presence of acceptors that are stronger and more polarizable than the C−F group. A set of compounds that contains only C, H, and F atoms is therefore more appropriate to assess the viability of this interaction. Accordingly, the crystal structures of **1**−**10** have been determined and analyzed. It is now pertinent to compare the C−H···F interactions in these crystal structures with all others in the CSD that contain only C, H, and F atoms.

---

[43] The prediction in $C2/c$ resulted in perfectly flat layers as observed in **9a**, with the packing of molecules within and between the layers identical to that found in the experimental structure. The prediction in $P2_1/n$ reproduced the diads and the general sandwich herringbone packing as seen in **9b**.

Consider the scatterplots of H···F distances, d versus C−H···F angles, θ shown in Figure 9 (a and b). There is no real difference between these scatterplots. Generally, there is some kind of inverse correlation between length and angle but there are many points in the top right-hand corner of these plots that simply add to the crystallographic noise. Some of these correspond to bifurcated interactions but no specific conclusion may be drawn on this or any other basis. In contrast, Figure 9c, which is the corresponding $d - \theta$ scatterplot for the compounds in this study, shows a strong inverse correlation that is very characteristic of hydrogen bonding. The top right-hand corner is now completely empty, suggesting convincingly that when a C−H···F geometry is present in these compounds, it is there for a chemical reason. Table 2 shows that the H···F distances decrease systematically with increasing C−H group acidity. Compounds **7** and **8** are especially noteworthy in this regard. An inspection of the plots Figure 9(a−c) reveals that *only when the carbon acidity is enhanced to the levels of the compounds in the present study and only in the absence of competing acceptors is the hydrogen-bond nature of the C-H···F interaction even revealed.*

The question of polymorphic structures needs some further clarification. We note that of all of the compounds studied here, only for **9** has another polymorph been characterized. Further, the polymorph was reported by another group. Would polymorphs be found for the other compounds studied here in due course and if so, would the conclusions arrived at here have to be modified? Answers to such questions are difficult but what is of significance is that the interaction of interest, namely the C−H···F hydrogen bond is found in both polymorphs of **9** and that both conform to the trend shown in Figure 9c. As for the other compounds, their crystal structures display such a striking similarity to the C−H···O and C−H···N analogues that one may confidently state that C−H···F geometries seem to display the structure-directing characteristics of weak hydrogen bonds. In particular, it is this resemblance to C−H···O and C−H···N hydrogen bonds that suggests that the C−H···F hydrogen bond may be used in synthetic strategies for crystal engineering.

Conclusions

It has been shown here that C−H···F interactions can be as important as C−H···O and C−H···N hydrogen bonds in stabilizing specific crystal structures. Supramolecular synthons based on the C−H···F interactions in **1**−**10** that are topologically similar to well-known C−H···O and C−H···N synthons have been identified. Such synthons can in principle be used in the design of novel and functional crystals. A comparison of **1**−**10** with the corresponding chloro, bromo and iodo structures unequivocally proves that F behaves distinctly differently from the other halogens. Fluorine would form C−H···F interactions rather than F···F contacts, whereas the heavier halogens seem to prefer the formation of halogen···halogen interactions. The general influence of C−H···F interactions has been shown to be the same in the polymorphic modifications **9a** and **9b**, other differences notwithstanding. Monte Carlo based crystal structure predictions of **9** in the experimentally observed space groups yield structures that are closely related to the experimental ones. An inverse $d - \theta$ correlation with little scatter for the C−H···F interactions in compounds **1**−**10** shows that these interactions have the characteristics of weak hydrogen bonds. As such, they could be of utility in crystal design and engineering.

Acknowledgment. G.R.D. and A.N. acknowledge financial support from the Department of Science and Technology (SP/S1/G19/94) and Council of Scientific and Industrial Research (1/1431/96/EMR-II) and helpful assistance from Molecular Simulations, Cambridge, England and San Diego, CA. R.B. thanks the Fonds der Chemischen Industrie for support. V.R.T. thanks the Department of Atomic Energy, Government of India, for fellowship support and the Heinrich Hertz-Stiftung des Landes Nordrhein-Westfalen for travel assistance. H.-C.W. acknowledges the Prof. Werdelmann-Stiftung im Stifterverband für die Deutsche Wissenschaft for travel assistance.

Supporting Information Available: ORTEP diagrams and tables giving crystal data and structure refinement, atomic coordinates, isotropic and anisotropic displacement parameters, and bond lengths and angles for **1**−**3** and **7**−**10** (29 pages, print/PDF). An X-ray crystallographic file, in CIF format, is available via the Web only. See any current masthead page for ordering information and Web access instructions.

JA981198E