Isolation of hydrazine oxidation products via halogen bonding: C–I bond scission and crystal polymorphism

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ARTICLE

Isolation of hydrazine oxidation products via halogen bonding: C–I bond scission and crystal polymorphism

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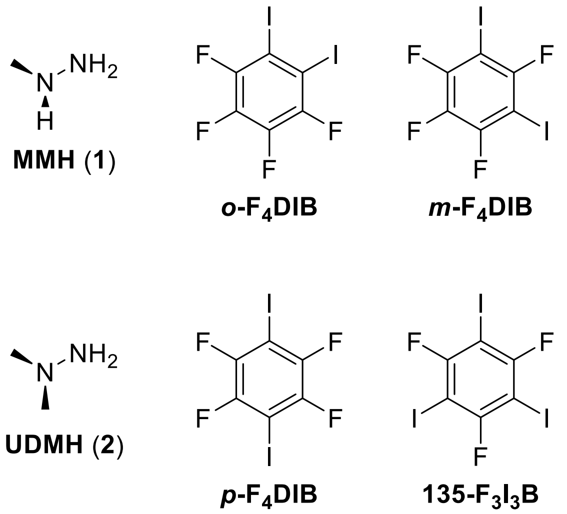
Reaction of methylhydrazine with 1,3- and 1,4-diiodotetrafluorobenzene produced cocrystals with the oxidation product *sym*-hexahydro-1,4-dimethyltetrazine. In contrast, reaction of 1,1-dimethylhydrazine with 1,2-, 1,3-, and 1,4-diiodotetrafluorobenzene, as well as 1,3,5-triiodotrifluorobenzene, yielded cocrystals with tetramethylammonium iodide (NMe_4I), via C–I bond scission. For each of the NMe_4I cocrystals, different polymoprhs or cocrystal stoichiometries were obtained via the C–I bond scission route, than were obtained by direct reaction of the halobenzene and NMe_4I by standard solution techniques.

Introduction

Despite their high toxicity, alkyl hydrazines have seen far-reaching utilization in heterocycle formation,[1–3] a common step in more complex organic syntheses.[4–6] Hydrazines have also seen extensive use as ligands in transition metal complexes due to their varied coordination modes.[7–9] Aerobic oxidation pathways for both methylhydrazine, or MMH (**1**), and 1,1-dimethylhydrazine, or UDMH (**2**), have been proposed based on GC MS analysis of the products.[10,11] In both cases, complex series of steps lead to dipolar intermediates, which further react via proton and methyl transfer steps, ultimately resulting in the dimerization of formaldehyde methylhydrazone to *sym*-hexahydro-1,4-dimethyltetrazine (**HHDMTZ**).

As nitrogen rich compounds, **1** and **2**, along with their oxidation products, provide promising targets for halogen bonding with electron deficient organoiodines. Halogen bonding is defined by IUPAC as, “a net attractive interaction between an electrophilic region associated with a halogen atom in a molecular entity and a nucleophilic region in another, or the same, molecular entity.”[12] Among the most common halogen bond donors are 1,2-, 1,3-, and 1,4-diiodotetrafluorobenzene (***o*-F₄DIB**, ***m*-F₄DIB**, and ***p*-F₄DIB** respectively), as well as 1,3,5-triiodotrifluorobenzene (**135-F₃I₃B**) (Scheme 1).[13–15] Between these four compounds, 126 crystal structures containing a C–I···I halogen bond have been deposited with the Cambridge Structural Database to date.[16]

In this study, we report the successful halogen bond promoted cocrystallization of **HHDMTZ** with ***m*-F4DIB** and ***p*-F₄DIB** by the direct reaction with **1**. When combined with **2**, cocrystals of tetramethylammonium iodide (**NMe_4I**) were obtained with each of the aforementioned iodofluorobenzenes (Scheme 2). A key intermediate in the formation of **HHDMTZ** from either MMH or UDMH is methyldiazene. When starting from **2**, dimethyldiazene is formed prior to its conversion to methyldiazene. One possibility from this point would involve a reaction between dimethyldiazene and a C–I bond of the iodofluorobenzenes contributing to iodide anion formation, as well as an alternative reaction pathway for the nitrogen containing fragment to the tetramethylammonium cation.



Scheme 1. Two hydrazines and four fluoroiodobenzene isomers utilized in this study

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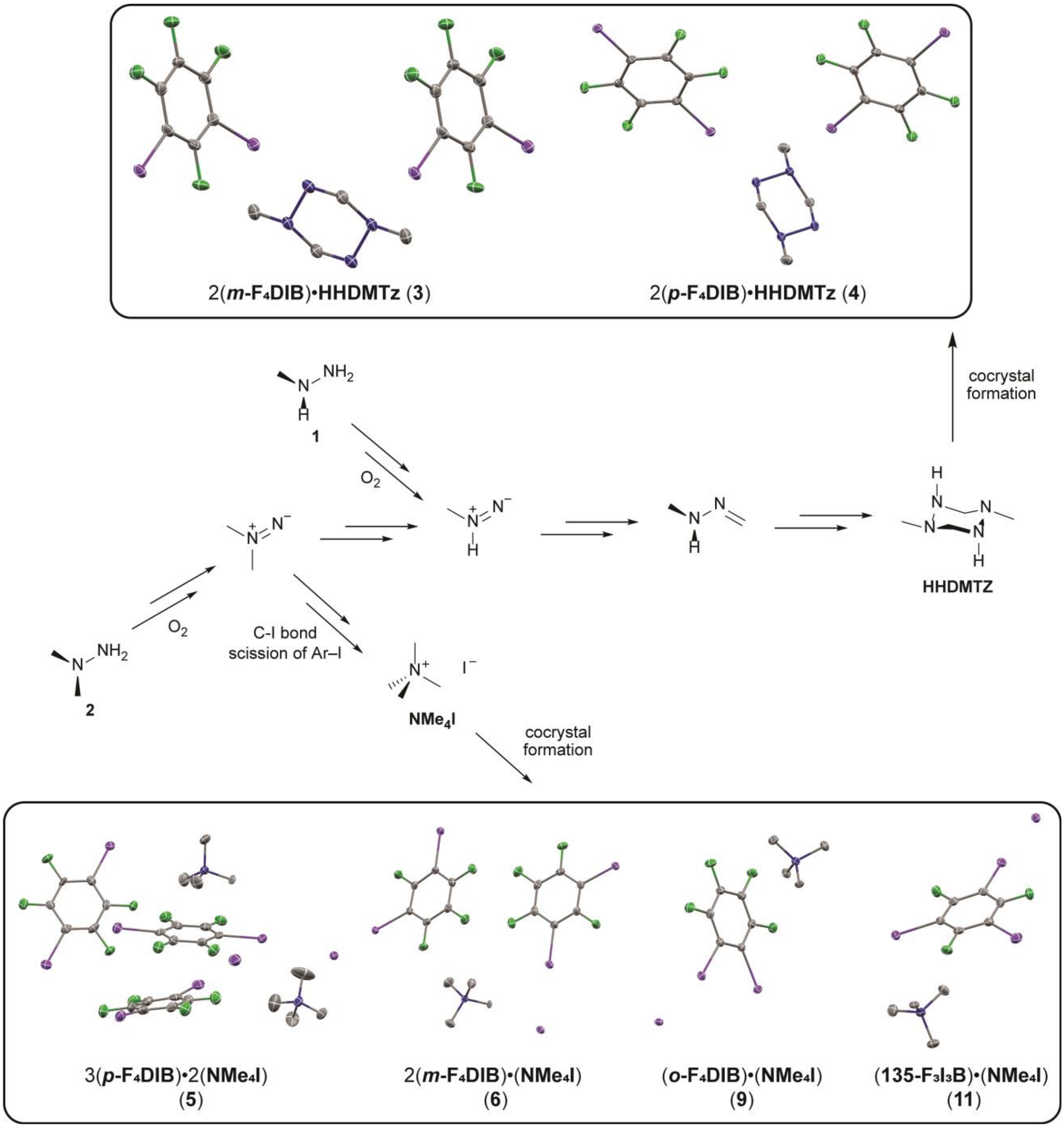


Scheme 2. Reaction of methylhydrazine (**1**) and 1,1-dimethylhydrazine (**2**) to form halogen bonded cocrystals

Additionally, **NMe$_4$I** cocrystals with each iodofluorobenzene were obtained by direct reaction with commercially available **NMe$_4$I**. The resulting cocrystals were either polymorphic or in differing stoichiometry to those obtained by reaction with **2**. Multiple halogen bond topologies are represented by this set of cocrystals.

Experimental Section

Materials

Methyl hydrazine (purity >99%, CAS registry number 60-34-4) and 1,2-dimethylhydrazine (purity >99%, CAS registry number 540-73-8) were obtained from Oakwood Chemicals. 1,2-diiodotetrafluorobenzene (purity >99%, CAS registry number 2708-97-6), 1,3-diiodotetrafluorobenzene (purity >99%, CAS registry number 67815-57-0), 1,4-diiodotetrafluorobenzene (purity >99%, CAS registry number 392-57-4), and 1,3,5-trifluoro-2,4,6-trifluorobenzene (purity >97%, CAS registry number 84322-56-5) were obtained from SynQuest Laboratories. Tetramethylammonium iodide (purity >99%, CAS registry number 75-58-1) was obtained from TCI America. Methanol (certified ACS, CAS registry number 67-56-1) and acetonitrile (certified ACS, CAS registry number 75-05-8) were obtained from Fisher Scientific. All the materials were used as received without further purification.

Physical measurements

Melting points were determined visually using an SRS DigiMelt MPA160 melting point apparatus and the onset of melting is reported. Elemental analyses were performed with a Thermo Elementar Vario EL III combustion analyzer.

Single crystal X-ray analysis

For single-crystal X-ray analysis, crystals were mounted on low background cryogenic loops using paratone oil. Data were collected using Mo Kα radiation (λ = 0.71073 Å) on a Bruker D8 Venture diffractometer with an Incoatec Iμs microfocus source and a Photon 2 detector. Diffraction data were collected using ϕ and ω-scans and subsequently processed (SAINT) and scaled (SADABS) using the APEX3 software suite.[17] The structures were solved by intrinsic phasing (SHELXT) and refined by full-matrix least square techniques (SHELXL) on *F*2 using the SHELXTL software suite.[18] All nonhydrogen atoms were refined anisotropically. All NH hydrogen atoms were refined with appropriate DFIX restraints, while all other hydrogen atoms were placed in geometrically optimized positions using the appropriate riding models. All geometric parameters reported within the manuscript text were calculated using *OLEX2*.[19] Selected crystallographic and data collection parameters are listed in Table 1. Halogen bonds were selected as those interactions occurring at less than the sum of the van der Waals radii,[20] and a comprehensive listing of geometric bond parameters is included in Table SI1.

Synthesis of cocrystals

2(***m*-F$_4$DIB**)·(**HHDMTZ**) (**3**). In a 1 mL glass tube, 1,3-diiodotetrafluorobenzene (50 mg, 0.12 mmol) was dissolved in MeOH (0.75 mL). Methylhydrazine (0.063 mL, 1.2 mmol) was added via syringe and the solvent allowed to slowly evaporate until colourless crystals were observed. The remaining solution was decanted and the crystalline material was washed with cold MeOH to obtain **3**. M.p. 115°C. Anal Calcd for $C_{16}H_{12}F_8I_4N_4$ (919.91): C, 20.89; H, 1.31; N, 6.09; Found: C, 20.66; H, 1.26; N, 6.09.

2(***p*-F$_4$DIB**)·(**HHDMTZ**) (**4**). Cocrystal **4** was obtained according to the same procedure as cocrystal **3**, utilizing 1,4-diiodotetrafluorobenzene (52 mg, 0.13 mmol) and methylhydrazine (0.068 mL, 1.3 mmol). M.p. 118°C. Anal Calcd for $C_{16}H_{12}F_8I_4N_4$ (919.91): C, 20.89; H, 1.31; N, 6.09; Found: C, 20.58; H, 1.25; N, 6.28.

3(***p*-F$_4$DIB**)·2(**NMe$_4$I**) (**5**). Cocrystal **5** was obtained according to the same procedure as cocrystal **3**, utilizing 1,4-diiodotetrafluorobenzene (48 mg, 0.12 mmol) and 1,2-dimethylhydrazine (0.087 mL, 1.2 mmol) M.p. 135°C. Anal Calcd for $C_{26}H_{24}F_{12}I_8N_2$ (1607.41): C, 19.42; H, 1.50; N, 1.74; Found: C, 19.16; H, 1.59; N, 2.06.

2(***m*-F$_4$DIB**)·(**NMe$_4$I**) (**6**). Cocrystal **6** was obtained according to the same procedure as cocrystal **3**, utilizing 1,3-diiodotetrafluorobenzene (57 mg, 0.14 mmol) and 1,2-dimethylhydrazine (0.10 mL, 1.4 mmol). M.p. 119°C. Anal Calcd for $C_{15}H_{12}F_8I_5N$ (1004.61): C, 19.13; H, 1.20; N, 1.39; Found: C,

Table 1. Crystallographic data and selected data collection parameters

	3	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
	2(***m*-F$_4$DIB**)· **HHDMTZ**	2(***p*-F$_4$DIB**)· **HHDMTZ**	3(***p*-F$_4$DIB**)· 2(**NMe$_4$I**)	2(***m*-F$_4$DIB**)· (**NMe$_4$I**)	2(***m*-F$_4$DIB**)· (**NMe$_4$I**)	2(***m*-F$_4$DIB**)· (**NMe$_4$I**)	(***o*-F$_4$DIB**)· (**NMe$_4$I**)	2(***o*-F$_4$DIB**)· (**NMe$_4$I**)	(**135-F$_3$I$_3$B**)· (**NMe$_4$I**)	(**135-F$_3$I$_3$B**)· (**NMe$_4$I**)
	$2(C_6F_4I_2)\cdot$ $(C_4H_{12}N_4)$	$2(C_6F_4I_2)\cdot$ $(C_4H_{12}N_4)$	$3(C_6F_4I_2)\cdot$ $2(C_4H_{12}NI)$	$2(C_6F_4I_2)\cdot$ $(C_4H_{12}NI)$	$2(C_6F_4I_2)\cdot$ $(C_4H_{12}NI)$	$2(C_6F_4I_2)\cdot$ $(C_4H_{12}NI)$	$(C_6F_4I_2)\cdot$ $(C_4H_{12}NI)$	$2(C_6F_4I_2)\cdot$ $(C_4H_{12}NI)$	$(C_6F_3I_3)\cdot$ $(C_4H_{12}NI)$	$(C_6F_3I_3)\cdot$ $(C_4H_{12}NI)$
crystal system	triclinic	triclinic	orthorhombic	monoclinic	monoclinic	monoclinic	monoclinic	orthorhombic	monoclinic	orthorhombic
space group	*P-1*	*P-1*	$P2_12_12_1$	$P2_1/n$	$P2_1/m$	$P2_1/n$	$P2_1/n$	*Pmmn*	$P2_1/n$	*Pnma*
a (Å)	6.3151(9)	8.6391(7)	11.7588(10)	9.9907(5)	6.9406(6)	10.0400(6)	7.5414(14)	22.6298(11)	7.3340(2)	21.6106(13)
b (Å)	8.5815(12)	8.8169(8)	14.0711(14)	21.4967(12)	20.4886(16)	20.5136(10)	22.618(4)	6.9472(3)	21.8848(7)	7.3407(5)
c (Å)	11.0306(15)	9.5619(8)	24.608(3)	11.4868(7)	8.7114(7)	12.0201(7)	9.2445(18)	7.9192(4)	11.0627(3)	11.3729(7)
α (°)	103.485(5)	81.638(3)	90	90	90	90	90	90	90	90
β (°)	96.047(6)	69.762(3)	90	103.673(2)	100.802(2)	103.127(2)	96.641(6)	90	98.8500(10)	90
γ (°)	93.183(5)	63.334(3)	90	90	90	90	90	90	90	90
V (Å^3)	576.08(14)	610.64(9)	4071.6(7)	2397.1(2)	1216.72(17)	2410.9(2)	1566.3(5)	1245.01(10)	1754.46(9)	1804.2(2)
Z	2	2	4	4	2	4	4	2	4	4
D$_c$ (g·cm^{-3})	2.652	2.502	2.623	2.784	2.743	2.768	2.557	2.680	2.691	2.617
μ (mm^{-1})	5.486	5.175	6.171	6.554	6.456	6.516	6.011	6.309	7.117	6.921
transmission coeff.	0.33/0.63	0.50/0.61	0.18/0.34	0.37/0.52	0.51/0.72	0.29/0.39	0.25/0.69	0.56/0.71	0.31/0.51	0.36/0.65
No. of ref. total	12764	31433	56179	59566	43360	40540	37815	9914	26043	28813
No. of ref. unique	2361	2472	8348	4901	2581	5504	4726	1406	3585	2218
No. of ref. obsd (I>2σ(I))	2288	2426	7946	4667	2318	5104	4333	1189	3421	2124
No. of param.	150	150	441	275	155	275	167	93	167	106
R^a	0.0213	0.0196	0.0340	0.0168	0.0262	0.0154	0.0190	0.0238	0.0166	0.0196
R_{all}	0.0219	0.0199	0.0367	0.0182	0.0311	0.180	0.0229	0.0337	0.0179	0.0211
$_wR^b$	0.0519	0.0559	0.0800	0.0399	0.0525	0.0332	0.0431	0.0382	0.0380	0.0467
$_wR_{all}$	0.0524	0.0560	0.818	0.0409	0.0553	0.0347	0.0454	0.0402	0.0387	0.0471

a. $R_1 = \Sigma||F_o| - [F_c||/\Sigma|F_o|$. b. $_wR_2 = \{\Sigma[w(F_o^2 - F_c^2)^2]/\Sigma[wF_o^2]^2\}^{1/2}$

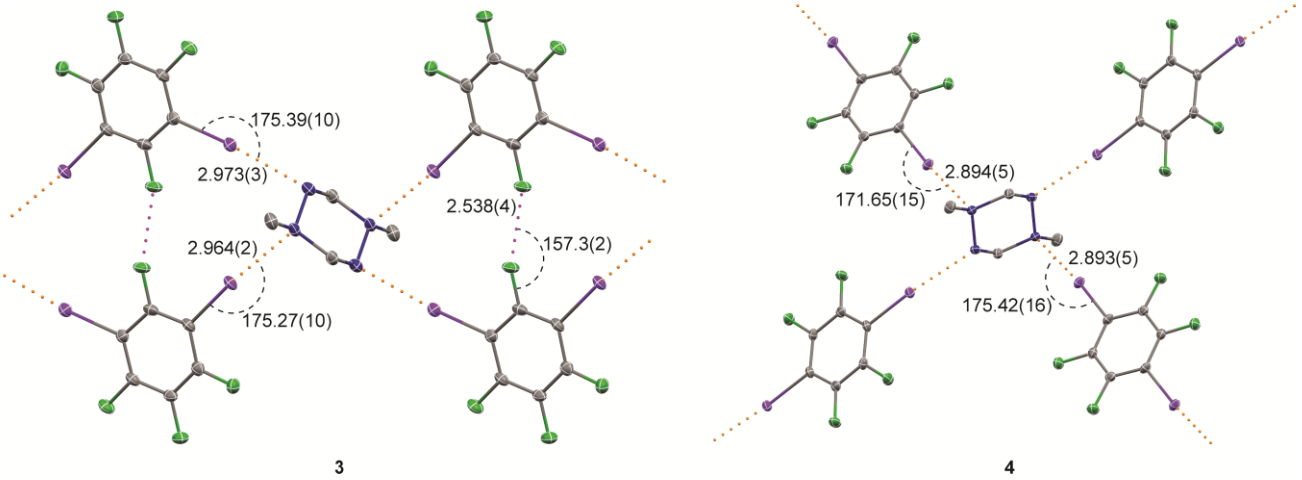


Fig. 1 Local halogen bonding in 2(**m-F$_4$DIB**)·**HHDMTZ** (**3**) and 2(**p-F$_4$DIB**)·**HHDMTZ** (**4**). Intermolecular C–I···N (orange) and C–F···F–C (magenta) interactions are indicated by dashed lines. H atoms have been omitted for clarity. Thermal ellipsoids are shown at the 50% probability level. Selected bond lengths are labelled in units of Å and angles in units of °. Carbon atoms are gray, nitrogen atoms are blue, fluorine atoms are green, and iodine atoms are purple.

19.01; H, 1.28; N, 1.46.

2(**m-F$_4$DIB**)·(**NMe$_4$I**) (**7** & **8**). Cocrystals **7** and **8** were obtained by dissolving 1,3-diiodotetrafluorobenzene (120 mg, 0.30 mmol) and tetramethylammonium iodide (30 mg, 0.15 mmol) in either MeOH (to yield cocrystal **7**) or MeCN (to yield cocrystal **8**). The solvent was allowed to slowly evaporate until colourless crystals were observed. The remaining solution was decanted and the crystalline material was washed with cold MeOH to yield the desired cocrystal. M.p. 118°C (**7**) and 116°C (**8**). Anal Calcd for $C_{26}H_{24}F_{12}I_8N_2$ (1607.41): C, 19.42; H, 1.50; N, 1.74; Found (**7**): C, 19.11; H, 1.25; N, 1.66; Found (**8**): C, 18.90; H, 1.29; N, 1.64.

(**o-F$_4$DIB**)·(**NMe$_4$I**) (**9**). Cocrystal **9** was obtained according to the same procedure as cocrystal **3**, utilizing 1,2-diiodotetrafluorobenzene (57 mg, 0.14 mmol) and 1,2-dimethylhydrazine (0.10 mL, 1.4 mmol) M.p. 115°C. Anal Calcd for $C_{10}H_{12}F_4I_3N$ (602.80): C, 19.92; H, 2.01; N, 2.32; Found: C, 19.68; H, 2.08; N, 2.53.

2(**o-F$_4$DIB**)·(**NMe$_4$I**) (**10**). Cocrystal **10** was obtained according to the same procedure as cocrystal **7**, utilizing 1,2-diiodotetrafluorobenzene (115 mg, 0.29 mmol) and tetramethylammonium iodide (29 mg, 0.14 mmol) in MeOH. M.p. 112°C. Anal Calcd for $C_{16}H_{12}F_8I_5N$ (1004.61): C, 19.13; H, 1.20; N, 1.39; Found: C, 19.01; H, 1.29; N, 1.50.

(**135-F$_3$I$_3$B**)·(**NMe$_4$I**) (**11**). Cocrystal **11** was obtained according to the same procedure as cocrystal **3**, utilizing 1,3,5-triiodo-2,4,6-trifluorobenzene (40 mg, 0.08 mmol) and 1,2-dimethylhydrazine (0.057 mL, 0.8 mmol). M.p. 143°C. Anal Calcd for $C_{10}H_{12}F_3I_4N$ (710.71): C, 16.90; H, 1.70; N, 1.97; Found: C, 16.89; H, 1.73; N, 2.14.

(**135-F$_3$I$_3$B**)·(**NMe$_4$I**) (**12**). Cocrystal **12** was obtained according to the same procedure as cocrystal **7**, utilizing 1,3,5-triiodo-2,4,6-trifluorobenzene (157 mg, 31 mmol) and tetramethylammonium iodide (62 mg, 31 mmol) in MeOH. M.p. 141°C. Anal Calcd for $C_{10}H_{12}F_3I_4N$ (710.71): C, 16.90; H, 1.70; N, 1.97; Found: C, 16.71; H, 1.78; N, 2.23.

Results and Discussion

By direct reaction of **m-F$_4$DIB** with **1**, the 2:1 cocrystal 2(**m-F$_4$DIB**)·**HHDMTZ** (**3**) is obtained, crystallizing in the space group *P*-1 (Fig. 1). The asymmetric unit consists of one **m-F$_4$DIB** molecule and one half of a **HHDMTZ** molecule. The methyl substituents of **HHDMTZ** are in axial positions. C–I···N halogen bonding interactions are observed to each nitrogen atom, while no significant N–H···N hydrogen bonds are observed (Fig. 1). The C–I···N halogen bond to the methyl substituted nitrogen atom in **HHDMTZ** occurs at a distance of 2.964(2) Å and C–I···N angle of 175.27(10)°. The halogen bond to the secondary amine nitrogen atom is nearly identical, at 2.973(3) Å and C–I···N angle of 175.39(10)°. This series of C–I···N halogen bonds results in the formation of chains propagating in the [0 1 1] direction (Fig. SI1). Additionally, a C–F···F–C interaction is observed between the 2-position fluorine atoms of neighbouring **m-F$_4$DIB** molecules with an F···F distance of 2.538(4) Å and C–F···F angle of 157.3(2)°. The structural parameters of the **HHDMTZ** molecule in this cocrystal are consistent with the previously published structure of **HHDMTZ**.[21]

Combination of **p-F$_4$DIB** and **1** provides cocrystal 2(**p-F$_4$DIB**)·**HHDMTZ** **(4)**, also crystallizing in the space group *P*-1. Two unique half molecules of **p-F$_4$DIB** and half a molecule of **HHDMTZ** lie within the asymmetric unit. The same pattern of C–I···N halogen bonding interactions are observed to each nitrogen atom, with a small contraction in the interaction distances relative to 2(**m-F$_4$DIB**)·**HHDMTZ**. The C–I···N halogen bond to the methyl substituted nitrogen atom in **HHDMTZ** occurs at a distance of 2.894(5) Å and 171.65(15)°, with the interaction to the secondary amine nitrogen atom at 2.893(5) Å and 175.42(16)°. These interactions contribute to the formation of halogen bonded sheets perpendicular normal to the *a** axis (Fig. SI2). A C–F···F–C interaction analogous to the one in the 2(**m-F$_4$DIB**)·**HHDMTZ** cocrystal is not observed in the **p-F$_4$DIB** containing cocrystal.[22] The two benzene ring planes

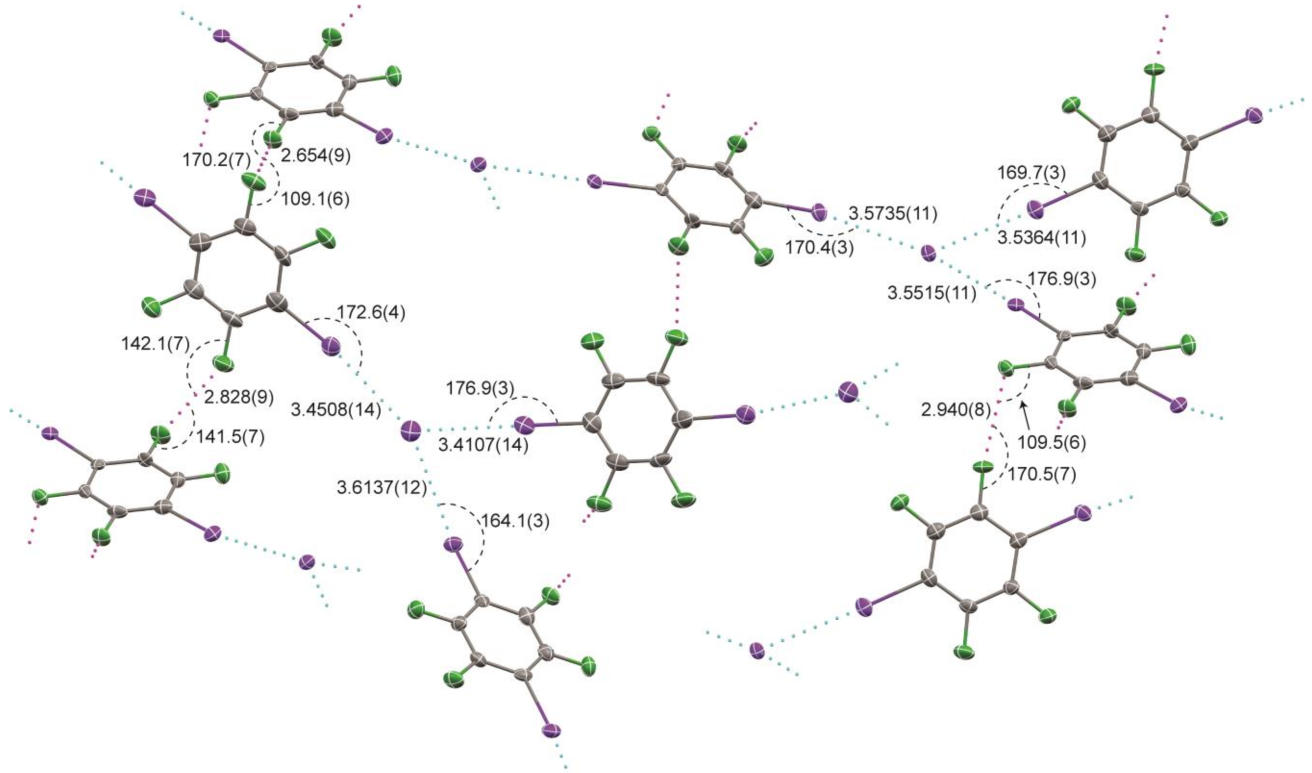


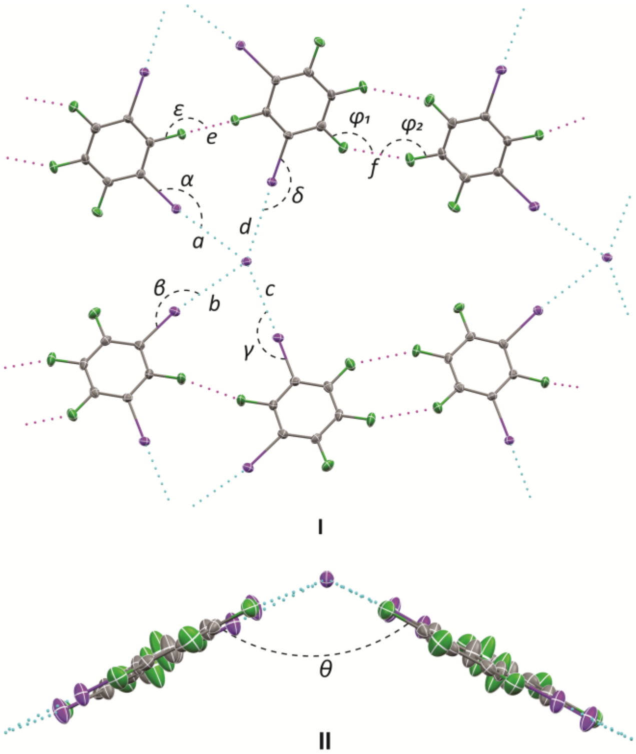
Fig. 2 Local halogen bonding in 3(***p*-F$_4$DIB**)·2(**NMe$_4$I**) (**5**). Intermolecular C–I···I (blue) and C–F···F–C (magenta) interactions are indicated by dashed lines. Tetramethylammonium cations removed for clarity. Thermal ellipsoids are shown at the 50% probability level. Selected bond lengths are labelled in units of Å.

are rotated by 14.2(2)° relative to one another, versus the coplanar arrangement in **3**, further discouraging a C–F···F–C interaction. Again, the structural parameters of the **HHDMTZ** system are consistent with the previously published structure of this molecule.

The combination of **2** with ***p*-F$_4$DIB** provided cocrystal 3(***p*-F$_4$DIB**)·2(**NMe$_4$I**) (**5**) (Fig. 2). The overall packing arrangement obtained is similar to a previously reported polymorph, with slight contraction in the unit cell dimensions.[23] This data also indicates the compound crystallizes in the space group $P2_12_12_1$ (Flack =0.036(16)), as opposed to *Pbca* in the previous polymorph. A series of C–I···I halogen bonds occur, with I···I distances ranging from 3.4107(14) Å to 3.6137(12) Å (Fig. 2). Three distinct C–F···F–C interactions are also present. One of these interactions is Type I in nature, with an F···F distance of 2.828(9) Å and C–F···F angles of 141.5(7)° and 142.1(7)°, with the other two interactions being Type II, defined by an F···F distances of 2.654(9) Å and 2.940(8) Å and C–F···F angles of 109.1(6)°/170.2(7)° and 109.5(6)°/170.5(7)° respectively.

Aerobic oxidation of **2** in the presence of ***m*-F$_4$DIB** produces cocrystal 2(***m*-F$_4$DIB**)·(**NMe$_4$I**) (**6**), crystallizing in the space group $P2_1/n$ with two ***m*-F$_4$DIB** molecules, one tetramethylammonium cation, and one iodide anion per asymmetric unit (Fig. 3). Two additional polymorphs with matching stoichiometry to cocrystal **6**, were obtained by standard solution techniques involving the combination of ***m*-F$_4$DIB** and tetramethylammonium iodide in methanol (**7**) and acetonitrile (**8**). In each polymorph, the iodide anion is involved in four C–I···I halogen bonds, ranging in I···I distance from 3.5156(5) Å to 3.6731(4) Å (due to the additional mirror symmetry in cocrystal **7**, the four C–I···I halogen bonds can be divided into two symmetry related pairs). Similar to the arrangement in cocrystal **3**, 2-position fluorines in neighbouring ***m*-F$_4$DIB** rings are involved in C–F···F–C interactions. In each case, these I···I interactions contribute to the formation of ribbons, which further consolidate into corrugated sheets via the C–F···F–C interactions (Fig. SI4–SI6). Another major difference between the three polymorphs is the plane-to-plane angle between the ***m*-F$_4$DIB** ring planes on either side of the iodide anion. This angle ranges from 44.73(3)° in cocrystal **6** to 56.58(5)° in cocrystal **7**. The angle in cocrystal **8** is nearly identical to cocrystal **7** at 56.057(19)°. The differences in **7** and **8** can likely be attributed to the differences in crystallization solvent (MeOH vs MeCN), while the difference between **6** and **7** appear attributable to reaction pathway, as both were obtained from MeOH.

While the three polymorphs comprised of ***m*-F$_4$DIB** and tetramethylammonium iodide were relatively similar to one another, the two cocrystals involving ***o*-F$_4$DIB** are quite different. When obtained by reaction of ***o*-F$_4$DIB** and UDMH, the 1:1 cocrystal (***o*-F$_4$DIB**)·(**NMe$_4$I**) (**9**) results, crystallizing in the space group $P2_1/n$ (Fig. 4 I). The asymmetric unit contains one ***o*-F$_4$DIB** molecule, one tetramethylammonium cation, and one iodide anion. Unlike cocrystals **6**–**8**, the iodide anion in cocrystal **9** is involved in only two C–I···I halogen bonds, at distances of 3.5588(6) Å and 3.5575(6) Å (Fig.4). No significant C–F···F–C interactions are observed. When obtained directly by reaction of tetramethylammonium iodide and ***o*-F$_4$DIB**, a 2:1 cocrystal 2(***o*-F$_4$DIB**)·(**NMe$_4$I**) (**10**) results. This system crystallizes in the space group *Pmmn*, with one ***o*-F$_4$DIB**



		6	7	8
C–I···I halogen bonds	*a*	3.7024(4)	3.6261(6)	3.5664(4)
	α	170.61(8)	172.77(13)	171.02(7)
	b	3.5961(4)	3.6261(6)	3.6731(4)
	β	167.91(10)	172.77(13)	171.98(6)
	c	3.5895(6)	3.5187(5)	3.5148(5)
	γ	177.05(9)	176.55(13)	174.56(6)
	d	3.5655(6)	3.5187(5)	3.5156(5)
	δ	174.11(9)	176.55(13)	176.79(6)
C–F···F–C halogen bonds	*e*	2.601(3)	2.481(8)	2.608(3)
	ε	162.9(2)	171.4(5)	145.48(16)
	f	2.778(2)	2.878(4)	2.8504(17)
	φ_1	145.89(18)	143.0(3)	141.97(12)
	φ_2	154.63(17)	157.8(3)	156.14(14)
ring plane-to-ring plane dihedral	θ	44.73(3)	56.58(5)	56.057(19)

Fig. 3. Representative halogen bonding in 2(***m*-F$_4$DIB**)·(**NMe$_4$I**) viewed perpendicular to (**I**) and in the plane (**II**) of the benzene rings. C–I···I (blue) and C–F···F–C (magenta) interactions are indicated by dashed lines. Thermal ellipsoids are shown at the 50% probability level. Selected bond lengths are labelled in units of Å and angles in units of °.

molecule, one half of tetramethylammonium cation, and one half of an iodide anion in the asymmetric unit. The packing in cocrystal **10** more closely resembles that of cocrystal **7** than that of cocrystal **9**. In cocrystal **10**, each iodide anion participates in two pairs of crystallographic equivalent C–I···I halogen bonds, at distances of 3.5317(5) Å and 3.7556(5) Å. Similar to cocrystal **7**, pairs of ***o*-F$_4$DIB** rings are coplanar, allowing C–F···F–C interactions between 3-position fluorines, with an F···F distance of 2.600(4) Å and a C–F···F angle of 160.0(3)°. The pairwise nature of the C–I···I halogen bonds in **9** do not directly contribute to long range packing, whereas in **10**, the 2:1 stoichiometry allows the formation of ribbons which propagate along the *b* axis (Fig. SI8). Numerous attempts were made to vary the reaction stoichiometry of the direct direction of **NMe$_4$I** and ***o*-F$_4$DIB**. Despite this, the 2:1 cocrystal always persisted from the direct reaction.

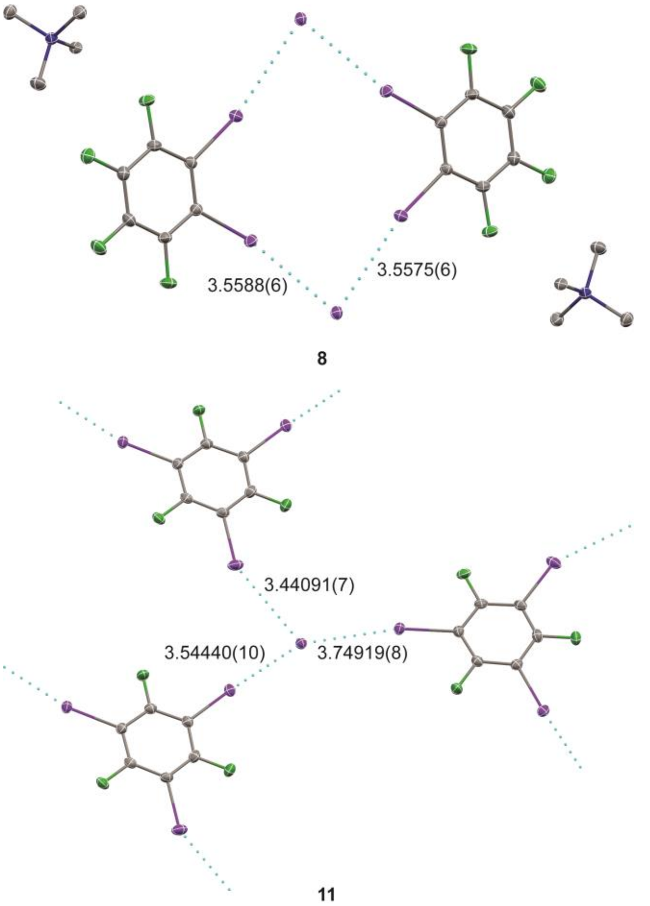


Fig. 4. Local halogen bonding in (***o*-F$_4$DIB**)·(**NMe$_4$I**) (**8**) and (**135-F$_3$I$_3$B**)·(**NMe$_4$I**) (**11**). Intermolecular C–I···I (blue) interactions are indicated by dashed lines. Hydrogen atoms, as well as the tetramethyl ammonium cation in **11**, are removed for clarity. Thermal ellipsoids are shown at the 50% probability level. Selected bond lengths are labelled in units of Å.

Finally, the two crystal polymorphs of (**135-F$_3$I$_3$B**)·(**NMe$_4$I**) obtained by the different approaches are quite similar in solid state structure to one another. When obtained by reaction with UDMH, the cocrystal (**11**) crystallizes in the space group P2$_1$/*n* with one **135-F$_3$I$_3$B** molecule, one tetramethylammonium cation, and one iodide anion per asymmetric unit. Each iodide anion is involved in three independent C–I···I halogen bonds, ranging in distance from 3.44091(7) Å to 3.74919(8) Å (Fig. 4 II). The cocrystal polymorph obtained by direct reaction with tetramethylammonium iodide (**12**) crystallizes in the orthorhombic space group *Pnma*. The unit cell parameters are nearly identical in both polymorphs, save the reduction in β angle from 98.8500(10)° in the monoclinic cell of cocrystal **11** to 90° in the orthorhombic cell of cocrystal **12** (Table 1). The asymmetric unit lies in a mirror plane, containing one half each of a **135-F$_3$I$_3$B** molecule, **NMe$_4$** cation, and iodide anion. A similar C–I···I halogen bonding pattern is observed, with I···I distances from 3.3932(5) Å to 3.7193(6) Å. No significant C–

F···F–C halogen bonds are indicated in either polymorph. While the **135-F_3I_3B** rings are coplanar in cocrystal **12**, the reduction in crystallographic symmetry imposed in cocrystal **11** occurs by a bending of the ring plane-to-ring plane angle by 12.3555(5)°. These interactions contribute to the formation of sheets, in which the bending in **10** is readily apparent in the packing of each polymorph (Fig. SI9 & SI10).

Conclusions

Halogen bonded cocrystals of ***m*-F_4DIB**, as well as ***p*-F_4DIB**, with *sym*-hexahydro-1,4-dimethyltetrazine were obtained by aerobic reaction with MMH. Additionally, cocrystals of **NMe_4I** with ***o*-F_4DIB**, ***m*-F_4DIB**, ***p*-F_4DIB**, and **135-F_3I_3B** were obtained by aerobic reaction with UDMH *via in situ* C–I bond scission. For the **NMe_4I** cocrystals, alternative crystalline polymorphs or cocrystal stoichiometries were obtained by direct reaction with **NMe_4I**. This suggests a significant structural sensitivity toward the reaction conditions. In particular, the stable halogen bonding networks provide useful information about the various reaction pathways available to MMH and UDMH precursors. A wide range of halogen bonding patterns were observed. Work is ongoing to expand the scope of hydrazine oxidations which can be probed by isolation of products *via* halogen bonding.

Conflicts of interest

There are no conflicts to declare.

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The reaction of methyl hydrazine and 1,1-dimethylhydrazine with 1,2-, 1,3-, and 1,4-diiodotetrafluorobenzene, as well as 1,3,5-triiodotrifluorobenzene, yielded a series of cocrystals with either *sym*-hexahydro-1,4-dimethyltetrazine or tetramethylammonium iodide (NMe_4I), which are either polymorphic or in differing stoichiometry to those obtained from reaction with commercially available NMe_4I.