

Halogen Bonding Driven Crystal Engineering of Iodophthalonitrile Derivatives

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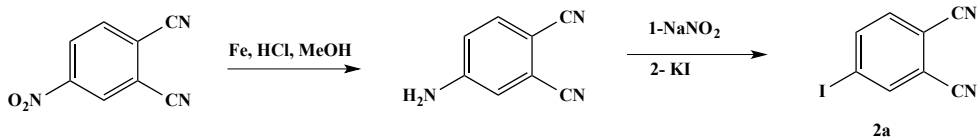
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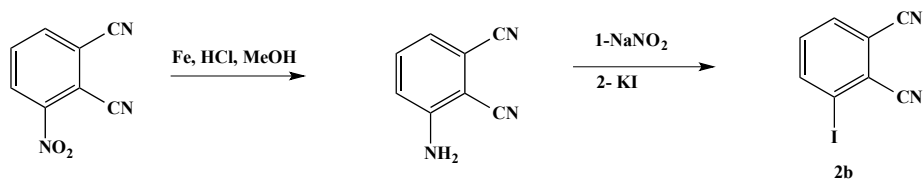
Experimental Procedure:

All chemicals were purchased from commercial sources and used without further purification.



4-Aminophthalonitrile: 4-Nitrophthalonitrile (0.44 g, 2.5 mmol) was added to a mixture of methanol (10 mL) and concentrated hydrochloric acid (3 mL) and stirred at 70 °C. Iron powder (0.6 g) was added in small portions over 45 min. After 1h, the mixture was poured into cold water and the precipitate filtered off. Yellowish solid (0.3 g, 82 %). ¹H NMR (CDCl₃): δ = 4.31 (s, 2H), 6.84 (d, 1H), 6.94 (d, 1H), 7.51 (d, 1H).

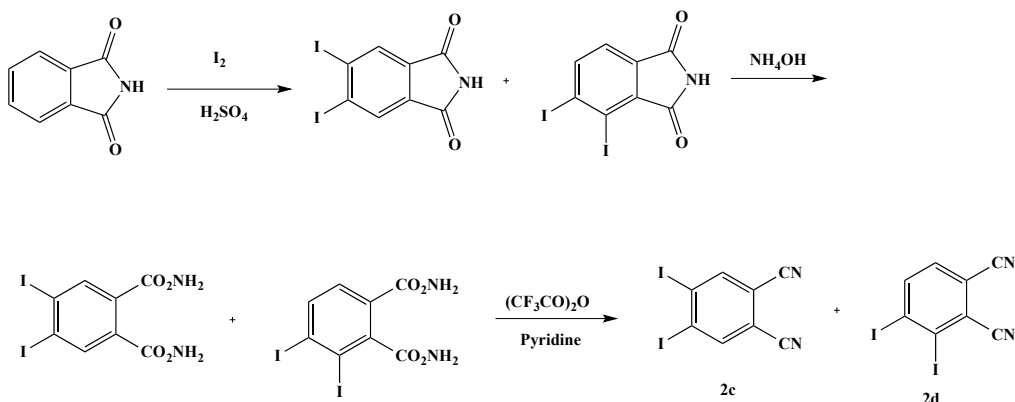
4-Iodophthalonitrile (2a): 4-Aminophthalonitrile (0.2 g, 1.4 mmol) was added to mixture of concentrated hydrochloric acid (6 mL), ice (20 g) and sodium nitrite (0.15 g, 2.15 mmol) in water (3 mL) in one portion at 5°C. After 2 hours, the solution was filtered. The diazonium salt solution was added dropwise to a stirred cool solution of potassium iodide in 5 mL water. The resulting dark brown mixture was stirred for 1 hour. Compound was extracted with toluene from mixture solution. Then organic phase was washed with cold water and cold 5 % NaHCO₃, then saturated Na₂S₂O₃ (sat). The toluene solution was dried over anhydrous sodium sulfate. White solid (0.25g, 70 %) ¹H NMR (d₆-DMSO): δ = 7.86 (d, 1H), 8.25 (dd, 1H), 8.59 (d,1H). ¹³C NMR (d₆-DMSO): δ = 102.56, 110.01, 114.28, 115.36, 116.14, 135.01, 142.30, 143.38.



3-Aminophthalonitrile: 3-Nitrophthalonitrile (0.44 g, 2.5 mmoles) was added to a mixture of methanol (10 mL) and concentrated hydrochloric acid (3 mL) and stirred at 70 °C. Iron powder (0.6 g) was added in small portions over 45 min. After 1h, the mixture was poured into cold water and the precipitate filtered off. Yellow solid (0.25g, 70%). ¹H NMR (CDCl₃): δ = 4.73 (s, 2H), 6.97 (d, 1H), 7.09 (d, 1H), 7.41 (t, 1H).

3-Iodophthalonitrile (2b): 3-Aminophthalonitrile (0.2 g, 1.4 mmoles) was added to mixture of concentrated hydrochloric acid (6 mL), ice (20 g) and sodium nitrite (0.15 g, 2.15 mmol) in water (3 mL) in one portion at 5°C. After 2 hours, the solution was filtered. The diazonium salt solution was added

dropwise to a stirred cool solution of potassium iodide in 5 mL water. The resulting dark brown mixture was stirred for 1 hour. Compound was extracted with toluene from mixture solution. Then organic phase was washed with cold water and cold 5 % NaHCO₃, then saturated Na₂S₂O₃ (sat). The toluene solution was dried over anhydrous sodium sulfate. White solid (0.2g, 56 %) ¹H NMR (CDCl₃): δ = 7.41 (t, 1H), 7.80 (m, 1H), 8.18 (m, 1H). ¹³C NMR (CDCl₃): δ = 144.25, 136.43, 132.81, 125.74, 118.65, 116.80, 116.40, 102.82.



4,5-Diiodophthalimide and 3,4-Diiodophthalimide: A mixture of oleum (15 ml, 30%), phthalimide (10 g, 0.07 mol) and I₂ (17.2 g, 0.07 mol) was stirred and heated at 90 °C for 24 h. The resulting suspension was poured over ice, the precipitate was filtered, washed with water (50 ml), 4% aq. K₂CO₃ (50 ml) and aq. Na₂SO₃ (50 ml). The crude product was recrystallized from acetone/water to give 18.1 g (65 %) mixture of 4,5-diiodophthalimide and 3,4-diiodophthalimide as an off-white solid. The mixture compounds were used without further purifications.

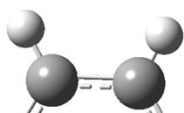
4,5-Diiodophthaldiamide and 3,4-Diiodophthaldiamide: A mixture of 4,5 diiodophthalimide and 3,4-diiodophthalimide (5.3 g, 13.2 mmol) and aq. NH₄OH (60ml, 25%) was stirred and heated at 60 °C for 1.5 h. The resulting suspension was filtered, the precipitate was washed with cold water (50 ml), methanol (50 ml) and air-dried to give 3.8 g (70 %) mixture of 4,5-Diiodophthaldiamide and 3,4-Diiodophthaldiamide as a white solid. The mixture compounds were used without further purifications.

4,5-Diiodophthalonitrile (2c) and 3,4-Diiodophthalonitrile (2d): Trifluoroacetic anhydride (10.6 ml, 75 mmol) was added dropwise to a mixture of 4,5-Diiodophthaldiamide and 3,4-Diiodophthaldiamide (5.5 g, 13 mmol), dioxane (100 ml) and pyridine (15 ml) at 0–5 °C. The resulting suspension was stirred at 25 °C for 12 h, poured over ice and extracted with ethyl acetate (100 ml). The combined organic extracts were washed with water (50 ml), 1M HCl (55 ml), aq. Na₂CO₃ (150 ml), water (50 ml) and dried (Na₂SO₄). The solvents were evaporated in vacuum and the residue was crystallized from acetone/water to give mixture of 4,5-diiodophthalonitrile (2c) and 3,4-diiodophthalonitrile (2d). These compounds were separated using silica gel chromatography with ethyl acetate-hexane (1:9) as eluent. 4,5-diiodophthalonitrile (2c) (2.96 g, 60% yield) and 3,4-diiodophthalonitrile (2d) (0.5 g, 10% yield):

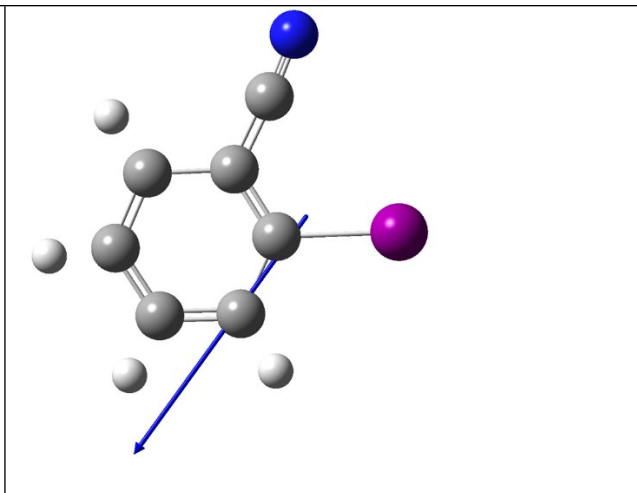
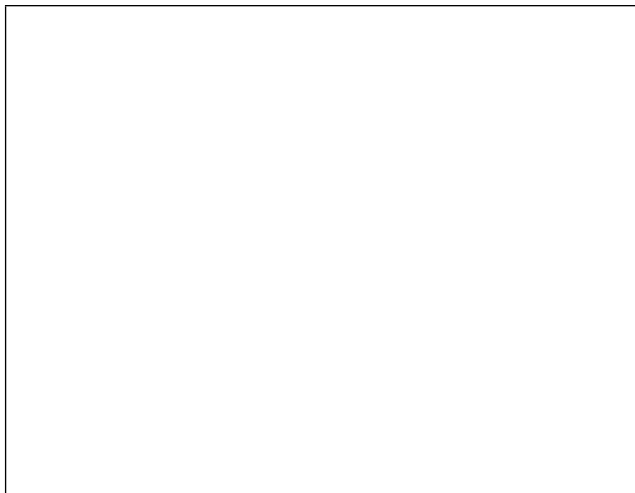
4,5-Diiodophthalonitrile (2c): IR: 2231 (CN) cm^{-1} . ^1H NMR (d_1 - CDCl_3): $\delta = 8.24$ ppm (s, 2H). ^{13}C -NMR (CDCl_3): 142.68, 115.32, 114.95, 113.38 ppm. MALDI-MS (DHB) m/z : 416.8607 ($[\text{M}+\text{H}]^+$)

3,4-Diiodophthalonitrile(2d): IR: 2236 (CN) cm^{-1} . ^1H NMR (d_1 - CDCl_3): $\delta = 8.22$ (d, 1H), 7.46 (d, 1H). ^{13}C -NMR (CDCl_3): $\delta = 144.54, 133.63, 126.72, 116.52, 115.83, 115.91, 113.14, 110.64$. MALDI-MS (DHB) m/z : 416.6 ($[\text{M}+\text{H}]^+$)

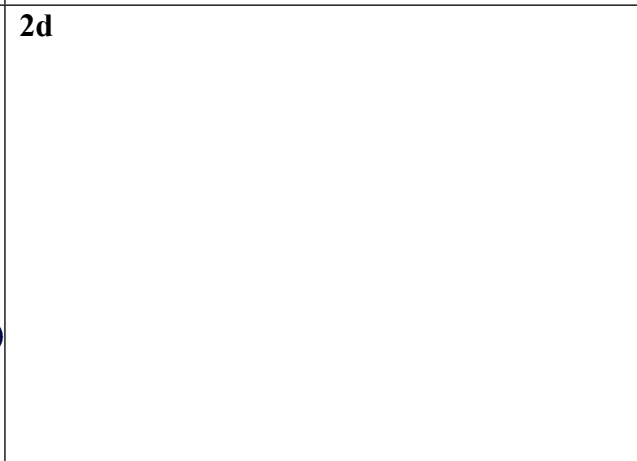
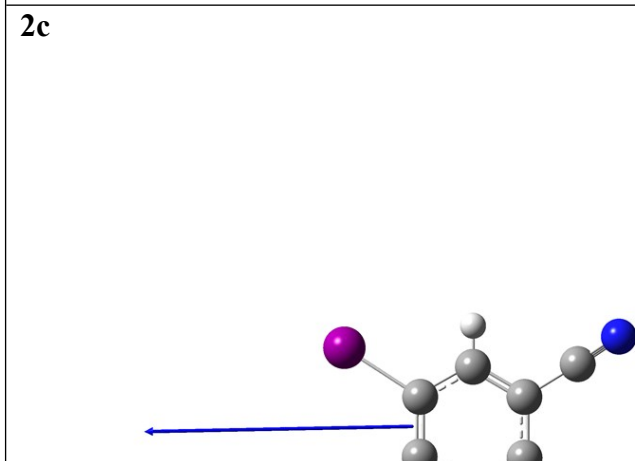
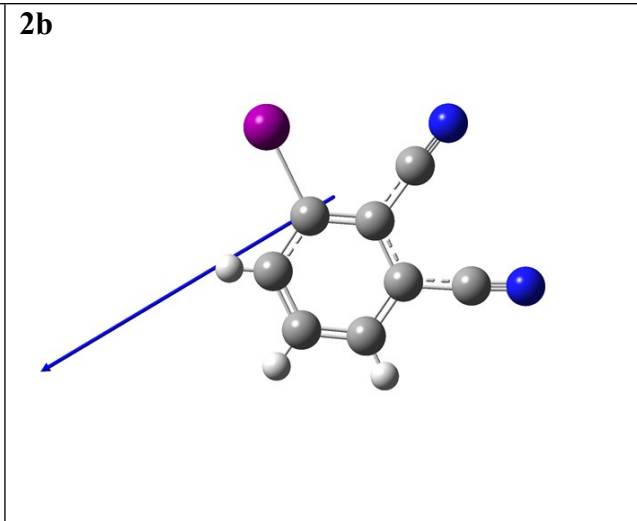
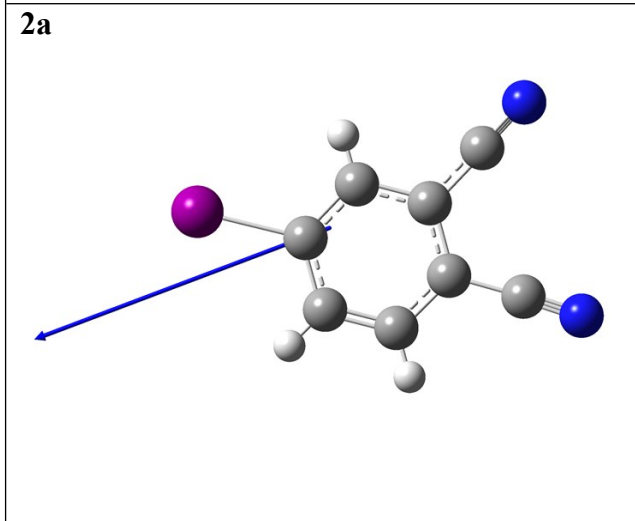
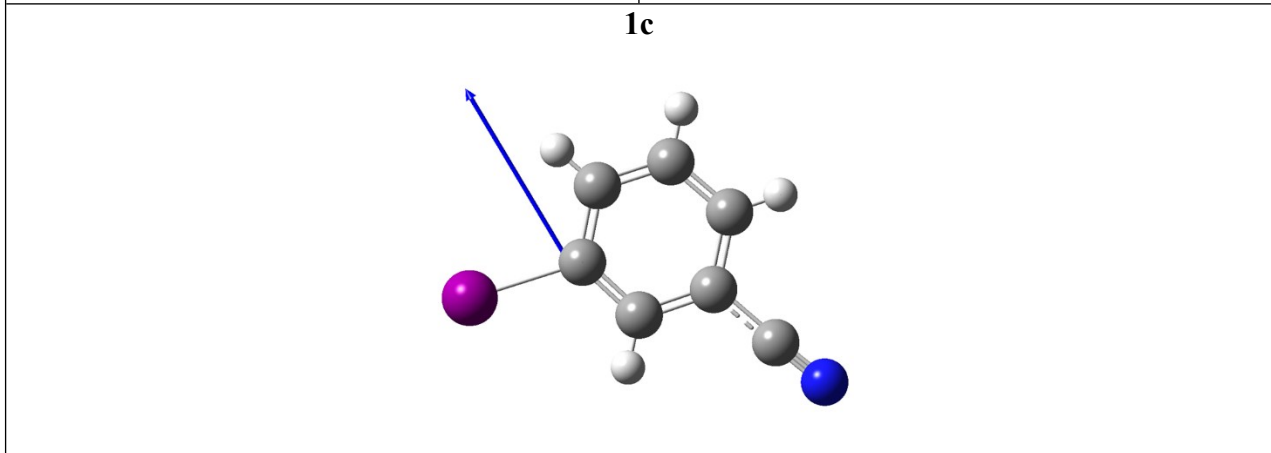
1a



1b



1c



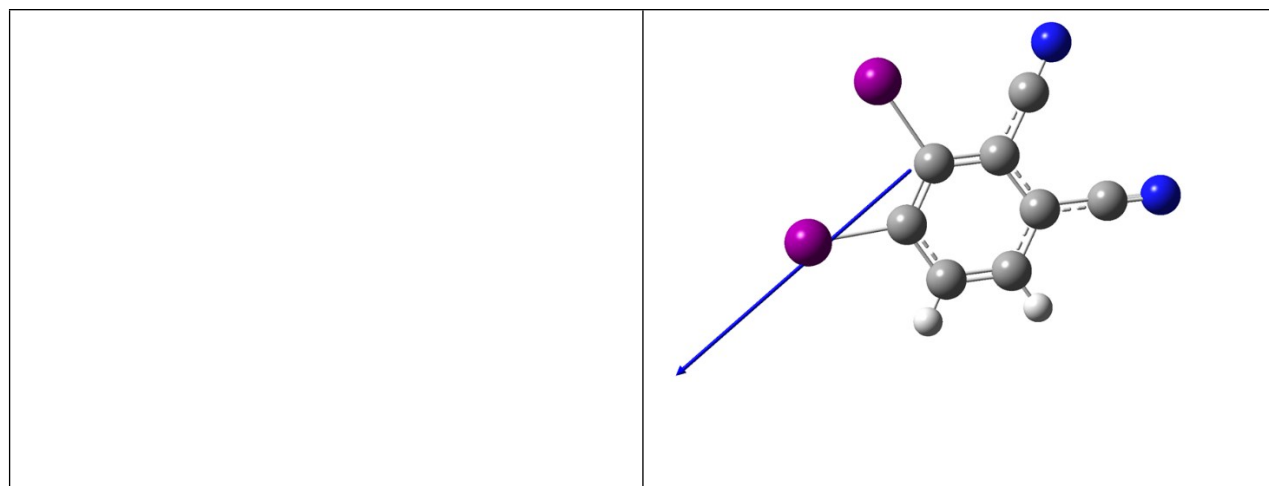


Figure S1. The orientation of monomers' dipole moments in **1a-1c. 2a-2d.**

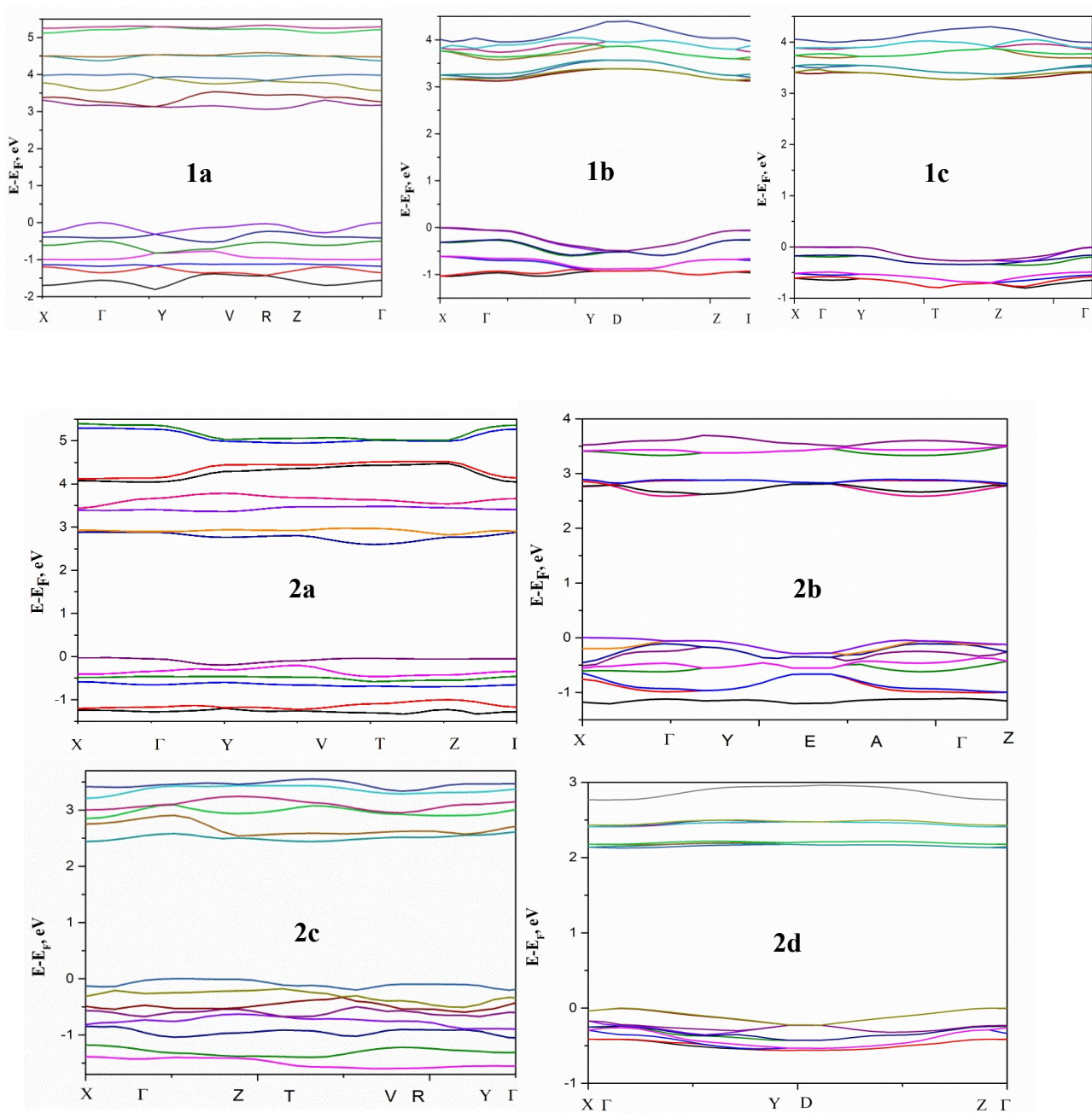


Figure S2. Band structures of the titled compounds. The reciprocal coordinates of high-symmetry points are **(1a)** $X = (0.5, 0, 0)$, $\Gamma = (0, 0, 0)$, $Y = (0, 0.5, 0)$, $V = (0.5, 0.5, 0)$, $R = (0.5, 0, 0.5)$, $Z = (0, 0, 0.5)$; **(1b)** $X = (0.5, 0, 0)$, $\Gamma = (0, 0, 0)$, $Y = (0, 0.5, 0)$, $D = (0, 0.5, 0.5)$, $Z = (0, 0, 0.5)$; **(1c)** $X = (0.5, 0, 0)$, $\Gamma = (0, 0, 0)$, $Y = (0, 0.5, 0)$, $T = (0, 0.5, 0.5)$, $Z = (0, 0, 0.5)$; **(2a)** $X =$

$(0.5, 0, 0)$, $\Gamma=(0, 0, 0)$, $Y=(0, 0.5, 0)$, $V=(0.5, 0.5, 0)$, $T = (0.5, 0, 0.5)$, $Z = (0, 0, 0.5)$, **(2b)** $X =$
 $(0.5, 0, 0)$, $\Gamma=(0, 0, 0)$, $Y=(0, 0.5, 0)$, $E=(0.5, 0.5, 0.5)$, $A = (0.5, 0, 0.5)$, $Z=(0, 0, 0.5)$, **(2c)** $X =$
 $(0.5, 0, 0)$, $\Gamma=(0, 0, 0)$, $Z = (0, 0, 0.5)$, $T = (0.5, 0, 0.5)$, $V = (0.5, 0.5, 0.5)$, $R = (0, 0.5, 0.5)$, $Y =$
 $(0, 0.5, 0)$, **(2d)** $X = (0.5, 0, 0)$, $\Gamma=(0, 0, 0)$, $Y=(0, 0.5, 0)$, $D=(0, 0.5, 0.5)$, $Z = (0, 0, 0.5)$.

Table S1. Comparison of the selected bond lengths (Å) for compounds **2a-2d**.

2a		2b	
C7-N1	1.159(7)	C7-N1	1.138(7)
C8-N2	1.147(6)	C8-N2	1.148(7)
C4-I1	2.083(5)	C3-I1	2.085(5)

2c		2d	
C7-N1	1.150(3)	C8-N2	1.133(19)
C8-N2	1.170(2)	C7-N1	1.128(17)
C4-I1	2.087(17)	C8a-N2a	1.121(15)
C3-I2	2.085(17)	C7a-N1a	1.132(18)
		C5-I1	2.092(11)
		C4-I2	2.087(13)
		C5a-I1a	2.064(12)
		C4a-I2a	2.097(13)

Table S2. Geometric parameters used for the determination of the $\pi\cdots\pi$ interactions between phenyl cycles. For compound **2c** the distances between centroids are presented for phenyl rings of **2c1** and **2c2** respectively.

d(CgI\cdotsCgI')		α	β	Symmetry transformation for CgI'.
1a	3.99	0	26.5	<i>1/2-X,1/2-Y,-1/2-Z</i>
1b	4.16	0	32.9	<i>X,-1+Y,Z</i>
1c	4.204	0	30.3	<i>X,Y,-1+Z</i>
2a	4.493	0	40.3	<i>-X,1-Y,-Z</i>
	4.356	0	37.6	<i>1-X,2-Y,1-Z</i>
2b	3.845	1.3	24.6	<i>X,1/2-Y,-1/2+Z</i>
	3.846	1.3	23.9	<i>X,1/2-Y,1/2+Z</i>
2c	5.399(10)	0	48.4	<i>1-X,-Y,1-Z</i>
	5.158(10)	0	46.7	<i>1-X,1-Y,1-Z</i>
2d	4.155(8)	0	25.7	<i>X,-1+Y,Z</i>
	4.155(7)	0	28.5	<i>X,-1+Y,Z</i>

Table S3. Calculated parameters for C-(N, I)...Cg (π -ring) interactions analysis.

	C-N...CgI'	N...CgI'	γ	Symmetry transformation for CgI'.
1b	C7-N1...Cg(1)	3.8595	25.1	$X, I+Y, Z$
2a	C7-N1...Cg(1)	3.657	21.42	$I-X, 2-Y, I-Z$
2c	C4-I1... Cg(1)	3.754	11.86	$I-X, I-Y, I-Z$
	C5-I2...Cg(1)	3.757	10.64	$I-X, -Y, I-Z$

Table S4. Donor-acceptor interaction energies E^2 (kcal mol⁻¹) and charge differences (e) for halogen bonding.

Compounds	Δq_I	Δq_N	Delocalization	$E^{(2)}$ [kcal/mol]
1a	-0.04	0.034	LP(1)N1 \rightarrow σ^* (I1-C4)	3.58
1b	-0.009	-	LP(3)I1 \rightarrow σ^* (C3-I1)	2.15
1c	0.004	-	LP(3)I1 \rightarrow σ^* (I1-C2)	2.5
2a	-0.025	0.031	LP(1)I1 \rightarrow σ^* (C8-N2)	1.76
			σ (C4-I1) \rightarrow RY*(4)N2	1.49
2b	-0.035	0.006	σ (C3-I1) \rightarrow RY*(5)N2	2.12
			LP(1)I1 \rightarrow RY*(2)N2	1.96
			LP(1)I1 \rightarrow σ^* (C8-N1)	1.84
2c	0.024	-0.023	σ (C3-I2) \rightarrow RY*(2)N1	1.88
			LP(1)I2 \rightarrow σ^* (C7-N1)	1.78
	0.018	-0.027	σ (C4-I1) \rightarrow RY*(2)N2	2.14
			LP(1)I1 \rightarrow σ^* (C8-N2)	1.75
2d1S	-0.024	0.012	LP(1)N2 \rightarrow σ^* (C5-I1)	2.48
2d1L	-0.004	-0,027	LP(1)N2a \rightarrow σ^* (C4-I2)	1.35
2d1I	-0.009	-	LP(3)I1 \rightarrow σ^* (C5a-I1a)	0.24
2d1T	0.011	0.044	σ (C5-I1) \rightarrow RY*(1)N2	2.08
			σ (C5-I1) \rightarrow RY*(2)N2	1.61
			σ (C5-I1) \rightarrow RY*(4)N2	1.36
	-0.028	-	LP(1)I1 \rightarrow RY*(4)I1a	1.32
			LP(1)I1 \rightarrow σ^* (C5a-I1a)	0.92

Table S5. Electron Density, ρ , Laplacian, $\nabla^2\rho$ (a.u.) at the halogen bonds' critical points and interaction energies (ΔE , kcal/mol) in **1a-1c**, **2a-2c**, **2d1S**, **2d1L**, **2d1I**. For **2b** and **2c** the interaction energy in brackets denotes ΔE per one XB while in **2d1S** and **2d1I** the two values for ΔE refer to dimer and trimer respectively.

Compounds	XB	ρ	$\nabla^2\rho$
1a	I1 \cdots N1	0.013	0.041
1b	I1 \cdots I1	0.009	0.02
1c	I1 \cdots I1	0.009	0.02
2a	I1 \cdots N2	0.011	0.034
2b	I1 \cdots N2	0.011	0.034
2c	I1 \cdots N2	0.01	0.031
	I2 \cdots N1	0.009	0.028
2d1S	I1 \cdots N2	0.012	0.038
2d1L	I2 \cdots N2a	0.009	0.028
2d1I	I1 \cdots I1a	0.011	0.027

Table S6. Natural charges and their differences (e) for halogen bonding.

	Atoms	q(monomer)	q(dimer)	Δq
1a	I1	0.209	0.249	-0.04
	N1	-0.306	-0.34	0.034
1b	I1	0.245	0.254	-0.009
1c	I1	0.211	0.207	0.004
2a	I1	0.244	0.269	-0.025
	N2	-0.261	-0.292	0.031
	N1	-0.271	-0.275	0.004
2b	I1	0.272	0.307	-0.035
	N2	-0.254	-0.302	0.048
	N1	-0.262	-0.269	0.006
2c	I1	0.276	0.293	0.018
	N1	-0.266	-0.289	-0.022
	I2	0.271	0.295	0.024
	N2	-0.265	-0.292	-0.027
2d-1S	I1	0.294	0.318	-0.024
	N2	-0.25	-0.262	0.012
2d-1L	I2	0.294	0.298	-0.004
	N2a	-0.26	-0.287	-0.027
2d-1I	I1a	0.31	0.31	0.06
	I1	0.275	0.266	-0.009
2d-1T	I1a	0.294	0.322	-0.028
	I1	0.31	0.32	0.011
	N2	-0.25	-0.294	0.044