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Crystal Environment Induced Symmetry Reduction (CEISR): Deep Analysis of *Para*-Chloroacetophenone Azine and Generalization

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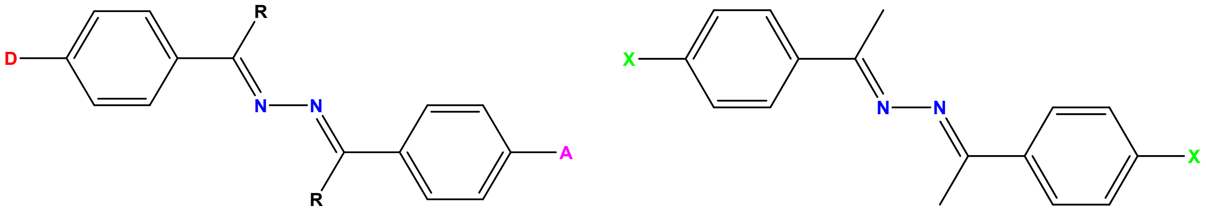
ABSTRACT: The morphologies are described of sixteen crystal structures of ten symmetrical X_{para}−Ph−(Me)C=N−N=C(Me)−Ph−X_{para} azines: **1** (Cl), **2** (Br), **3** (I), **4** (OH), **5** (PhO), **6** (CF_3), **7** (F), **8** (Me), **9** (NO_2), and **10** (PrO). All azines crystallize forming idioteloamphiphile monolayers (IAM) and their morphologies fall into the two main classes of "flat" and "shiplap" depending on the lateral offsets between next-neighbors in the monolayer. Ab initio studies show that the (*E*,*E*)-configured p-disubstituted acetophenone azines are C_2-symmetric in the gas phase and that the azine and phenyl twists are correlated and give rise to *P*- and *M*-chirality. The crystal structures of **1-10** are true racemates and, remarkably, the majority feature *asymmetric* (C_1) azines rather than *dissymmetric* (C_2) azines. To understand the origin of the symmetry reduction we studied the supramolecular structures and IAM characteristics of the five azines that crystallize with flat morphology **1-I** (Cl), **2-Ia** (Br), **3** (I), **5** (PhO), and **10** (PrO). The deep analyses of the chloroazine **1-I** shows that the symmetry reduction is the result of qualitatively different coordination environments of the two chloroarene moieties and presents a case of crystal environment induced symmetry reduction (CEISR). The crystal structure of **1-I** is of the type "AABB Kick/Flat" and the advantages of the double-stripe motif are explained. Careful analysis of the crystal structure showed arene-arene T-contacts of the types edge-to-face (e|f), face-to-edge (f|e), and face-to-face (f|f), a new arene-azine interaction (e|Az), H---Cl, Cl---π, and Cl---Cl contacts. *Intra*- and *inter*layer interaction inventory analyses show in a compelling fashion that the arenes A_i and A_s in each azine engage in qualitatively different intermolecular interactions. To demonstrate the usefulness of the interaction inventory analysis, we also compare and contrast the crystal environments of the C_1-symmetric azines in crystals of **2-Ia** (Br) and **10** (PrO) and the C_2-symmetric azines in crystals of **3** (I) and **5** (PhO). Intermolecular interactions are quantified using Hirshfeld surface analyses, pairwise interaction energies, and electrostatic potential maps. We will also describe a fast method for the detection of CEISR based on N···H Hirshfeld 2-D fingerprint plots.

1. INTRODUCTION

Azines belong to the group of organic compounds with the connectivity, RR'C=N−N=CRR', where R and R' can be alkyl or aryl groups.[1] They are basically 2,3-diaza derivatives of butadienes and can also be considered as N−N connected diimines. Azines play important roles in crisscross cycloadditions[2] and heterocycle synthesis.[3] Extensive applications of azines have emerged in medicinal chemistry as neuroinflammatory agents,[4] antifungal agents,[5] anticancer agents,[6] and MDR reversal agents.[7] Azines are important precursors for the fabrication of conducting polymers to serve as cathode materials for organic batteries,[8] covalent organic frameworks for hydrogen evolution,[9] NLO-active photovoltaic materials,[10] organic field-effect transistors (OFET)[11], film transistors etc.[12]

Scheme 1. 1,4-Diphenyl azines commonly are derived from benzophenone (R = H) and acetophenone (R = CH_3). It is our goal to fabricate ferroelectric crystals of *unsymmetrical* azines with para-phenyl substitution by donors and acceptors. In the present paper, we focus on *symmetrical* azines with X = Cl, Br, I, PhO, and PrO.



We have been interested in unsymmetrical donor-acceptor substituted azines D−Ph−(R)C=N−N=C(R)−Ph−A (Scheme 1, left) because of their non-linear optical properties. These materials stand out because we have been able to fabricate crystals with perfect dipole alignment in several acetophenone azine series RO−Ph−(Me)C=N−N=C(Me)−Ph−X_{para}. Initial success came with the methoxy series (RO = H_3CO) with X = Cl,[13] Br,[14] I,[15] and we have since realized several materials in the phenoxy series (RO = PhO)[16-21] and the decyloxy series (RO = DecO).[22-25] The concepts guiding the fabrication of these ferroelectric materials have been described.[26-28] While our primary interest always has been with *unsymmetrical* azines, we have also studied intensively the *symmetrical* azines to learn about the intermolecular interactions in azine crystals.[29-36]

Here we report on the supramolecular structure of a series of symmetrical azines (Table 1). First, we will discuss morphologies of idioteloamphiphile monolayer architectures (IAMs) of azines and show that they fall into two major classes described as flat and shiplap. Second, we report on the supramolecular structure of polymorph **I** of para-chloroacetophenone azine **1** (Scheme 1, right). We reported polymorph **1-Ia** many years ago[30,37] and the recent crystallization of polymorph **1-II**[38] called for a careful comparison of the polymorphism. Third and most importantly, the deep analysis of flat **1-I** reveals an unexpected feature of the crystal packing. We will show that **1** adopts a C_2 symmetric structure (dissymmetric) in the gas phase. A cursory analysis also might suggest the occurrence of dissymmetric azine molecules in the crystal structure. However, careful analysis reveals that the azine molecules are experiencing an asymmetric environment causing the inequivalence of their two arenes. This inequivalence was initially revealed because of the recognition that only one arene of every azine engages in an arene-azine contact. To make this point in a comprehensive fashion, we will describe the full *intra*layer and *inter*layer interaction inventories of the two arenes in one azine molecule. The next-neighbor analysis demonstrates in a compelling fashion that the two arenes serve entirely different purposes in the layer architecture of the crystal. A survey of sixteen crystal structures of ten symmetrical azines shows that C_2 symmetry is the exception and crystal environment induced symmetry reduction (CEISR) occurs in twelve of those cases (Table 1).

Table 1 Overview of IAM types of symmetrical azines

#	X	CCDC Code	CCDC #s	Temp.	IAM Type	Azine twist	Ph1 twist	Ph2 twist	Symm.	CEISR	References
1-Ia	Cl	LIKHUI	1207287	295 K	AABB kick/flat	134.71	-29.31	-30.53	C_1	YES	*JOC*, 1994 [ref. 30]
1-Ib	Cl	LIKHUI02	2251374	100 K	AABB kick/flat	134.77	-28.96	-31.70	C_1	YES	This work
1-II	Cl	LIKHUI01	2027206	100 K	Ideal-shiplap/flat	180.00	-26.37	26.37	C_i	NO	This work
2-Ia	Br	LIKJEU	1207288	295 K	AABB kick/flat	131.85	-20.96	-27.26	C_1	YES	*JOC*, 1994 [ref. 30]
2-Ib	Br	LIKJEU03	2241667	100 K	AABB kick/flat	132.07	-29.39	-29.85	C_1	YES	This work
2-II	Br	LIKJEU02	2234130	150 K	Ideal-shiplap/flat	180.00	-26.33	26.33	C_i	NO	This work
3	I	LIZNEN	139916	173 K	Flat/flat-zigzag	141.82	-8.07	-8.07	C_2	NO	*JCC*, 1999 [ref. 33]
4	OH^a	BITTIH	1111781	295 K	Shiplap/ideal-flat	148.37	19.57	12.82	C_1	YES	*JCS PT2*, 1995 [ref. 51]
5	OPh	KIGBAG	1838227	293 K	Ideal-flat	143.34	-12.47	-12.47	C_2	NO	*CSD*, 2018 [ref. 41]
6	CF_3	WEWMET	1843926	173 K	Shiplap/double flat	114.38	-2.34	10.42	C_1	YES	*CSD*, 2018 [ref. 35]
7	F	LIKHOC	1207286	295 K	ABB/shiplap	137.99	1.87	-18.61	C_1	YES	*JOC*, 1994 [ref. 30]
8	Me	PIYYAX	1235041	295 K	ABB/shiplap	142.76	0.45	-19.89	C_1	YES	*ACIEE*, 1994 [ref. 32]
9-Ia	NO_2	ZEHJUR	1310588	295 K	AABB shiplap/flat	152.00	1.21	13.98	C_1	YES	*JCS PT2*, 1995 [ref. 50]
9-Ib	NO_2	ZEHJUR02	984384	130 K	AABB shiplap/flat	155.22	-0.93	12.34	C_1	YES	*JCS*, 2015 [ref. 34]
9-II	NO_2	ZEHJUR01	984383	140 K	Shiplap/flat	113.37	2.0	11.78	C_1	YES	*JCS*, 2015 [ref. 34]
10	OPr	HUXMIZ	2027208	100 K	Flat	134.40	-6.85	-15.11	C_1	YES	*CSD*, 2020 [ref. 36]

[a] Crystallized as hydrate.

The results of interaction inventory analyses also are provided for other flat azines **2-Ia** (Br),[39] **3** (I),[40] **5** (PhO),[41] and **10** (PrO)[42] to examine generality. The structural analyses focus on the topology of contacts between synthons, and the intermolecular interactions are quantified using Hirshfeld surface analyses, pairwise interaction energies, and electrostatic potential maps. We will also describe a fast method for the detection of CEISR based on N···H Hirshfeld 2-D fingerprint plots.

2. RESULTS AND DISCUSSION

2.1. Correlations of Azine and Phenyl Conformations

Azine **1**, 1,4-bis(p-chlorophenyl)-1,4-dimethyl-2,3-diazabutadiene crystallizes with a monoclinic unit cell in space group $P2_1/c$ and contains one independent molecule, see Fig. 1. The crystal structure of **1-I** was determined at 295 K (**1-Ia**) and 100 K (**1-Ib**) and we will discuss **1-Ia** or **I** for short. Form **I** contain two enantiomers **I-A** and **I-B** in equal numbers, that is, the crystal is a true racemate.[43] The azine is characterized by the torsion angle $\tau = \angle(\mathrm{C{=}N{-}N{=}C})$ and the phenyl twists ϕ_i, that is, the dihedral angles $\phi_1 = \angle(\mathrm{C7{-}C2{-}C1{=}N1})$ and $\phi_2 = \angle(\mathrm{C15{-}C10{-}C9{=}N2})$. In form **I**, the phenyl twists are *conrotatory* because the dihedral angles $\phi_1 = 29.32°$ and $\phi_2 = 30.53°$ have the same sign. Note the small difference in the twist angles.

The helicities of the C=N−N=C conformation (azine twist), the N1=C1−C2−C7 conformation (Ph1 twist) and the N2=C9−C10−C15 conformation (Ph2 twist) are defined as follows. For the C=N−N=C conformation, the helicity is referred to as *P* if a clockwise rotation is required about the N−N bond for the proximate C=N bond to eclipse the distal C=N bond and it is *M* if a counter-clockwise rotation is required.[44] For the phenyl twists at the two ends, *P*-helicity indicates that a clockwise rotation is required to eclipse the phenyl ring to the C=N bond while the *M*-helicity indicates a counter-clockwise rotation. The helicities and the conformations of both **I-A** and **I-B** are shown in Table 2. Enantiomers **I-A** and **I-B** have *P*- and *M*-helicity about the N−N bond as shown in Fig. 1. The azine *P*-helicity of **I-A** occurs with phenyl twist *M*-helicities for Ph1 and Ph2.

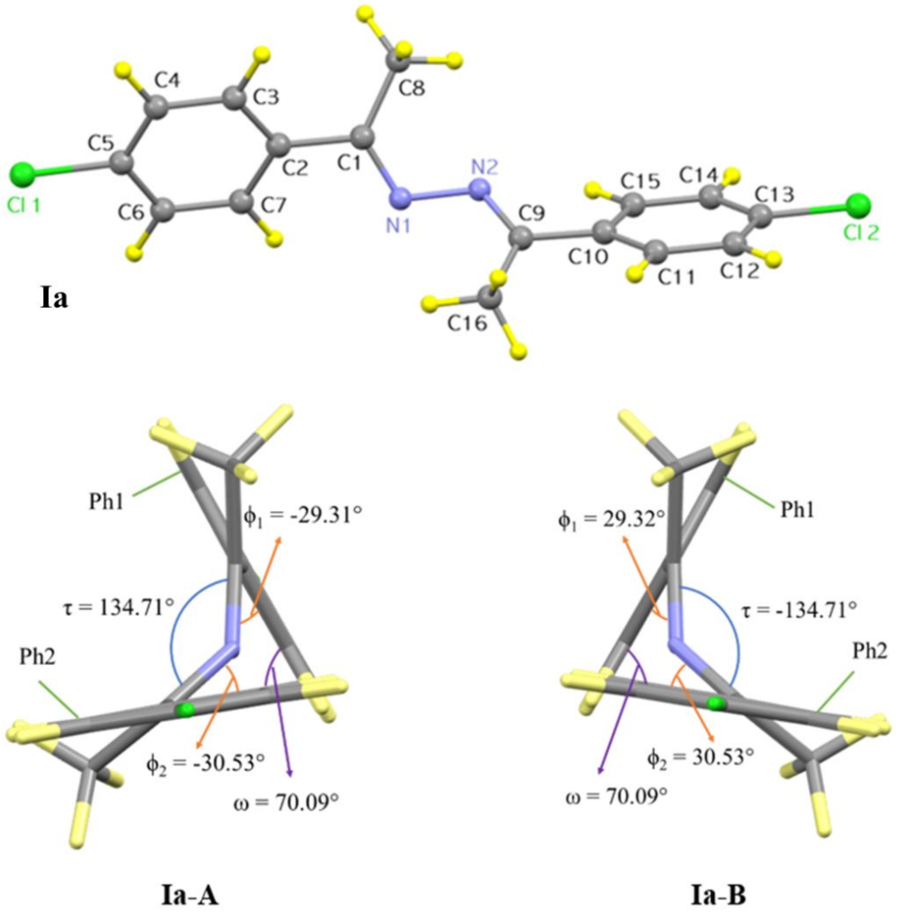


Fig. 1 ORTEP images of *(E,E)*-configured **1** azine in polymorphic form **I**. Newman projections viewed along the N–N bonds show the different helicities in enantiomers **I-A** (*P*-helicity) and **I-B** (*M*-helicity).

In **I**, the helicities of the two Ph twists are always the same in each azine molecule, so the accumulation of τ, ϕ_1 and ϕ_2 causes the two phenyl groups to be in two planes that intersect with angle $\omega = 70.09°$ (Fig.1).

Conformational preferences of the free azine **1** were studied with density functional theory (DFT)[45] at the APFD/6-311G* theoretical level, that is, we employed the Austin-Frisch-Petersson functional with dispersion (APFD)[46] together with the 6-311G* basis set.[47-49] Computations were performed with Gaussian 16[50] on the high-performance computer system at the University of Missouri.

Table 2. Azine and Phenyl Twists in Polymorph **I** of **1** and Helicity[a,b]

	Molecule	**I-A**	**I-B**
Azine twist	Helicity	*P*	*M*
	Angle (τ)	+134.71	-134.71
	Conformation	+ac	-ac
Ph1 twist	Helicity	*M*	*P*
	Angle (ϕ_1)	-29.31	+29.32
	Conformation	-sp	+sp
Ph2 twist	Helicity	*M*	*P*
	Angle (ϕ_2)	-30.53	+30.53
	Conformation	-sc	+sc

[a]Conformation are described as anticlinal (ac), anticlinal (ac), antiperiplanar (ap), synperiplanar (sp), and synclinal (sp) based on the torsion angle of τ and ϕ. [b]See text for definition of twist angles.

In the crystal structure of **I**, the helicity of the Ph twist is always opposite to the helicity of the azine twist. We wanted to know whether this feature is due to packing or whether we could locate additional minima with all possible permutations of azine and Ph helicities. Therefore, we performed APFD/6-311G* optimizations of **1** starting with the geometries of **I-A** and **I-B** but with opposite helicity of the Ph1 twist only ($\phi_1' = -\phi_1$, $\phi_2' = \phi_2$), with opposite helicity of the Ph2 twist only ($\phi_1' = \phi_1$, $\phi_2' = -\phi_2$), and with opposite helicity at both Ph1 and Ph2 ($\phi_1' = -\phi_1$, $\phi_2' = -\phi_2$). Information about the initial trial structures is provided in Table S1. It was found that no matter what initial helicities were chosen, all optimizations returned to the C_2-symmetric enantiomers of **1**. We conclude that the Ph and azine twists are strongly correlated and exhibit the same correlation in the gas phase and the crystal structure.

2.2. Idioteloamphiphile Monolayer Architectures

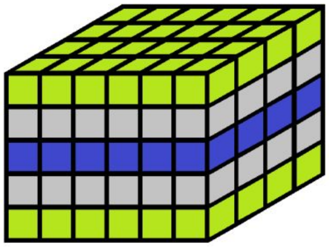
We have previously discussed possible arrangements of idioteloamphiphile monolayers (IAM) and of beloamphiphile monolayers (BAM).[22,26] Scheme 2 shows several options for IAMs. One symmetrical azine molecule is schematically represented by five units to indicate the substituents chlorine (green), the arenes (grey), and the azine bridge (blue). The simplest arrangement is the "ideal-flat" IAM, that is, all molecules are packed in the layer without any longitudinal offset *LOS* in either layer direction. The molecules are perpendicular to the layer surfaces and the molecule length *m* equals the distance between the IAM surfaces. We refer to a stripe as a slice of an IAM along either one of the IAM directions.

The longitudinal offset of a neighboring molecule is relative to the long axis of the parent molecule. We define "non-alternating" offset if the offset direction is the same from one molecule to the next in the same layer direction. And "alternating" offset occurs if the offset direction alternates from one molecule to the next in the same layer direction. The "flat" motif exemplifies a non-alternating offset in one layer direction (*LOS1*). Equivalently, the flat motif may be viewed as resulting from slanting all molecules relative to the IAM surface in one layer direction.

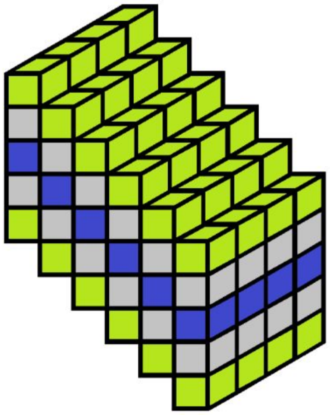
The "shiplap" motif exemplifies an alternating offset in one layer direction (*LOS1*) and Scheme 2 shows a general "shiplap" motif with the large *LOS1* = 3/5 *m* offset and the special case of the "ideal-shiplap" motif where *LOS1* = 1/2 *m*. The "ideal-shiplap" motif is realized in some other symmetrical azines[51] including **1-II** and **2-II**.[52] Arrangements with shiplap motifs with large *LOS* values can hardly be described as traditional monolayers. However, shiplap-like arrangements with *small* offsets do form monolayers. The "AB-Kick" and the "AABB-Kick" motifs are special shiplap-type IAMs with small *LOS1* values. The AABB-Kick architecture essentially is a double-stripe shiplap motif. The variation "AABB-Kick/Flat" combines the AABB-Kick motif in one layer direction (modest *LOS1*) with flat stripes (modest *LOS2*) in the orthogonal layer direction (Scheme 2, bottom center) and this layer architecture is central to the understanding of polymorph **I**.

Scheme 2. Types of Longitudinal Offsets in IAMs

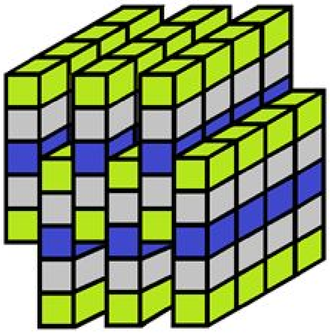
Ideal-Flat
LOS1 = 0
LOS2 = 0



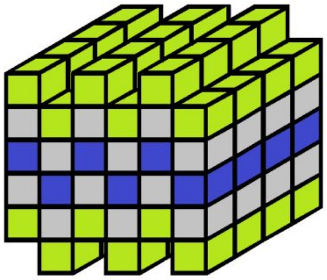
Flat
modest *LOS1*
non-alternating



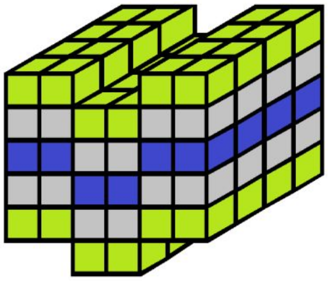
Ideal-Shiplap
LOS1 = 1/2 *m*
alternating



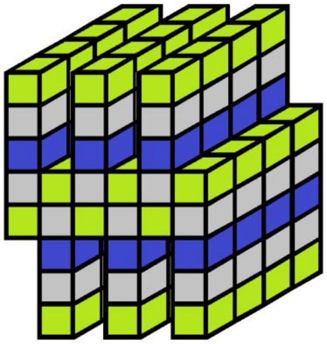
AB-Kick
modest LOS1
alternating



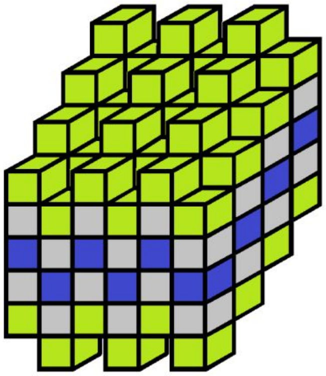
AABB Kick
modest *LOS1*
alternating



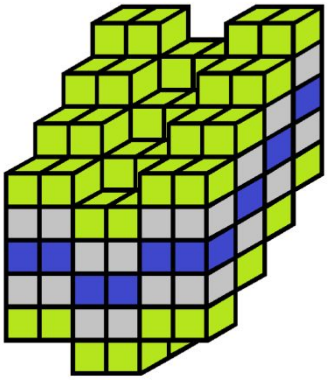
Shiplap
LOS1 = 3/5 *m*
alternating



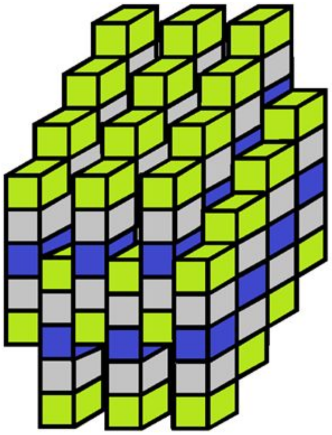
AB-Kick/Flat
modest LOS1
alternating
modest *LOS2*
non-alternating



AABB Kick/Flat
modest *LOS1*
alternating
modest *LOS2*
non-alternating



Ideal-Shiplap/Flat
LOS1 = 1/2 *m*
alternating
modest *LOS2*
non-alternating

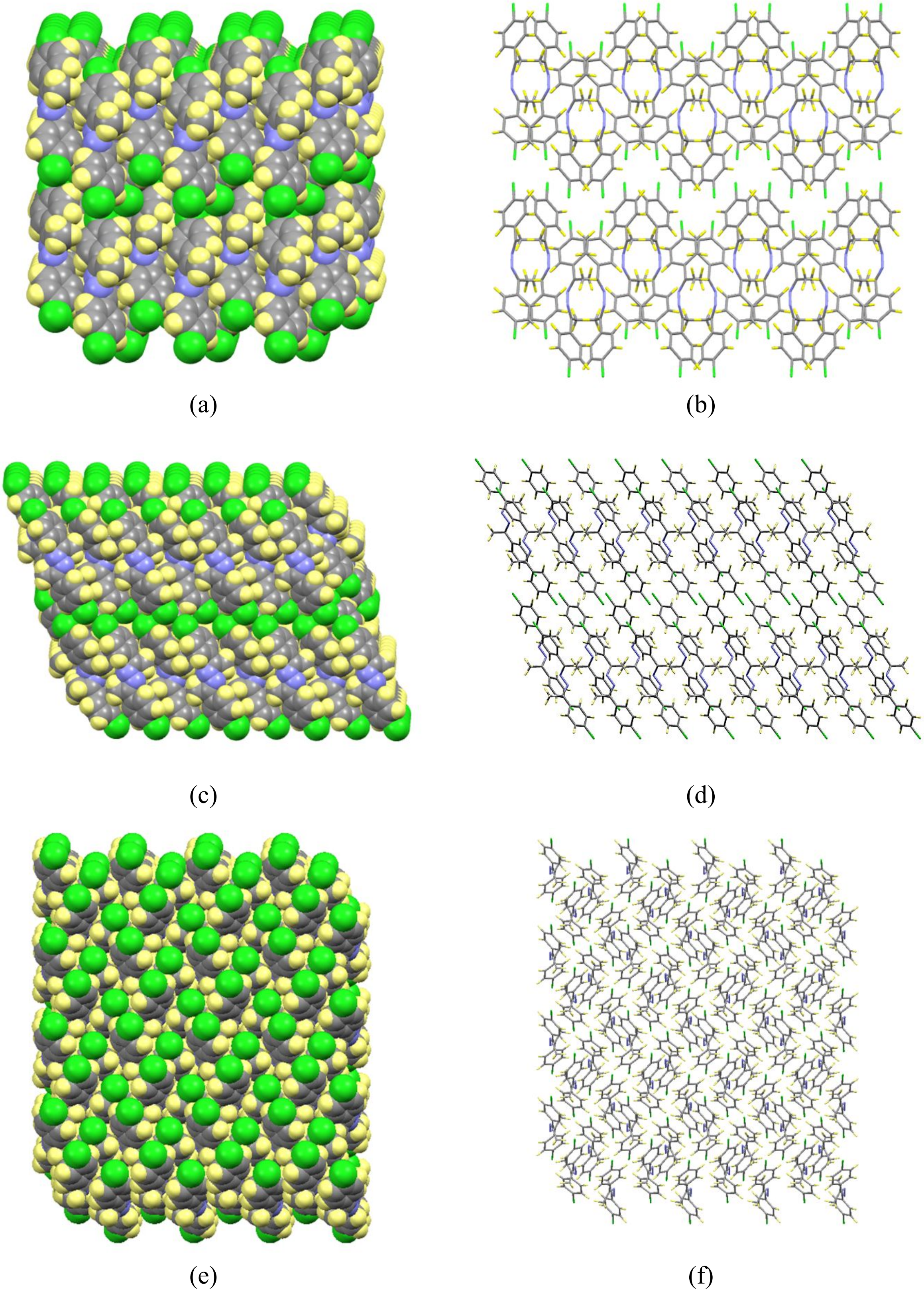


The description of Scheme 2 provides a rough overview of layer morphologies. In the following sections, we will add details about *intra*layer interactions, that is, the lateral interactions within the stripes in both layer directions and discuss the stacking of the IAMs and *inter*layer interactions.

2.3. Crystal Packing of Polymorph I

The IAM of polymorph **I** is of the AABB-Kick/Flat type and the layer directions are aligned with the crystallographic *b* and *c* axes and the layers are stacked in the *a* direction. The AABB-Kick motif in the *b* direction is illustrated beautifully by the space-filling model in Fig. 2a, and the flat nature of the stripes in the *c* direction results in the slanting seen in Fig. 2c.

The near C_2-symmetry of the unique molecule in polymorph **I** might lead one to assume that the two arenes in each azine molecule are more or less equivalent. In particular, one might expect that the intermolecular interactions of each arene with its neighborhood are essentially the same. Attentive readers may have noticed that the phenyl twists $\phi_1 = 29.32°$ and $\phi_2 = 30.53°$ are slightly but significantly different in polymorph **I** (Fig. 1). In fact, we will demonstrate that the *intra*layer coordination modes of the two arenes in one azine molecule differ greatly. This will be accomplished by analysis of the *intra*layer pairs **Q** - **W** as well as the *inter*layer pairs **X** and **Y**. The entire analysis is made from the perspective of one azine molecule denoted by *, which we chose to have *P* helicity, and the analysis results in the interaction inventory of Table 3.



(a) (b)

(c) (d)

(e) (f)

Fig. 2 Crystal alignment of **1** polymorph **I** in four layers. Space filling models (left) and tube models (right) are shown. (a, b) View down the *c* axis with the *b* axis pointing to the right and *a* axis pointing up (top row). (c, d) View down the *b* axis with *a* axis pointing up and *c* axis pointing to the left (bottom row)

Table 3. *Intra*layer and *Inter*layer Interaction Inventory of **1-I**

<table>
<tr><th>X</th><th>*(<i>P</i>)</th><th colspan="8">Neighbors of the starred molecule</th></tr>
<tr><td>Cl</td><td></td><td>Q(<i>M</i>)</td><td>T(<i>M</i>)</td><td>R(<i>M</i>)</td><td>U(<i>M</i>)</td><td>V(<i>P</i>)</td><td>W(<i>P</i>)</td><td></td><td></td></tr>
<tr><td><i>Intra</i></td><td>A_i*</td><td>f|e(A_s)</td><td>e|f(A_i)</td><td>Cl|Me(A_s)</td><td>f|e(A_s)</td><td>vdW</td><td>e|Az</td><td></td><td></td></tr>
<tr><td>IAM</td><td>A_s*</td><td>e|f(A_i)</td><td>f|e(A_s)</td><td>Me|Cl(A_i)</td><td>e|f(A_i)</td><td>vdW</td><td>vdW</td><td></td><td></td></tr>
<tr><td></td><td>Az*</td><td></td><td></td><td></td><td>Az|Me(A_i)</td><td>Az|e(A_i)</td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td>Me(A_i)|Az</td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td>Z_1’(<i>M</i>)</td><td>Z_1(<i>M</i>)</td><td colspan="2">X(<i>M</i>)</td><td>Z_2(<i>P</i>)</td><td>Z_2(<i>P</i>)</td><td>Y’(<i>P</i>)</td><td>Y(<i>P</i>)</td></tr>
<tr><td><i>Inter</i></td><td>A_i*</td><td>Cl|e(A_s)</td><td></td><td colspan="2"></td><td></td><td></td><td>Cl|Cl(A_s)</td><td></td></tr>
<tr><td>IAM</td><td>A_s*</td><td></td><td>e|Cl(A_i)</td><td colspan="2">f|Cl(A_s) & Cl|f(A_s)</td><td>e|Cl(A_s)</td><td>Cl|e(A_s)</td><td></td><td>Cl|Cl(A_i)</td></tr>
</table>

[a]See Fig. 5 for definition of *intra*layer neighbors **Q** - **W** and Fig. 6 for definition of *inter*layer neighbors **X** – **Z_2**.
[b]vdW = non-specific van der Waals interaction.

2.3.1. Double-T Contacts Stabilize the Double-Stripes

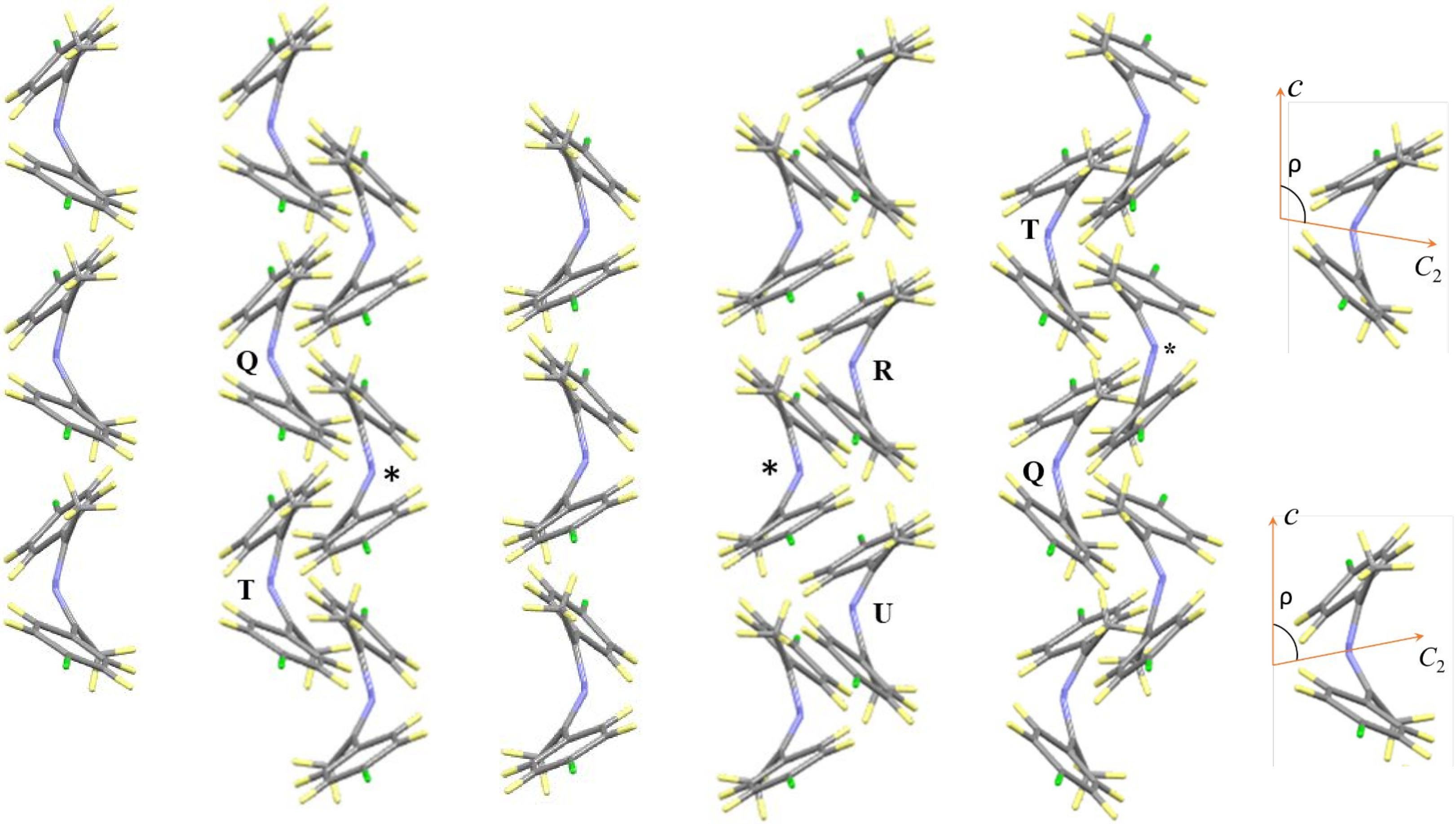
We now refine the discussion of the packing of polymorph **I** with the help of Fig. 3. The double-stripes AA and BB are shown together with their respective single stripes. Every stripe contains azine molecules stacked along the *c* direction. Inspection of Fig. 3 shows that the “AA” and “BB” double-stripes each contains one stripe composed entirely of azine with *M* helicity and another one with *P* helicity. The double-stripe is energetically favorable because it allows for strong double-T contacts between the molecules in both stripes.

A T-contact between two arenes involves CH---π interaction and may involve one C−H bond pointing toward the center of an arene face (^{1}T). The geometry of the benzene dimer in the gas phase involves a ^{1}T-contact.[53] However, in the crystal structures of benzene a new type of T-contact occurs.[54] In this T-contact, the geometry of neighboring arenes involves an arene edge of the C−H donor to be almost parallel to an arene face and creates a ^{2}T-contact. Such a ^{2}T contact may involve one C−H bond or two C−H bonds of the arene edge (e) to engage in CH---π interactions with an arene face (f). For the characterization of such an edge-to-face T-contact (e|f), it suffices to specify the distance between the arene center and the closest C−H hydrogen. Unless otherwise noted, all ^{2}T-contacts discussed in the following are simply referred to as T-contacts and denoted (f|e) or (e|f). This nomenclature is used in Table 3 where column 2 refers to the arene of the starred molecule in position 1 and the arene of the neighbor in position 2 is listed explicitly.

A double T-contact occurs if the arene moieties of one azine forms two T-contacts with a neighbor.[26] For a twisted azine, one arene functions as a face (f) in a T-contact while the other arene serves as an edge (e). The neighboring molecule uses one arene as a face and one as edge, but in the opposite direction. The double T-contact comes in two varieties, the closed and the open forms. In the closed form, the arene edge that is close to the methyl group engages in the T-contact whereas in the open form, the arene edge that is close to the azine-N engages in the T-contact.

The difference between the AA and BB double-stripes is subtle. Note that none of the C_2 axes of the azines in double-stripe AA or BB are parallel to the *b* direction. Instead, in the AA double-stripe, the *M* molecules all are rotated a few degrees counterclockwise around the *a* direction whereas the *P* molecules are rotated in the opposite direction. As the consequence, the angle ρ enclosed between the *c* direction and any of the C_2 axes will be smaller than 90° for the AA double-stripe. In the BB double-stripe, all rotations about the *a* direction are opposite to what they are in the AA double-stripe with the result that $\rho > 90°$. The AB interface is illustrated by the A(*P*)B(*M*) double stripe (Fig. 3). We have already discussed each of the stripes, and the only novelty concerns the formation of open double-T contact between the stripes.

The starred molecule in the double stripe AA is engaged in two next neighbor interactions with the molecules **Q** and **T** as well as the two next neighbor interactions **R** and **U** in the adjacent B stripe. Any molecule in any stripe interacts with four neighbors with the same four interactions. The BB stripe in Fig. 3 results by rotation of the AA stripe around the *b* axis and illustrates the presence of the same **Q** and **T** pairs.



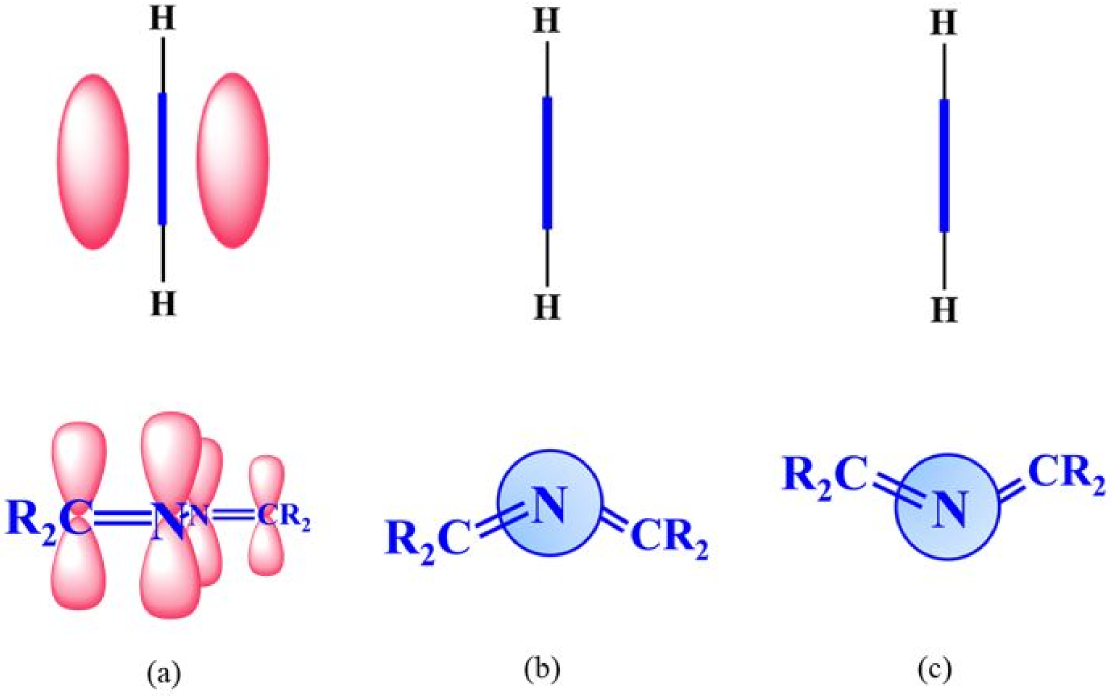
A(*M*) “AA” = A(*M*)A(*P*) A(*P*) “AB” = A(*P*)B(*M*) “BB” = B(*M*)B(*P*)

Fig. 3 The subtle difference between the AA and BB double-stripes is due to different rotations of the azines about the *a* direction. See texts for detail.

2.3.2. Arene-Azine Contacts and Enantiopure Directed Chains

A second, and unexpected, intermolecular interaction in our crystals is the arene-azine contact shown in Scheme 3. An arene-azine contact occurs between the azine bridge (−C(Me)=N−N=C(Me)−) of one molecule and a phenyl ring of an adjacent molecule. We have reported an *ab initio* study of the quadrupole moment of the parent azine, $H_2C=N-N=CH_2$, and we showed that the azine group is highly quadrupolar.[55] The illustration in Scheme 3a depicts an e|Az contact with a planar azine; the π clouds are shown of the arene and the azine which are the negative pole regions surrounding the positive pole region containing the atoms. In fact, on a per electron basis, the azine functional group is almost as quadrupolar as benzene. For a twisted azine, two options could be realized as shown in Schemes 3b and 3c.

Scheme 3. An Arene-Azine Contact e|Az Involves the Approximate Edge-To-Face Alignment of One Arene Edge with the Azine Face with the Arene Edge Approaching the N−N Bond. (a) The e|Az Contact with a Planar Azine. An Azine with an Azine Twist may Engage in Either (b) A Convex e|Az Contact or (c) A Concave e|Az Contact.



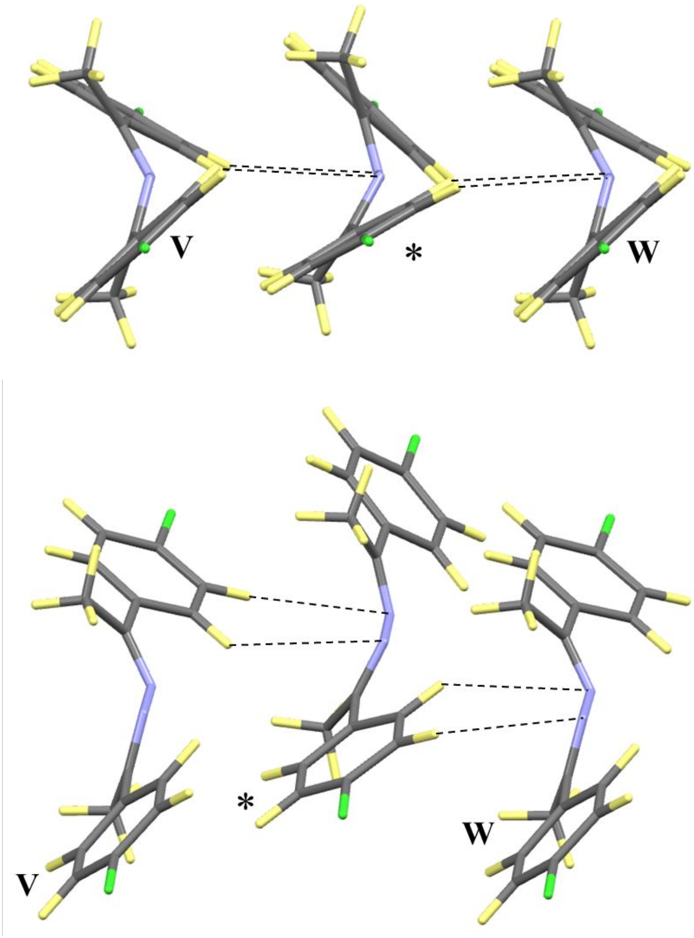


Fig. 4 Two perspectives are shown of an aggregate of three azines with dashed lines indicating short distances in two concave e|Az contacts. The starred molecule in the center engages its azine moiety in an e|Az contact with the distal arene on the left (**V**) and it also engages its proximate arene moiety with the azine moiety of its neighbor to the right (**W**).

In crystals of **I**, only the concave e|Az option is observed. Each azine molecule engages in two e|Az contacts serving as an azine receptor in the contact with neighbor **V** and as an arene edge in one contact with neighbor **W** (Fig. 4). The result of the e|Az contacts is a directed e|Az bonded chain of azines. Note that all three molecules in Fig. 4 are the same enantiomer (*P*) and that the molecule in the center is flipped around the direction of the e|Az bonded chain. In Fig. S1 (ESI†), we show two adjacent anti-parallel e|Az bonded chains.

2.3.3. Arene Interaction Inventory: Inside and Surface Arenes

It is crucial to realize that it is only one arene of every azine that engages in such an e|Az contact and, moreover, it is the same arene in every molecule. It was this insight into the arene-azine contacts that shattered the assumption that the arenes in the near-C_2 azine experience the same environments. The coordination modes of the inside arene (A_i) and the surface arene (A_s) differ greatly, and it is only the inside arene A_i that engages in one e|Az contact while the surface arene does not. All next-neighbor interactions of A_i* and A_s* of the starred molecule are shown in Fig. 5, and their analysis allows for the completion of the *intra*layer interaction inventory of Table 3. Here and in similar tables below arene-arene T-contacts are highlighted in red, interactions between an arene edge and an azine moiety are listed in blue, and contacts between arene and a substituent atom are listed in green. Special attention will be placed on the arene interaction inventories of A_i and A_s to demonstrate their inequality or equality.

In Fig. 5a, we show one slab of the IAM of polymorph **I** with five stripes and one molecule in stripe 3 is marked by "*" and surrounded by eight azines. The starred molecule and the two molecules marked **S** all belong to the same stripe, and the interaction of the starred molecule with either one of the molecule **S** must be the same. We refer to the pair interaction between the starred molecule and one of its neighbors by the label of that neighbor. Pair **S** is shown in Fig. 5b and it is a stacked dimer with flat offset *LOS2*. While the stripe motif is the preferred building block to describe the lattice architecture, the binding within the stripe is negligible with the centers of stacked arenes more than 10 Å away from each other. The molecules in stripe 3 are stabilized by their interactions with the proximate molecules in the directly attached stripes (stripes 2 and 4) and in the second-nearest stripes (stripes 1 and 5).

We began with an analysis of the coordination of the inside arene of the starred molecule A_i*. Stripe 2 forms double-T contacts with stripe 3 and their ρ angles identify this double-stripe as BB type. Molecules **Q** and **T** engage in modest offset double-T contacts with the starred molecule, see Fig. 5c. Arene A_i* engages as a face in a T-contact with the edge of the A_s(**Q**); this $f(A_i)|e(A_s)$

contact is abbreviated as "f|e(A_s)" in Table 3. The same arene A_i* engages as an edge in a T-contact with the face of the A_i(**T**); "e|f(A_i)" for short. Molecules **R** and **U** in stripe 4 are easily identified as belonging to an A stripe and the pairs **R** and **U** (Fig. 5d) are vastly different. The geometry of pair **R** may formally be described as a pair of methyl halogen contacts Cl|Me(A_s). The dimer **U** features a beautiful open double-T contact in which the face of A_i* forms an f|e(A_s) contact. Note that all these *intra*layer edge contacts involve just one of the edge hydrogens, namely the hydrogen in the ortho position (H_o) with respect to the azine, and such edges are abbreviated e_o. We will see later that the meta hydrogens (H_m) may be engaged in *inter*layer contacts with e_m edges. While the Me(A_s) methyl groups engage halogens in **R**, the Me(A_i) methyl groups engage azine-N in **U** and the Me(A_i)|Az and Az|Me(A_i) contacts are illustrated in Fig. 5d.

In Table 3, a border is drawn around pairs of T-contacts between the starred molecule and the same neighbor and they define a double T-contact. For example, the double T-contact of the starred molecule with neighbor **Q** includes the f(A_i*)|e(A_s) and e(A_s*)|f(A_i) T-contacts. Molecules **Q** and **T** engage in closed double T-contacts (shaded light red) while molecule **U** forms an open double T-contact (shaded light blue). Comparison of the rows for A_i* and A_s* shows that the inside arene A_i* engages in two T-contacts as edge (e|f(A_i), e|Az) and in two more T-contacts as face (both f|e(A_s)). The surface arene A_s* also engages in two T-contacts as edge (both e|f(A_i)), but only in one T-contact as face (f|e(A_s)). Therefore, the arene interaction inventory reflects in a compelling fashion that the coordination modes of the two arenes of **1** are not equivalent. While it was the analysis of the arene-azine contacts that initially brought this inequivalence to the fore, the analysis of the arene-arene contacts is easier to perform and therefore advantageous to examine arene equivalence or inequivalence.

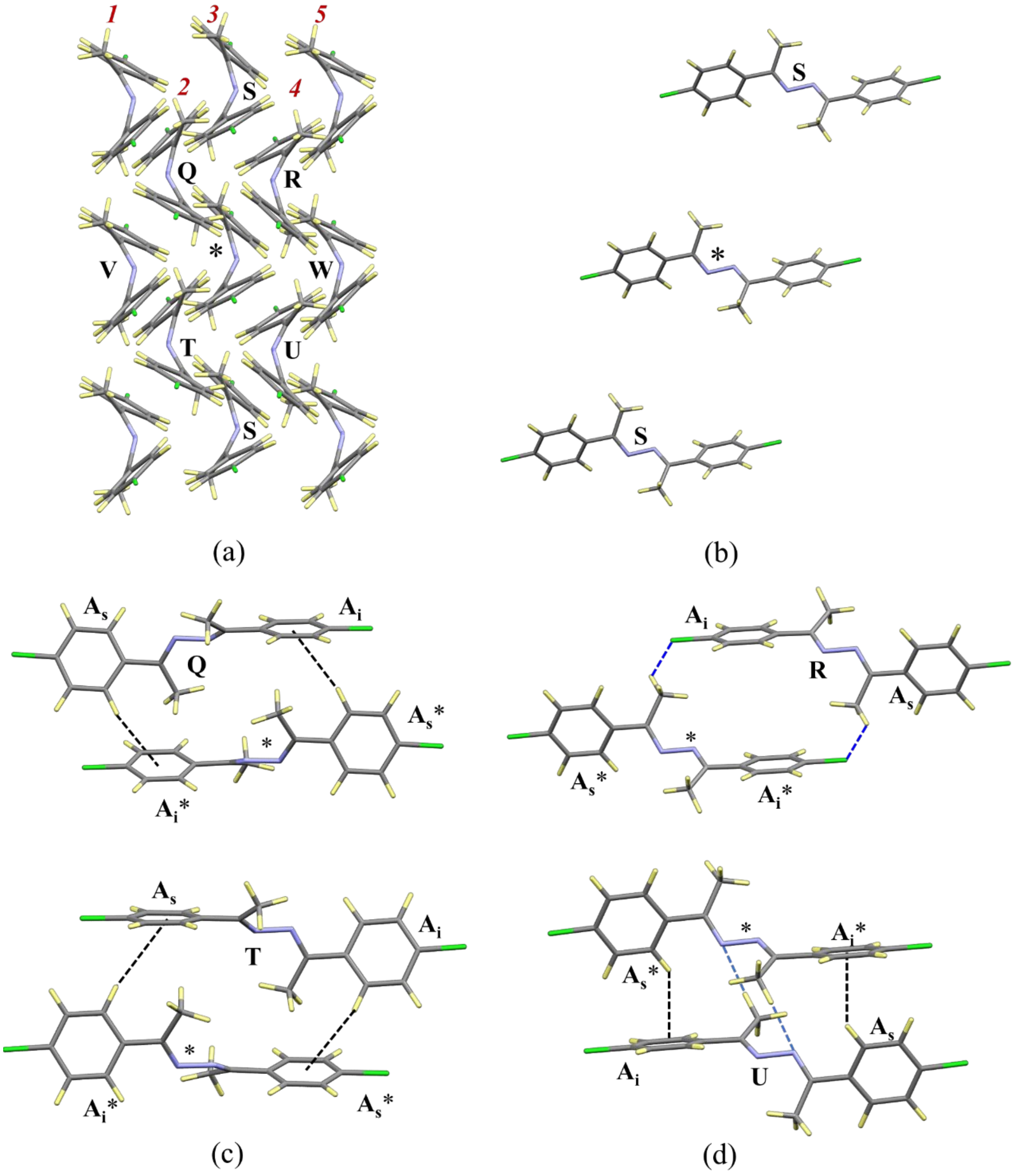
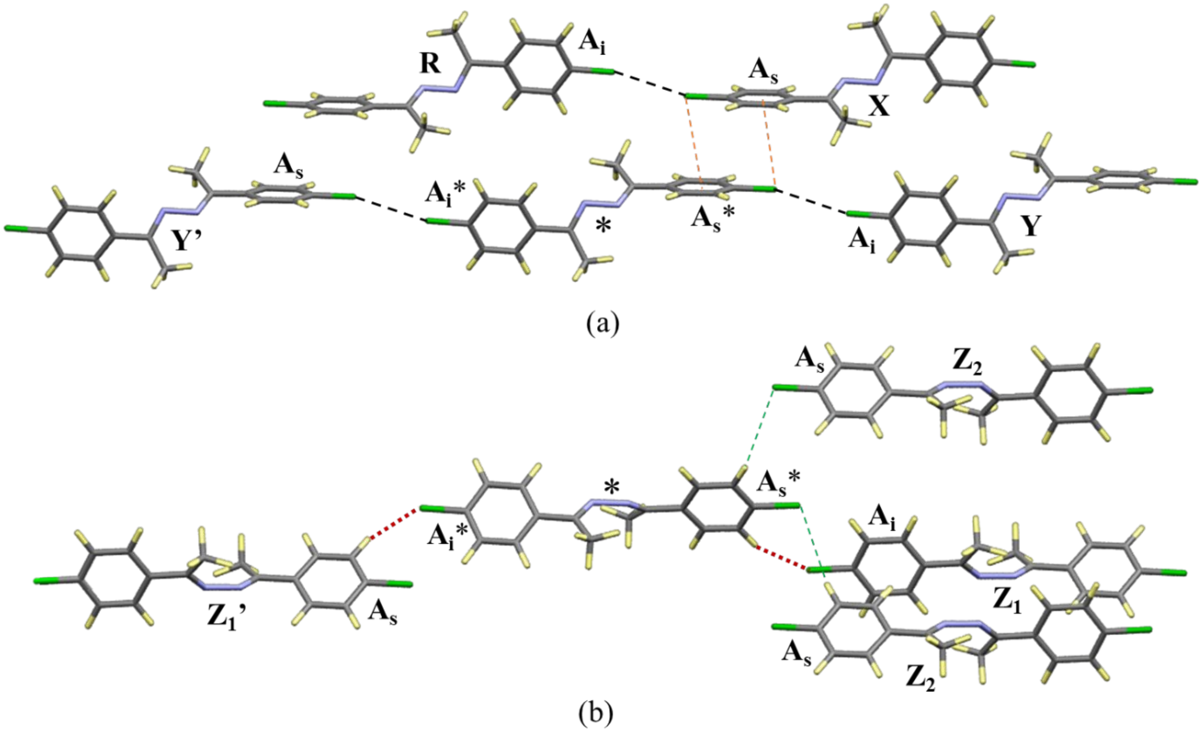


Fig. 5 The starred molecule **1** in polymorph **I** interacts with six neighbors using five types of interactions **Q**, **R**, **S**, **T** and **U**. (a) IAM structure viewed down the N-N bond axis (*a* axis). (b) Stripe 3 is shown along the *b* direction and illustrates **S** type pairing. (c) The pairing of the starred molecule in stripe 3 with molecules **Q** and **T** of stripe 2 is shown along the *b* direction. (d) The pairing of the starred molecule in stripe 3 with molecules **R** and **U** of stripe 4 is shown along the *b* direction.

2.3.4. IAM Stacking Interaction

The remaining face of the surface arene A_s* engages in face-on type Cl---π *inter*layer interaction with neighbor **X**, f|Cl(A_s) in Table 3. The f|Cl(A_s) contact is associated with a contact between the chlorine substituent Cl(A_s*) and the face of the A_s arene in neighbor **X**. At the same time, the arene A_s engages in the same type of contact with the chlorine of the same neighbor, Cl|f(A_s). In addition, the Cl atom on A_s* engages in *inter*layer halogen bonding with Cl(A_i) of neighbor **Y** (right in Fig. 6a). For the Cl atom of A_i*, the *inter*layer halogen bonding interaction with Cl(A_s) of neighbor **Y'** is the only important contact (left in Fig. 6a).



(a)

(b)

Fig. 6 The surface arene A_s* engages in one face-to-face stacking interaction with the surface arene of the *inter*layer neighbor **X**. Halogen bonding contacts occur between the Cl atoms attached to A_s* and A_i* with the inside arene of neighbor **Y**, A_i[**Y**] and the surface arene of neighbor **Y'**, A_s[**Y'**], respectively. In (b) A_s* engages in three H---Cl contacts but A_i* only engages in one such contact.

Fig. 6b illustrates four *inter*layer contacts of the type Cl|e between a chlorine of one chloroarene and one hydrogen of the other chloroarene (the edge-H meta to the azine). Again, the A_s arene is much more engaged in these kinds of *inter*layer interactions compared to the A_i arene; A_s engages in three Cl|e contacts (right in Fig. 6b) while A_i engages in only one (left in Fig. 6b). The chloroarene with A_s serves as e|Cl(A_i) contact with a $\mathbf{Z_1}$ neighbor and it serves both as Cl|e(A_s) and e|Cl(A_s) contacts with two $\mathbf{Z_2}$ neighbors. A_i* engages only in one such contact Cl|e(A_s) with $\mathbf{Z_1}$'.

2.3.5. Quantifying Structural Parameters of Intermolecular Interactions

We want to supplement the topological analysis of intermolecular interactions with quantitative measures. In Table 4 all of the discussed pair interactions are characterized with focus on chlorine-chlorine, arene-arene, and arene-chlorine distances; *d*(Cl*---Cl), *d*(Ph*---Ph), *d*(Cl*---Ph), and *d*(Ph*---Cl). We also characterize the shortest distance between the arene center and the proximate edge H atom (H_e); *d*(H_e*---Ph) and *d*(Ph*---H_e). For contacts **V** and **W**, the distances are given between the center of the N–N bond and the closest proximate H_e atom; *d*(H_e*---Az) and *d*(Az*---H_e). The most important distances are shown in red face. For contacts $\mathbf{Z_1}$ and $\mathbf{Z_2}$, the distances are given between the chlorine atom and the proximate edge H atom (H_e); *d*(H_e*---Cl) and *d*(Cl*---H_e).

The Cl---π interaction between the Cl–A_s moieties is of the face-on type.[56,57] The distance between the Cl atom of the starred molecule and the center of the arene of the **X** is *d*(Cl*, A_s[X]) = 3.86 Å, and the distance between the centers of the two arenes is *d*(A_s*,A_s[**X**]) = 4.51 Å. The Cl atom of the Cl–A_s moiety of the starred azine is also interacting with the Cl atom of Cl–A_i moiety of *inter*layer neighbor **Y** (Fig. 6a). This Cl interaction is characterized by the very short non-bonded distance *d*(Cl---Cl) = 3.34 Å. The van der Waals radius of chlorine is 3.70 Å,[58] and the very short distance between the chlorines suggests rather strong halogen bonding.[59] Note that the comparable non-bonded Cl---Cl distance in the crystal of chlorobenzene is 3.7 Å.[60]

Our topological discussion was based on the analysis of arene-arene interactions and T-contacts in particular. While this approach is conceptually appealing, a more refined analysis requires the consideration of chloro-arene contacts. With the exception of the two long Cl---Cl distances of pairs **S** and **R**, all Cl---Cl distances are significantly shorter than their van der Waals distance of 7.4 Å.[58] We already stressed the rather short *inter*layer Cl---Cl contact of 3.34 Å in pair **Y**. Also, of note is the *intra*layer Cl---Cl contact of 4.73 Å in pair **U**.

*Inter*layer bonding is provided by C−H---Cl contacts[61,62] between para-Cl and meta-CH groups (Fig. 6b). The C−H---Cl contacts are reasonable if the distance *d*(Cl---H) is shorter than 3.35 Å. The Cl atom of the Cl–A_i moiety of the starred azine interacts with the H atom of *inter*layer neighbor **Z_1'** with the very short non-bonded distance *d*(Cl*---H) = 2.92 Å (red dots, Fig. 6b). Similar contact involves the A_s moiety of the starred molecule, where the arene A_s* provides its hydrogen to form a contact with the Cl atom of neighbor **Z_1**. Arene A_s* forms two more C−H---Cl contacts with the neighbors **Z_2** and the distance *d*(Cl*---H) = *d*(H*---Cl) = 3.36 Å (green dots, Fig. 6b).

The geometry of the benzene dimer in the gas phase was measured by microwave spectroscopy and the ^{1}T-contact is characterized by a distance between the arene centers of 4.96 Å.[53] For the crystal structure of benzene, the ^{2}T-contact features a C−H---π distance of 2.96 Å and an arene-arene distance of 5.05 Å.[54] For chlorobenzene, the ^{1}T-contact features a C−H---π distance of 2.81 Å and an arene-arene distance of 4.92 Å (CCDC number: 1050587).[60] In a ^{2}T-contact, the typical distance between the center of the face arene and the proximate edge-Hs is 2.91±0.12 Å[63] and the typical distance between the arene centers is 4.85±0.15 Å. Strong face-to-face contacts are characterized by arene-arene distances of typically 3.7±0.3 Å.[64-66] Para-chloroacetophenone exemplifies a donor-acceptor substituted benzene and its crystals feature an arene stacking distance of 4.01 Å (CCDC number: 248149).[67]

Table 4. Intermolecular Distances Characterizing *Intra*- and Inter-layer Chloroarene Pair Interactions in Polymorph **I**[a-e]

	Cl*---Cl	Ph*---Ph	Cl*---Ph	Ph*---Cl	H_e*---$(\frac{Ph}{Az})$	$(\frac{Ph}{Az})$*---H_e	H_e*---Cl	Cl*---H_e
$(A_i\text{-}Cl)*$								
S	10.46	10.46	8.99	12.55	8.79	8.78	11.17	7.96
Q	5.86	5.71	4.90	7.89	5.68	3.77	7.18	3.44
T	5.86	5.71	7.89	4.90	3.77	5.56	3.44	7.18
R	8.44	8.51	6.12	11.20	6.74	7.57	9.59	5.39
U	4.73	**4.86**	5.19	6.19	5.15	4.40	5.72	3.04
V	6.05	5.99	4.74	8.33	3.13	**2.99**	3.46	3.46
W	6.22	6.28	4.77	8.65	**2.99**	3.13	3.37	3.37
Y'	**3.34**	9.46	6.38	6.38	NA	NA	5.44	5.40
Z_1'	4.29	7.56	5.31	5.28	NA	NA	3.05	**2.92**
$(A_s\text{-}Cl)*$								
S	10.46	10.46	12.55	8.99	9.20	9.18	7.96	11.17
Q	5.96	5.87	7.99	5.05	3.56	5.49	3.31	7.40
T	5.96	5.87	5.05	7.99	5.49	3.56	7.24	3.26
R	8.44	8.51	11.20	6.12	7.57	6.74	5.39	9.59
U	4.73	**4.86**	6.19	5.19	4.75	5.15	3.04	5.72
V	6.22	6.28	8.64	4.77	7.01	6.67	6.74	6.74
W	6.05	5.99	8.33	4.74	6.67	7.01	6.38	6.38
X	5.37	**4.51**	**3.86**	**3.86**	NA	NA	4.03	4.03
Y	**3.34**	9.46	6.38	6.38	NA	NA	5.40	5.44
Z_1	4.29	7.56	5.28	5.31	NA	NA	**2.92**	3.05
Z_2	4.83	7.24	5.22	5.22	NA	NA	3.36	3.36

[a]All distances are in Ångström. [b]Column "Cl*---Cl" lists the intermolecular Cl---Cl distances between in a chloroarene pair. [c]Column "Ph*---Ph" lists the intermolecular distances between the centers of the arenes in a chloroarene pair. [d]Columns "Cl*---Ph" and "Ph*---Cl" list the intermolecular distances between the chlorine of one chloroarene and the center of the other. [e]Columns "H_e*---Ph" and "Ph*---H_e" list the intermolecular distances between the center of one chloroarene and the closest edge H of the other. For **V** and **W**, the values "H_e*---Az" and "Az*---H_e" are given in italics and specify the distance between an edge H and the center of the azine N–N bond.

We cast the topological analysis in terms of double T-contacts **Q**, **T**, **R**, and **U** as an explanatory device. Only numbers shown in Table 4 in red and bold face indicate strong arene-arene interactions. It becomes immediately clear that only the pair interaction **U** is a strong double T-contact, while pairs **Q** and **T** are marginal double T-contacts at best. *Intra*layer Cl---Cl interactions are unimportant and there is only strong *inter*layer Cl---Cl interaction associated with pair **Y**. Finally, the data in Table 4 demonstrate that the Cl---π interactions are only important for the *inter*layer interaction **X**.

2.4. CEISR Concept and Its Generality

We have demonstrated the origin of the symmetry reduction of azine **1** from C_2 to C_1 and we have shown in a compelling fashion that the arenes A_i and A_s in each azine engage in qualitatively different intermolecular interactions. The packing related molecular symmetry reduction described for chloroazine **1** results from qualitatively different coordination environments of moieties that otherwise could be symmetric. We refer to this consequence of the crystal packing as crystal environment induced symmetry reduction (CEISR) effect. We believe that a new term is warranted because the observed phenomenon is not limited to this one case. Following the analysis of the chloroazine **1**, we reviewed sixteen crystal structures of symmetrical azines and that could be C_2 symmetric (Table 1). As with Table 3 for chloroazine **1**, we created *intra*layer and *inter*layer interaction inventories for crystals with similar supramolecular structures as **1** to examine the possible occurrence of CEISR. As can be seen, C_1 symmetry occurs for **2-Ia** (Br) and **10** (PrO) whereas C_2 symmetry occurs for **3** (I) and **5** (OPh). The results for **2-Ia** (Br) and **10** (PrO) summarized on top of Table 5, **3** (I) and **5** (PhO) are summarized on the bottom of Table 5, and the intermolecular pair interactions are described in Fig. S3-S6 (ESI†).

The entries in Table 5 show that the *intra*molecular contacts of **2-Ia** are qualitatively the same as with **1-I**. The dominant *inter*molecular contacts again are Br---π interactions between bromoarenes. The f|Br(A_s) contact involves the bromine Br(A_s*) and the face of the A_s arene in neighbor **X**, Br|f(A_s) contact in Table 5. While the Cl---π contacts in **I** occur between pairs of chloroarenes, the Br---π contacts in **2-Ia** create chains (Fig. S10b, ESI†).

The arene inventory of **10** shows that the inside arene A_i* engages in two T-contacts as face (f|e_o(A_s) with **Q** and **U**) and in one more T-contact as an edge (e_o|f(A_s) with **T**). The surface arene A_s* also engages in three T-contacts overall, but A_s* serves as edge twice (e_o|f(A_i) with **Q** and **U**) and as face only once (f|e_o(A_i) with **T**). This difference between the coordination of A_i and A_s in the three arene-arene T-contacts already suffices to establish the inequivalence of A_i and A_s. Further evidence for their inequivalence is provided by the nature of the **R** contacts. The edge-H_{ortho} (e_o) of A_i* engages in a contact with azine-N (e_o|Az and Az|e_o(A_i) with **R**) whereas A_s* serves as a face in a contact with a methylene-H of the propoxyl group attached to A_i (f|CH_2(A_i) and CH_2|f(A_s) with **R**). While the edge of A_i* engaged with neighbor **R** only uses its H_o, the other edge of A_i engaged with neighbor **T** employs both its H_o and H_m; H_o for the arene-arene T-contact and H_m for the contact with the propoxyl-O attached to A_s (e_m|O(A_s) with **T**).

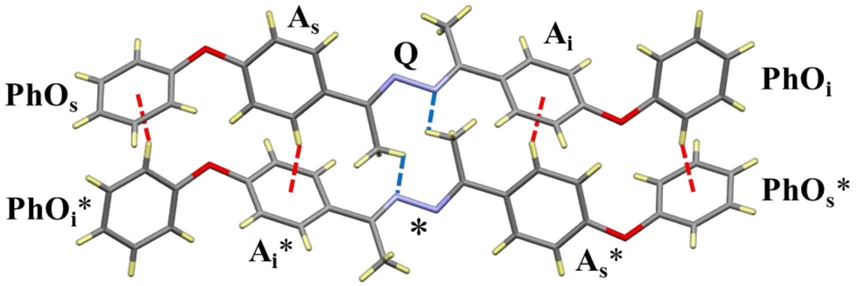
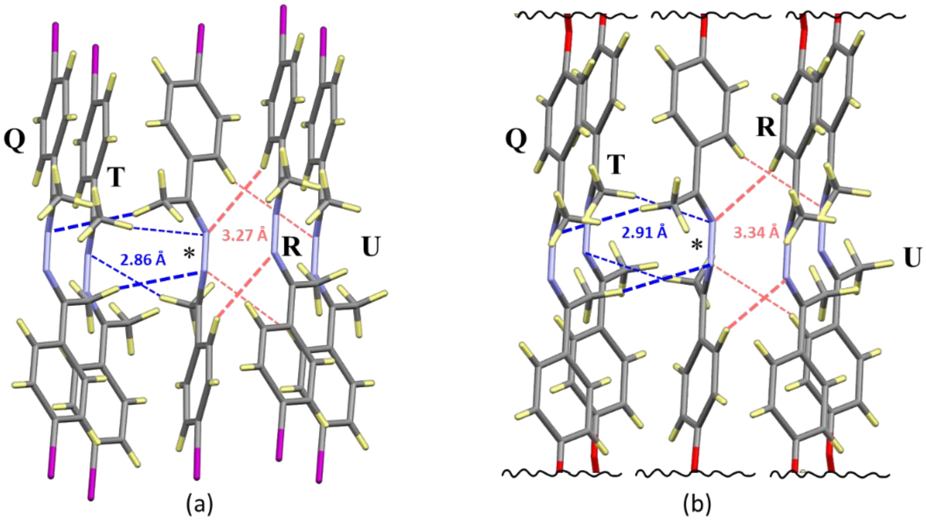


Fig. 7 The pair **Q** of phenoxyazine **5** illustrates an arene-arene quadruple T-contact. See text for details.

The IAM architectures of **3** (I) and **5** (PhO) are easier to describe. These crystals contain C_2 symmetric azines and each azine engages its A_i and A_s arenes in four double T-contacts, two closed ones and two open ones (Table 5). Phenoxyazine **5** is special in that it exemplifies the first pair of azines featuring well defined quadruple T-contacts, and Fig. 7 exemplifies one such quadruple T-contact in pair **Q**. Not only do the A_i and A_s arenes engage in double T-contacts but the arenes of the phenoxy groups PhO_i and PhO_s also engage in T-contacts. Two more rows are needed in Table 5 to describe the arene-arene interactions between the phenoxy-phenyls and each T-contact is represented by one purple shaded cell.

The *inter*layer interactions involve only iodine-iodine bonding for **3** while the *inter*layer interactions for **5** are provided by face-to-face contacts between phenoxy phenyls. We have pointed out the Az|e contacts as a prominent feature of the crystals with C_1-symmetric azines in **1-I**, **2-Ia** and **10** and these contacts only engage one arene (A_i) of the starred azine. In the crystals of the C_2-symmetric azines **3** and **5** the Az|e contacts involves both A_i and A_s.



(a) (b)

Fig. 8 The starred molecule in the center of (a) **3** (I) and (b) **5** (PhO)-azines engages its azine moiety with both of its arenes A_i and A_s in e|Az and Az|e contacts, shown in light red (**R** and **U**), and it also engages its azine moiety in Me|Az and Az|Me contacts with the methyl groups, shown in dark blue (**Q** and **T**).

With this discussion of the structures of **2-Ia** (Br) and **10** (PrO) we have shown that their interaction inventories reflect the inequivalence of their two arenes just like we demonstrated for **1-I** (Cl) in Table 3. All three of the crystals with their C_1-symmetric azines have the one shared feature that the option of *four* double T-contacts for *intra*layer interactions was forfeited to realize only *three* double T-contacts. This major inequivalence in A_i and A_s is reflected in all cases in a symmetry reduction from C_2-symmetry to C_1-symmetry. However, this symmetry reduction manifests itself in more or less noticeable fashion. It just so happens that we first analyzed the azine with the smallest symmetry reduction. For **1**, the difference in the phenyl twists ϕ_1 = -29.31° and ϕ_2 = -30.53° is hardly noticeable, and this very small difference obfuscates the very significant difference in the coordination environments of its two arenes. The difference in the phenyl twists of **2-Ia** is more pronounced, ϕ_1 = -20.96° and ϕ_2 = -27.26°, and in **10** (PrO) the difference between ϕ_1 = -6.85° and ϕ_2 = -15.11° is even larger, and both cases provide clear manifestations of CEISR not only in the arene inventories but also in their molecular structures.

In the crystal structures that contain C_2-symmetric azines, the environments of arenes A_i and A_s are identical and the environments between *P*- and *M*-azines are enantiomeric, and therefore the electronic structures of A_i and A_s are the same. On the other hand, azines in crystal structures that feature CEISR contain arenes A_i and A_s as well as arene substituents X_i and X_s with different electronic structures, and these differences should manifest themselves in all kinds of measurements using vibrational (IR, Raman) or electron spectroscopies (UV/Vis, PES, XPS) as well as solid-state NMR spectroscopy.

Table 5. *Intra*layer and *Inter*layer Interaction Inventories of Flat Symmetrical (X, X)-Azines **2-Ia** (X = Br) and **10** (X = PrO) Show Crystal Environment Induced Symmetry Reduction (CEISR) whereas **3** (X = I) and **5** (X = PhO) Show Equivalent Arenes

X	*(*P*)	**Neighbors of the starred molecule**							
Br		**Q**(*M*)	**T**(*M*)	**R**(*M*)	**U**(*M*)	**V**(*P*)	**W**(*P*)		
Intra	A_i*	f|e(A_s)	e|f(A_i)	Br|Me(A_s)	f|e(A_s)	vdW	e|Az		
IAM	A_s*	e|f(A_i)	f|e(A_s)	Me|Br(A_i)	e|f(A_i)	vdW	vdW		
	Az*				Az|Me(A_i)	Az|e(A_i)			
					Me(A_i)|Az				
		Z$_1$'(*M*)	**Z**$_1$(*M*)	**X**(*M*)	**X**(*M*)	**Z**$_2$(*P*)	**Z**$_2$(*P*)	**Y'**(*P*)	**Y**(*P*)
Inter	A_i*	Br|e(A_s)						Br|Br(A_s)	
IAM	A_s*		e|Br(A_i)	f|Br(A_s)	Br|f(A_s)	e|Br(A_s)	Br|e(A_s)		Br|Br(A_i)
PrO		**Q**(*M*)	**T**(*M*)	**R**(*M*)	**U**(*M*)				
Intra	A_i*	f|e_o(A_s)	e_o|f(A_s)	e_o|Az	f|e_o(A_s)				
IAM	A_s*	e_o|f(A_i)	f|e_o(A_i)	f|CH_2(A_i)	e_o|f(A_i)				
	A_i*	O|e_m(A_s)	e_m|O(A_s)						
	A_s*	e_m|O(A_i)	O|e_m(A_i)	CH_2|f(A_s)					
	Az*	Az|Me(A_s)	Az|Me(A_i)	Az|e_o(A_i)					
		Me(A_s)|Az	Me(A_i)|Az						
		Y(*P*)	**Y'**(*P*)	**Z**$_1$(*P*)	**Z**$_2$(*M*)	**Z**$_3$(*M*)	**Z**$_4$(*P*)		
Inter	A_i*		Pr|O(A_s)			vdW	vdW		
IAM	A_s*	O|Pr(A_i)		Pr|Pr(A_i)	vdW				
I		**Q**(*M*)	**T**(*M*)	**R**(*M*)	**U**(*M*)				
Intra	A_i*	f|e(A_s)	e|f(A_s)	e|f(A_s)	f|e(A_s)				
IAM	A_s*	e|f(A_i)	f|e(A_i)	f|e(A_i)	e|f(A_i)				
	Az*	Az|Me(A_s)	Az|Me(A_i)	Az|e(A_i)	Az|e(A_s)				
		Me(A_s)|Az	Me(A_i)|Az	e(A_i)|Az	e(A_s)|Az				
				X(*P*)	**X'**(*P*)				
Inter	A_i*				I|I(A_s)				
IAM	A_s*			I|I(A_i)					
PhO		**Q**(*M*)	**T**(*M*)	**R**(*M*)	**U**(*M*)				
Intra	A_i*	f|e(A_s)	e|f(A_s)	e|f(A_s)	f|e(A_s)				
IAM	A_s*	e|f(A_i)	f|e(A_i)	f|e(A_i)	e|f(A_i)				
	PhO_i*	e|f(PhO_s)	f|e(PhO_s)	f|e(PhO_s)	e|f(PhO_s)				
	PhO_s*	f|e(PhO_i)	e|f(PhO_i)	e|f(PhO_i)	f|e(PhO_i)				
	Az*	Az|Me(A_s)	Az|Me(A_i)	Az|e(A_i)	Az|e(A_s)				
		Me(A_s)|Az	Me(A_i)|Az	e(A_i)|Az	e(A_s)|Az				
		X(*M*) & **Y**(*M*)		**X'**(*M*) & **Y'**(*M*)		**Z and Z'**			
Inter	A_i*	PhO|PhO(A_s)				vdW			
IAM	A_s*			PhO|PhO(A_i)		vdW			

[a] See Fig. S3-S6 (ESI†) for definition of *intra*layer and *inter*layer neighbors.
[b] vdW = non-specific van der Waals interaction.

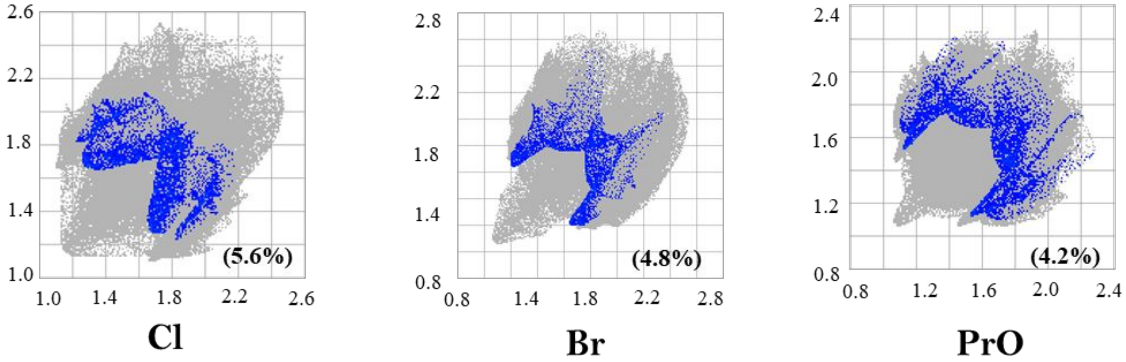
2.5. Hirshfeld Surface Analyses

We have computed the Hirshfeld surfaces and the 2-D Hirshfeld fingerprint plots for the (X, X)-azines using *CrystalExplorer*.[68-70] The results for the chloroazine **1** and for all other azines are shown in Fig. S7 (ESI†).

The Hirshfeld fingerprint plots for **1-I** in Fig. S7 (ESI†) allow to inform about the relative significance of the *intra*layer and *inter*layer contacts. The most crucial *intra*layer contacts are double T-contacts which constitute 28.2% of the full fingerprint plot. The spikes concentrated in the small light-blue regions in the C···H fingerprint plot correspond to C···H distances in double T-contacts. This feature supports the strong contribution of double T-contacts to *intra*layer binding, i.e., the interactions between the starred molecule and the neighbors **Q**, **T** and **U**. The second type of purely *intra*layer contacts, N···H contacts constitute 5.6% of the 2-D fingerprint plot. The spikes in the fingerprint plot of N···H contacts are no very sharp which reflects their strengths. These correspond to the interaction between the starred molecule and the neighbors **V**, and **W**.

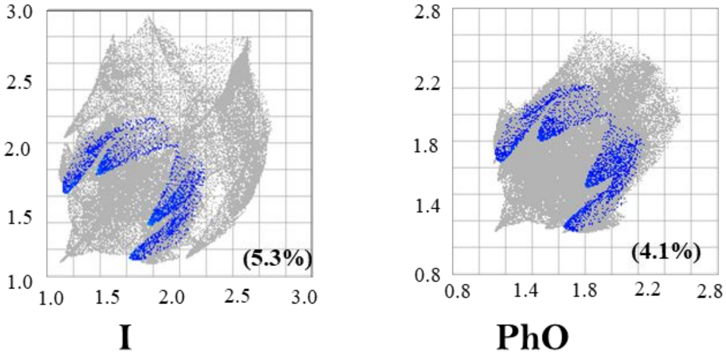
Second type of *intra*layer contacts, H···H contacts are associated with more than 33.8% of the surface area of the fingerprint plot but have no spikes. The absence of spikes show that these interactions are weaker. The fingerprint plot for these contacts includes the points corresponding to *inter*layer π···π contacts which we will discuss with the *inter*layer contacts. Lastly, the H···Cl contact which includes both the intralayer and interlayer contacts constitutes 25.9% of the area of the fingerprint plot. The spikes in the fingerprint plot reflects their significant contribution to the *intra*layer binding. The interaction between the starred molecule and the neighbor **R** corresponds to this contact.

Next, we discuss the contributions to the *inter*layer binding, which comes from three types of contacts, H···Cl, Cl···Cl and π···π contacts. First and most important *inter*layer contacts, H···Cl contacts appear as sharp spikes on the fingerprint plot which reflect their significant contribution to the *inter*layer binding. The interactions between the starred molecule and the neighbors $\mathbf{Z_1}$, $\mathbf{Z_1'}$, and $\mathbf{Z_2}$. Second type of contacts, Cl···Cl contacts constitute only 2.1% of the area of the fingerprint plot. The spike in the plot indicates a directional *inter*layer binding interaction. This corresponds to the interaction between the starred molecule and the neighbors **Y**, and **Y'**. The last and another important contact is the π···π contact which appear in the mid region of the H···H plots also contribute to the *inter*layer binding. These close contacts result from the Cl···π interaction between the starred molecule and the neighbor **X**.



(a)Azines with C_1-symmetry (with CEISR)

Curtain like pattern



(b) Azines with C_2-symmetry (no CEISR)

Flower pattern with four petals

Fig. 9 Hirshfeld 2-D fingerprint plots for (X, X)-azines resolved into N···H contacts.

The inspection of Hirshfeld 2-D fingerprint plots resolved into N···H contacts allows one to decide whether an acetophenone azine crystallizes with or without CEISR. This information is easily accessible and does not rely on structural analysis. Fig. 9 shows the respective plots for the five azines analyzed. The pattern displayed by the crystals with C_2-symmetric azines resembles a flower with four petals, two sets that are symmetric about the diagonal. One set with the shorter N···H contacts is due to Az|Me contacts (dark-blue in Fig. 8) and the other set with the longer N···H contacts is due to Az|e contacts (light-red in Fig. 8). The pattern becomes complex for the crystals with C_1-symmetric azines. The longitudnal offset between pairs of azines in the crystal structures leads to a curtain like pattern instead of the two distinct sets of petals.

2.6. Pairwise Interaction Energies and Electrostatic Potential Maps

Our crystal structure analyses revealed short contacts between synthons and their directionality, and we will now quantify the interactions. Pairwise interaction energies were computed with *CrystalExplorer* at the level CE-B3LYP, that is, B3LYP/6-31G(d,p)+D2 for all *intra*- and *inter*layer pairs within 3.8 Å of the selected reference molecule * in chloroazine **1-I**, bromoazine **2-Ia**, and propoxyazine **10**. We also analyzed the phenoxyazine **5** and iodoazine **3** to establish a reference for a case with *intra*layer interactions greatly dominating over *inter*layer interactions. The calculations result in color-coded interaction energy mappings and the results for the chloroazine and the other azines are given in Figs. S8-S12 (ESI†). In Table 7 are listed the most pertinent pair interaction energies between the starred molecule and neighbor specified in column 1. In Table S2 (ESI†), also are provided for each pair, the electrostatic (E_{ele}), polarization (E_{pol}), dispersion (E_{dis}), and exchange-repulsion (E_{xrep}) terms together with the sum of all energy components (E_{tot}).

Table 7. Color-coded pairwise interaction energies relative to starred molecule in **5** (PhO), **3** (I), **1-I** (Cl), **2-Ia** (Br) and **10** (PrO)

With CEISR					
Cl	E_{tot}	**Br**	E_{tot}	**PrO**	E_{tot}
U	**-45.6**	**U**	**-43.5**	**U**	**-68.1**
Q, T	**-34.4**	**Q, T**	**-37.7**	**T**	**-67.2**
V, W	**-33.7**	**V, W**	**-30.3**	**Q**	**-65.4**
R	-11.8	**X**	**-30.3**	**R**	**-62.3**
Z_1	-7.5	**R**	**-19.0**	**S**	**-37.0**
Z_2	-4.2	**Z_1**	-7.4	**Y**	-11.9
X	-3.0	**Y**	-5.5	**Z_1**	-9.9
Y	0.2	**Z_2**	-3.9	**Z_2**	-6.2
				Z_3	-3.7
				Z_4	-2.3

Without CEISR			
PhO	E_{tot}	**I**	E_{tot}
Q, T	**-70.6**	**R, U**	**-52.9**
R, U	**-67.9**	**Q, T**	-49.2
S	-26.0	**S**	-27.5
Y	-7.9	**Y**	6.2
X	-6.0		
Z	-4.4		

[d] E_{tot} (CE-B3LYP) = 1.057 E_{ele} + 0.740 E_{pol} + 0.871 E_{dis} + 0.618 E_{xrep} for **5** (PhO), **1-I** (Cl), **2-Ia** (Br) and **10** (PrO).

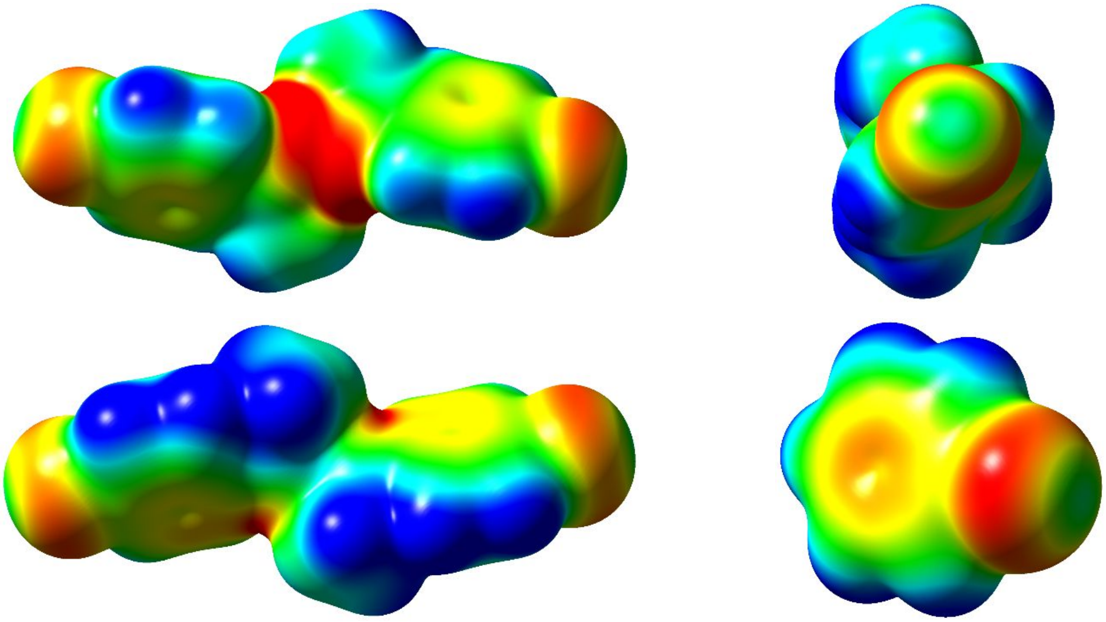
[e] E_{tot} (CE-HF) = 1.019 E_{ele} + 0.651 E_{pol} + 0.901 E_{dis} + 0.811 E_{xrep} for **3** (I).

To obtain a first impression of the relative strengths of the pair interactions we categorized the total energies as follows: weak (0-4 kJ/mol, black), moderate (4-15 kJ/mol, red), strong (15-50 kJ/mol, **bold red**), and superior (above 50 kJ/mol, burgundy).

The **U** pair in chloroazine **1-I** features a double T-contact with the least longitudinal offset and the associated pair energy shows significantly stronger bonding compared to the double T-contacts in pairs **Q**, **T**, and **R**. Note the inverse correlation between E_{tot} and the R values, which specify the distance between the molecular centroids and provide a rough measure of longitudinal offset. Considering the data for the **U** pair suggests a binding energy for a strong T-contact between two para-disubstituted arenes (i.e., *p*-substituted 1-iminomethylbenzenes) of about E_b(T,ds) = -23 kJ/mol. The longitudinal offsets of the quadruple T-contacts in phenoxyazine **5** are very close to that of pair **U** in **1-I** and hence one might expect a binding energy of -92 kJ/mol. The actual binding energies of pairs **Q**, **T**, **R**, and **U** in **5** are close to -70 kJ/mol and these numbers suggest that the

T-contacts between the phenoxy groups are less binding than the T-contacts involving arenes A_i and A_s. Assuming to a first approximation that the T-contacts involving A_i and A_s are about the same, one would conclude that the terminal T-contacts involving two mono-substituted arenes (i.e., phenoxy groups) contribute only about E_b(T,ms) = -12 kJ/mol to the pair binding energy. Of course, the E_b(T,ds) and E_b(T,ms) terms are not transferable from one azine to the next because the details of the T-contact structures vary (distance, offset). However, it is safe to say that $E_b(\mathrm{T,ms}) < E_b(\mathrm{T,ds})$ and electrostatic potential maps provide a clear rationale.

The electrostatic potential maps of azines **1**, **2**, and **5** are shown in Fig. 10 along with the maps of the respective benzenes Ph-X. The B3LYP/6-311G(d,p) electron densities were computed based on partially optimized structures of the azines (X-ray structure with H positions optimized) and fully optimized Ph-X structures. Two perspectives are shown for each azine with their C_2-axis perpendicular to the paper plane and viewing the convex (top) and concave surfaces. To the right are shown the map of the azine viewed down the N-N axis and the map of the respective Ph-X.



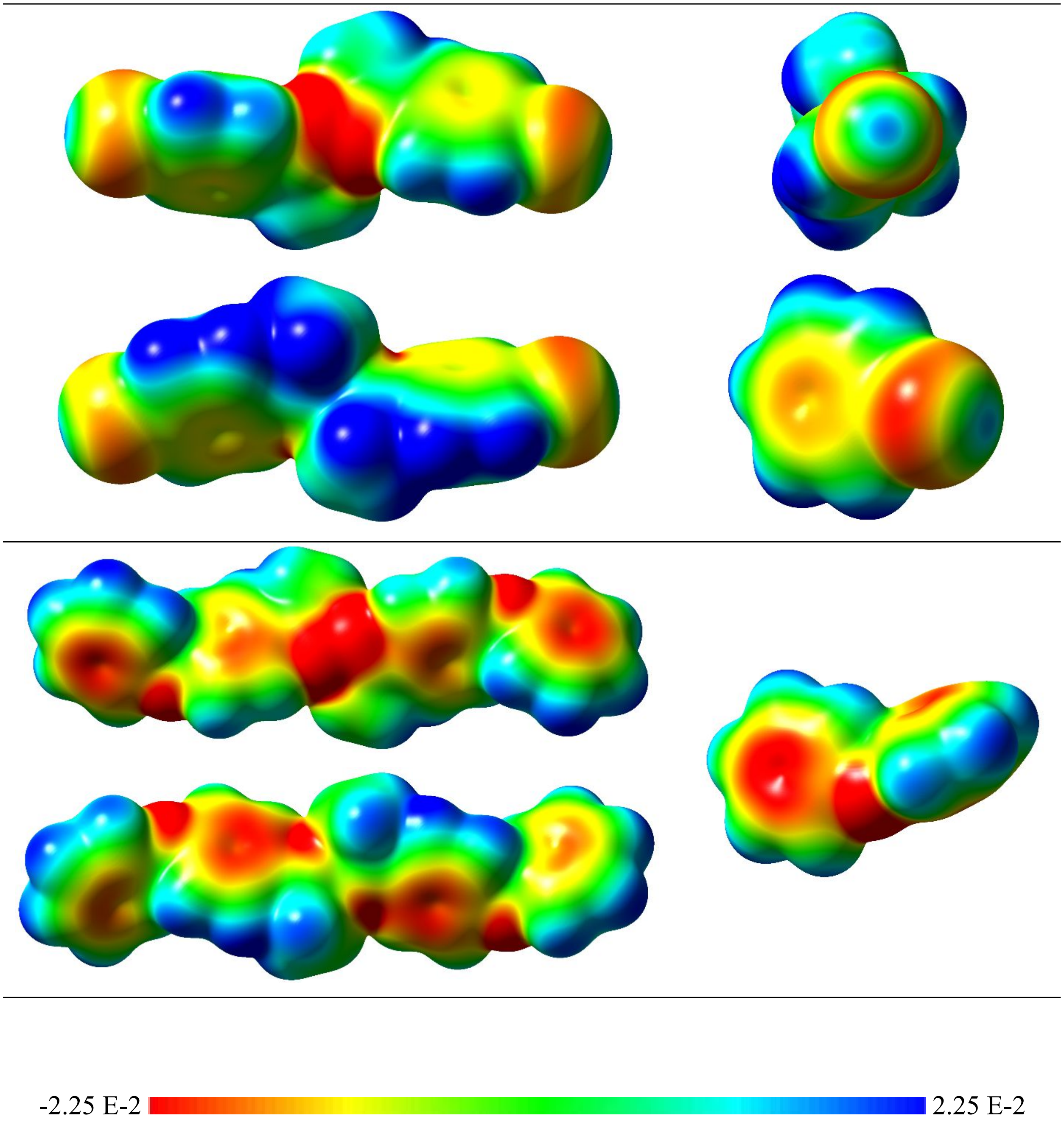


Fig. 10 Electrostatic potential (ESP) maps of the symmetrical (X, X) acetophenone azines and of the monosubstituted benzenes Ph-X with X = Cl (top), Br (middle), and PhO (bottom). ESPs are mapped on electron density isosurfaces with $\rho = 0.001$ e/au^3 and the ESP values are color-coded as shown. See text for orientations.

All X_{para} groups are -I/+M substituents.[71] The ESP maps of the Ph-X molecules feature positive potential at all aromatic hydrogens reflecting the -I property of X. The halogens show their usual red ring of negative potential and a more or less developed σ-hole. Note the negative potential on the face of the phenyl ring which is consistent with the +M effect. The magnitude of the +M effect greatly depends on the overlap between the π-densities of the X group and the arene. The orbital expansions of the arene carbons match much better for the OR substituent than for the larger halogens, and the strong +M effect is clearly visible in Fig. 10.

The azine group is a -I/-M substituent. The first consequence of the overall electron withdrawing ability of the azine group is an area of intense negative potential associated with the N_2 group visible only on the convex face of the azine. Because of the azine twist angle the convex and concave faces are remarkably different. The dominant feature on the concave face of the azine are the two areas of positive potential and each of these includes two edge Hs and two of the methyl Hs. Note the marked difference in the electrostatic potential of the methyl H pointed towards the lone pair of one of the azine N. It is a common feature of the azines that the edge regions of both arenes on the convex face of the azine indicate much lower electrophilicity for just the two Hs as compared to the expansive region of high electrophilicity associated with four Hs on the concave face.

The combination of the azine -I/-M effect with the -I/+M para-substituent has several consequences. The two overall electron withdrawing substituents in (X, X)-azines compete for electron density from four arene Hs whereas the one substituent in a Ph-X molecule may draw electron density from five arene Hs. This fact in combination with the discussed difference between the edges on the convex and concave faces makes it clear that the edge electrophilicity on the convex face is greatly diminished compared to Ph-X while the edge electrophilicity on the convex face exceeds that of Ph-X by a greater amount. The combination of the azine -M effect with the +M effect of the X group results in reduced nucleophilicity on both arene faces, and the reduction of nucleophilicity is more pronounced on the convex face (green-yellow) than on the concave face (red-yellow).

3. CONCLUSION

Ab initio studies show that the molecular structure of (*E*,*E*)-configured p-chloroacetophenone azine **1** is C_2-symmetric in the gas phase. Furthermore, computational analysis shows that the azine twist angle and the phenyl twists are correlated in a manner that minimizes the intersection angle between the best planes of the two arenes in one azine molecule. The crystal structure of polymorph **1-I** contains equal amounts of enantiomers which are very nearly but not exactly C_2-symmetric: the molecules are *asymmetric* rather than *dissymmetric*. We have provided several lines of evidence to show that the modest $C_2 \rightarrow C_1$ symmetry reduction of the azines in the crystal is due to crystal architecture: the inside arene A_i and the surface arene A_s in each azine engage in qualitatively different intermolecular interactions. We refer to this consequence of the crystal packing as crystal environment induced symmetry reduction (CEISR) effect. A new term is warranted because the observed phenomenon is not limited to this one case (Table 1).

The analysis of the crystal architecture emphasizes the importance of arene-arene and chloroarene-chloroarene interactions and resulted in the *intra*layer and *inter*layer interaction inventory presented in Table 3 and the structural characteristics of each synthon in Table 4. The deep analyses revealed a remarkable and non-obvious qualitative difference between the coordination modes of arenes A_i and A_s in the *intra*layer namely that only A_i engages in arene-azine contacts. While it was this analysis of the arene-azine contacts that initially brought this inequivalence to our attention, the analysis of the arene-arene contacts is comparatively easier to perform for the demonstration of the inequivalence. While azines have the potential to form four double T-contacts, the arenes A_i and A_s in **1-I** engage only in *three* double T-contacts. The arene A_i serves as a face twice and only once as an edge while the arene A_s serves as an edge twice and only once as a face. The unexploited edge of A_i engages in the *intra*layer arene-azine contact while the remaining face of the A_s participates in *inter*layer contacts.

The inequivalence of arenes in the *intra*layer has a direct consequence on the contacts of both the arenes in the *inter*layer. Two main types of *inter*layer contacts, f|Cl type between the chlorine of one chloroarene and an arene face of the other chloroarene, and Cl|e type between a chlorine of one chloroarene and a hydrogen of the other chloroarene (the edge-H meta to the azine) occur . Only the arene A_s engages in two f|Cl type contacts as listed in Table 3 and no such contact occurs for the inside arene A_i. The arene A_s is clearly much more engaged in the *inter*layer contacts compared to the A_i arene which is also true for the Cl|e type contacts. A_s engages in three Cl|e contacts while A_i engages in only one such contact (Fig. 6).

To explore the generality of the CEISR concept, we studied the IAM characteristics of the four other azines that crystallize with flat morphology **2-Ia** (Br), **3** (I), **5** (PhO), and **10** (PrO). The interaction inventories in Table 5 show that the two arenes in azines **2-Ia** and **10** engage in three inequivalent double T-contacts as in **1-I**. Only the inside arene is engaged in the arene-azine contact. The *inter*layer contacts are also different for both the arenes because of the differences in the contacts within the *intra*layer. On the other hand, the crystal structures of **3** and **5** feature two equivalent coordination modes for both arenes.

Comprehensive interaction inventory analysis is a powerful method to detect CEISR. However, this topological analysis is an arduous task, and it is easily possible to overlook significant contacts only revealed by pairwise interaction energy analyses. We showed that N···H contact Hirshfeld 2-D fingerprint plot analyses provide the fastest and most direct method for the detection of CEISR. The plots in Fig. 10 show similar curtain like patterns for crystals **1-I**, **2-Ia**, and **10** in evidence of CEISR while the plots for **3** and **5** show a flower pattern with two distinct set of petals indicative of arene equivalence.

Azines in crystal structures that feature CEISR contain arenes A_i and A_s as well as arene substituents X_i and X_s with different electronic structures. These differences should manifest themselves in measurements using vibrational spectroscopies (IR, Raman), electron spectroscopies (UV/Vis, PES, XPS), as well as solid-state NMR spectroscopy. The availability of series of (X, X)-disubstituted acetophenone azines allows for such systematic studies going forward.

The results of our studies suggest that the crystallographic record contains many crystal structures for which packing related molecular symmetry reductions may not have been fully recognized. In our approach we compared the next neighbor interactions of two arenes and showed them to be different. The approach does not rely on the presence of arenes and can be generalized to any molecular system with two moieties of the same constitution.

Author contributions

H. Bhoday and K. Yang: synthesis and crystallization, formal analysis, computational analysis, methodology, visualization, writing; S. P. Kelley: X-ray crystallography, X-ray data curation; R. Glaser: conceptualization, formal analysis, methodology, visualization, funding acquisition, project administration, resources, supervision and mentoring, writing.

Conflicts of Interest

The authors declare no conflicts of interest.

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