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Halogen bond effect on bundling of hydrogen bonded 2-fold helical columns

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Bundling of the hydrogen bonded 2-fold helical columns has been altered on the basis of a robust halogen bond between an iodine and anionic oxygen atom. This alteration causes a change of the space groups of the resulting crystals.

10 Helices are one of the most essential structural motifs in nature and originate sophisticated functions of DNA and proteins. Even artificial helices exhibit fascinating functions for asymmetric catalysts, optoelectronics materials and so on. Such functions motivate chemists to develop various helices in liquids, liquid 15 crystals and crystals.¹ However, we usually face difficulties for bundling the helices. For example, it still remains a challenge whether we can design organic crystals with desired space groups

owing to the controlled bundling of helical motifs.

In the crystalline phase, organic molecules tend to construct $_{20}$ two-fold (2) helical assemblies due to dense packing and cancelling of dipole moments.² This tendency is strongly supported by the fact that crystals involving 2_1 helices occupy over seventy percent of the crystals registered on the Cambridge Structural Database (CSD)³, including crystals with enantiopure

- 25 and racemic 2_1 helices belonging to chiral (*ca.* fifteen percent) and achiral space groups (ca. fifty-five percent), respectively. For the purpose of controlling the bundles, a useful tool may come from supramolecular synthons which make characteristic molecular associations through various non-covalent
- ³⁰ interactions.⁴ Figure 1a shows three typical examples. Chargeassisted hydrogen bonds (caH-Bs), CH- π bonds (CH π -Bs) and halogen bonds (X-Bs) afford the corresponding robust networks,⁵ herringbone associations of aromatic molecules,6 and halogeninvolved associations,7 respectively.
- This article deals with an effective use of the X-Bs for 35 bundling the 2_1 helical columns. As far as we know, there is no research for selectively bundling the columns with the aid of the X-Bs. For design of the crystals we propose a method, termed as three-stepwise and three-directional associations, which is based
- 40 on the bundling with three kinds of the supramolecular synthons. Figure 1b exemplifies the method. Firstly, the one-dimensional (1-D) 2₁-helical columns of supramolecular building blocks are constructed with the caH-Bs along a vertical direction (Figure 1b(i)). Secondly, the columns are combined with the inter-
- ⁴⁵ columnar CHπ-Bs along a front-back direction to provide a 2-D sheet motif (Figure 1b(ii)). Thirdly, the motifs are piled with the inter-columnar halogen bonds (X-Bs) along a horizontal direction (Figure 1b(iii)), yielding 3-D crystals which belong to any space



R-NH[⊕][⊕]O₂C-R'

herringbone

X-R R-NH3[⊕]····[⊕]O₃S-R' R-X etc (X = F, Cl, Br, I) mirror image = 1. Asssembly of ecular building blo Θ Ð inter-molecular caH-B F, Cl, Br, I dowr down left-handed right-handed Molecular Building Blocks Supramolecular Building Blocks (iii) (1-D 2₁ helices) (iiii) 3. Piling of the 2-D sheet motifs 2. Bundling of the 1-D 21 helices bundling • x 2-D sheet motifs crystals (iv) $P2_1$ C2 $P2_{1}2_{1}2_{1}$ anti-parallel paralle parallel the 3-D crystals

Figure 1. (a) Representative supramolecular synthons in organic crystals: (i) charge-assisted hydrogen bonds (caH-Bs), (ii) CH- π bonds (CHπ-Bs) and (iii) halogen bonds (X-Bs). (b) Hierarchical 55 construction of organic crystals on the basis of a "three-stepwise and three-directional associations" method. (i) Construction of 1-D 2₁ helices by caH-Bs, (ii) bundling of the helices in 2-D sheet motifs by *inter*-columnar CH π -Bs and (iii) piling of the sheet motifs by inter-columnar X-Bs (iv) in 3-D crystals with specific 60 space groups. Green, blue and red balls exhibit halogen atoms, a chiral primary amine (1) and *p*-halo-substituted achiral benzoic acid derivatives (2), respectively. Green, light blue and black dotted lines exhibit X-Bs, caH-Bs and CH π -Bs, respectively.

Regarding the building blocks, we focused on the chiral 65 columns of organic salts composed of an aromatic amine and carboxylic acid (Figure 1b(i)). This is because the chiral salts form definite right- or left-handed 21 helical columns with the caH-Bs.⁸ Additional aromatic rings associate in a herringbone manner with the CH π -Bs so as to bundle the 2₁ helices. This 70 combination of the caH-Bs and CHπ-Bs enabled us to examine an



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effect of the inter-columnar X-Bs on the bundling. Taking into account these considerations, we employed the X-Bs of a series of halogen atoms attached at *p*-positions of benzoic acids. Their inter-columnar X-Bs would work for the control of the columnar

- ⁵ bundles. Plausible bundle manners of the chiral columns are as follows; a parallel fashion with an inter-columnar two-fold rotation axis, parallel or anti-parallel fashions with an inter-columnar 2_1 helical axis, which correspond to the space groups; *C*2, *P*2₁ or *P*2₁2₁2₁, respectively (Figure 1b(iv)).
- ¹⁰ Chiral salts, which are composed of (*R*)-1-(2naphthyl)ethylamine (**1**) and benzoic acid (**2-H**) or its *p*-halosubstituted derivatives (**2-F**, **2-Cl**, **2-Br**, **2-I**), were prepared by mixing them in methanol with a 1:1 molar ratio. Evaporation of the solution yielded their powdered salts. Their single crystals ¹⁵ were obtained by recrystallization of the salts from ethanol.
- Crystallographic studies revealed that the crystals of **2-H**, **2-F**, **2-Cl**, **2-Br** belong to the space groups *C*2 while the crystal of **2-I** does to the $P2_12_12_1$ (Table 1 and Figure S1). The resulting regulation of the bundles can be explained below.
- Figure 2a shows formation of almost the same columns in shape, which is confirmed by small differences of their helical pitches (*p*) and length of the caH-Bs (*d*₁, *d*₂, *d*₃) (Figure 2b and Table 1). The hydrogen bonded …N…O…N…O… linkages consist of the left-handed 2₁ helices, which are denoted by ^{sup}*M*, ²⁵ according to the supramolecular-tilt-chirality method (Figure 2b, Figure S1a).^{8,9} The columns are stabilized by the *intra*-columnar CHπ-Bs which provide herringbone associations between the benzene and naphthalene rings. The CHπ-Bs have distances of 2.6 to 3.1 Å between a hydrogen atom of the benzene or ³⁰ naphthalene ring and a π-plane of the other neighbour ring.

Table 1.	Crystal	parameters	of 1	•2-H	to 1	·2-I
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Entries	SG ^a	SMC ^b	p (Å) ^c	$d_1, d_2, d_3 \left(\text{\AA} \right)^d$	$d_{x-x} (\text{\AA})^{e}$
1·2-H	<i>C</i> 2	^{sup} M	6.200	d_1 : 2.794 d_2 : 2.777 d_3 : 2.758	-
1·2-F	<i>C</i> 2	^{sup} M	6.217	d_1 : 2.801 d_2 : 2.754 d_3 : 2.762	3.516
1·2-Cl	<i>C</i> 2	^{sup} M	6.196	d_1 : 2.809 d_2 : 2.771 d_3 : 2.757	3.574
1·2-Br	<i>C</i> 2	^{sup} M	6.195	d_1 : 2.811 d_2 : 2.769 d_3 : 2.751	3.819
1·2-I	<i>P</i> 2 ₁ 2 ₁ 2 ₁	^{sup} M	5.961	d_1 : 2.763 d_2 : 2.761 d_3 : 2.734	5.691 (3.038) ^f

^{*a*}Space groups of the resulting crystals. ^{*b*}Supramolecular chirality of the caH-Bs. ^{*c*}Pitches of the 2₁ helical columns with caH-Bs. ^{*d*}Length of the caH-Bs in the columns as distance of O^{...}N. ³⁵ ^{*e*}Distances between the closest halogen atoms. ^{*f*}Length of I^{...}O type X-Bs.

Subsequently, the columns are connected by the *inter*columnar CHπ-Bs and X-Bs (Figure 2c), yielding different crystal structures (Figure 2d). Table 1 shows that C2 crystals of ⁴⁰ **1·2-F**, **1·2-Cl** and **1·2-Br** have the X-Bs such as F^{...}F, Cl^{...}Cl and Br^{...}Br with distances of 3.52 to 3.82 Å, while the P2₁2₁2₁ crystal

of **1·2-I** has I^{...}O type of the X-Bs with a distance of 3.04 Å. This difference can be explained by the three-stepwise and threedirectional association method as mentioned below. As for 2-F, 45 2-Cl and 2-Br, the 1-D columns are connected through the intercolumnar CH π -Bs, producing the herringbone associations between the benzene and naphthalene rings in a parallel fashion along the crystallographic c axis (Figure 2c(i)). This bundling results in the 2-D sheet motifs spreading on the bc plane. The 50 third step is that the sheet motifs pile up in a parallel fashion along the *a* axis through fits of asperities with the subsidiary inter-columnar X-Bs (Figure S2 and Table S1), yielding the 3-D crystals with the space group C2 (Figure 2d(i)). On the other hand, the second step of 1.2-I consists of the herringbone associations 55 between the naphthalene rings in a parallel fashion, resulting in the zigzag sheet motif on the ab plane (Figure 2c(ii)). The third step is that the 2-D sheet motifs pile up in an anti-parallel fashion along the c axis through the I···O type of the X-Bs, yielding the 3-

D crystals with the space group $P2_12_12_1$ (Figure 2d(ii)). Such a regulation of the bundling manners is clearly 60 attributable to the strength of the X-Bs. The theoretical study clarifies that the interaction energy originates from negative electrostatic potential around halogen atoms and positive potential on the center of the C-X axis denoted as "\sigma-hole", and $_{65}$ increase in the order; F < Cl < Br < I.¹⁰ Especially, iodide has the largest positive potential on its σ -hole region, and therefore preferentially interacts with anions. Actually, I...O type X-Bs (d = 3.04 Å) is observed in the $P2_12_12_1$ crystal, where the iodide atom is located on the major axis and the anionic oxygen atom is 70 on the center of the minor axis in the column (Figure 2b(i)). Such a position causes the zigzag bundle of the columns, leading to generation of different 21 helical axes which are perpendicular to those of the 2_1 hydrogen bonded helices. As a result, the crystal belongs to the space group $P2_12_12_1$ with the helical axes along 75 three axes, a, b and c.

In order to confirm the strength of the I...O type X-B, ab initio calculation (MP2/6-311G^{**}) was conducted (Figure S3 and Table S2).^{11,12} Carboxylate anions (A to D) and amino cations (E to H) have negative and positive charges, respectively. The charges ⁸⁰ cause strong repulsive forces between the anions (**B-D**) or the cations (E-F), as well as strong attractive forces between the cation and the anion (A-E and B-E, Figure S3a). It is difficult under this ionic condition to discuss the energy of X-Bs, which localizes and have much smaller interaction energies than that 85 between ionic molecules, on the basis of calculation on whole interaction energies among the ions. For getting over the problem, the anionic carboxylate group of the molecule **D** was replaced by hydrogen atom to neutralize, resulting in neutral molecule **D** (Figure S3b). The calculated energy of the I···O type of the X-B 90 (B-D') is -5.0 kcal/mol which is comparable to hydrogen bonds of water molecules. This result suggests that the I...O type X-B acts preferentially for the bundling of the columns in the crystal.

In conclusion, we have demonstrated the fusion method for obtaining organic crystals on the basis of the bundling of the 2₁ ⁹⁵ helical columns through supramolecular synthons such as caH-Bs, CHπ-Bs and X-Bs. The X-Bs are effective for controlling bundling manners of the columns, leading to the selective acquisition of the C2 and P2₁2₁2₁ crystals with a parallel and zigzag bundling manners, respectively. The I^{...}O type of the X-

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Figure 2. Crystal structures of the chiral salts. (a) The 1-D 2_1 helical hydrogen bonded columns of (i) **1-2-H**, (ii) **1-2-F**, **2-Cl**, **2-Br** (superimposed) and (iii) **1-2-I** drawn with thermal ellipsoid with 50% probability. (b) Schematic representation of the column. (c) The bundling of the columns through the CH π -Bs and X-Bs for **1-2-H**, **-F**, **-Cl**, **-Br** (i) and **1-2-I** (ii). (d) The crystals with the space group *C*2 involving X^{...}X type of the X-Bs. (i) and *P* $2_12_12_1$ involving I^{...}O type of the X-Bs (ii). Their packing diagram are drawn with unit cells and symmetry symbols, which include our proposed symbols representing right- and left-handed 2_1 helices.⁹ Amplifications around the X-Bs in the crystals were exhibited in insertion boxes.

Bs provides a directional and robust association between the molecules so as to yield the zigzag-type bundles.

This kind of research will contribute to set up a new and useful strategy for designing functional crystals as aggregates of the 2_1

5 helical columns. Further study has been going on to clarify the effects of the X-Bs as well as the other functional groups on the bundling of the columns.

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Notes and references

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- † Electronic Supplementary Information (ESI) available: Detailed experimental procedure, theoretical calculation and crystallographic data. CCDC 884890-884894. See DOI: 10.1039/b000000x/
- (a) E. Yashima, K. Maeda, Y. Furusho, Acc. Chem. Res., 2008, 41, 1166; (b) E. Yashima, K. Maeda, H. Iida, Y. Furusho, K. Nagai, Chem. Rev., 2009, 109, 6102. (c) Chirality at the Nanoscale, ed. D. B. Amabilino, WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim, 2009.
- 2 A. I. Kitaigorodskii, *Molecular Crystals and Molecules*, Academic 30 Press, London, 1973.
- 3 http://www.ccdc.cam.ac.uk/products/csd/
- 4 (a) G. R. Desiraju, Angew. Chem., Int. Ed. Engl., 1995, 34, 2311; (b)
 V. R. Thalladi, B. S. Goud, V. J. Hoy, F. H. Allen, J. A. K. Howard and G. R. Desiraju, Chem. Commun., 1996, 401.
- ³⁵ 5 (a) M. D. Ward, Struct. Bond., 2009, **132**, 1; (b) M. Meot-Ner(Mautner), Chem. Rev., 2005, **105**, 213; (c) K. Sada, T. Tani, S. Shinkai, Synlett, 2006, 2364; (d) N. Tohnai, Y. Mizobe, M. Doi, S.

Published on 20 July 2012 on http://pubs.rsc.org | doi:10.1039/C2CE26081F

Downloaded by Cornell University on 20 July 2012

Sukata, T. Hinoue, T. Yuge, I. Hisaki, Y. Matsukata and M. Miyata, Angew. Chem. Int. Ed., 2007, 46, 2220.

- (a) O. Takahashi, Y. Kohno, M. Nishio, *Chem. Rev.*, 2010, **110**, 6049; (b) M. Nishio, Y. Umezawa, K. Honda, S. Tsuboyama, H.
- Suezawa, *CrystEngComm*, 2009, **11**, 1757; (c) Y. Umezawa, S. Tsuboyama, H. Takahashi, J. Uzawa and M. Nishio, *Tetrahedron*, 1999, **55**, 10047.
- 7 (a) Halogen Bonding: Fundamentals and Applications, Structure and Bonding, ed. P. Metrangolo and G. Resnati, Springer, Berlin, 2007.
- (b) F. F. Awwadi, R. D. Willett, K. A. Peterson and B. Twamley, *Chem. Eur. J.*, 2006, **12**, 8952; (c) G. R. Desiraju and R. Parthasarathy, *J. Am. Chem. Soc.* 1989, **111**, 87225; (d) P. Metrangolo, H. Neukirch, T. Pilati and G. Resnati, *Acc. Chem. Res.*, 2005, **38**, 386; (e) E. Parisini, P. Metrangolo, T. Pilati, G. Resnati and
- G. Terraneo, *Chem. Soc. Rev.*, 2011, **40**, 2267; (*f*) A. Matsumoto, T. Tanaka, T. Tsubouchi, K. Tashiro, S. Saragai and S. Nakamoto, *J. Am. Chem. Soc.*, 2002, **124**, 8891; (*g*) J. W. Lauher, F. W. Fowler and N. S. Goroff, *Acc. Chem. Res.*, 2008, **41**, 1215. (*h*) K. Merz and V. Vasylyeva, *CrystEngComm*, 2010, **12**, 3989.
- 20 8 T. Yuge, T. Sakai, N. Kai, I. Hisaki, M. Miyata and N. Tohnai, *Chem. Eur. J.*, 2008, **14**, 2984.
- 9 (a) I. Hisaki, T. Sasaki, K. Sakaguchi, W. T. Liu, N. Tohnai and M. Miyata, *Chem. Commun.*, 2012, **48**, 2219; (b) A. Tanaka, I. Hisaki, N. Tohnai and M. Miyata, *Chem. Asian J.*, 2007, **2**, 230; (c) M. Miyata,
- N. Tohnai, I. Hisaki, Acc. Chem. Res., 2007, 40, 694; (d) II. Hisaki, N. Tohnai and M. Miyata, Chirality, 2008, 20, 330; (e) I. Hisaki, N. Shizuki, T. Sasaki, Y. Ito, N. Tohnai and M. Miyata, Cryst. Growth Des., 2010, 10, 5262; (f) I. Hisaki, T. Sasaki, N. Tohnai and M. Miyata, Chem. Eur. J. 2012, in press (DOI: 10.1002/chem.201200688).
- 10 (a) P. Politzer, P. Lane, M. C. Concha, Y. G. Ma and J. S. Murray, J. Mol. Model., 2007, 13, 305; (b) S. Tsuzuki, A. Wakisaka, T. Ono and T. Sonoda, Chem. Eur. J. 2011, 18, 951; (c) K. E. Riley and K. M. Merz, Jr., J. Phys. Chem. A, 2007, 111, 1688.
- Gaussian 09, Revision C01, M. J. Frisch, G. W. Trucks, H. B. Schlegel, G. E. Scuseria, M. A. Robb, J. R. Cheeseman, G. Scalmani, V. Barone, B. Mennucci, G. A. Petersson, H. Nakatsuji, M. Caricato, X. Li, H. P. Hratchian, A. F. Izmaylov, J. Bloino, G. Zheng, J. L. Sonnenberg, M. Hada, M. Ehara, K. Toyota, R. Fukuda, J. Hasegawa, M. Ishida, T. Nakajima, Y. Honda, O. Kitao, H. Nakai, T. Vreven, Jr.
- J. A. Montgomery, J. E. Peralta, F. Ogliaro, M. Bearpark, J. J. Heyd, E. Brothers, K. N. Kudin, V. N. Staroverov, R. Kobayashi, J. Normand, K. Raghavachari, A. Rendell, J. Burant, S. S. Iyengar, J. Tomasi, M. Cossi, N. Rega, N. J. Millam, M. Klene, J. E. Knox, J. B.
- 45 Cross, V. Bakken, C. Adamo, J. Jaramillo, R. Gomperts, R. E. Stratmann, O. Yazyev, A. J. Austin, R. Cammi, C. Pomelli, J. W. Ochterski, R. L. Martin, K. Morokuma, V. G. Zakrzewski, G. A. Voth, P. Salvador, J. J. Dannenberg, S. Dapprich, A. D. Daniels, □. Farkas, J. B. Foresman, J. V. Ortiz, J. Cioslowski, D. J. Fox, D. J. 50 Gaussian, Inc., Wallingford CT, 2009.
- 12 GaussViews Version 5, R. Dennington, T. Keith, J. Millam, Semichem Inc., Shawnee Mission KS, 2009.