Self-Assembly

Deutsche Ausgabe: DOI: 10.1002/ange.201510912
Internationale Ausgabe: DOI: 10.1002/anie.201510912

Halogen-Bond-Templated [2+2] Photodimerization in the Solid State: Directed Synthesis and Rare Self-Inclusion of a Halogenated Product

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Abstract: *A ditopic halogen-bond acceptor organizes a diiodooctafluorostilbene for a [2+2] photodimerization reaction to take place between two stilbene molecules in the solid state. The resultant cyclobutane product is functionalized with halogen atoms and undergoes self-assembly to form a channel-type host–guest compound that exhibits a very rare form of self-inclusion.*

Halogen bonding is now well-recognized as a directional noncovalent bond that mediates the assembly of molecules in solution,[1] the gas phase,[2] and the solid state,[3] with applications in supramolecular chemistry[4] and beyond. Defined[5] as the "attractive interaction between an electrophilic region associated with a halogen atom in a molecular entity and a nucleophilic region in another, or the same, molecular entity", it is becoming clear that halogen bonds can be used to affect the organization of molecules to even direct chemical reactions.

In this context, while there have been considerable advances on the use of halogen bonds to direct reactions in solution, there have been limited cases to direct reactivity in the solid state.[6] Developments on the use of halogen bonds to direct reactions in solids include topochemical polymerizations of diynes in the field of host–guest chemistry, where the directed synthesis of halogenated polydiacetylenes was achieved (Figure 1).[7] However, the only documented example on the use of halogen bonds to direct the synthesis of a small molecule is the pioneering work of Metrangolo, Resnati, and co-workers that employed cocrystallization of a tetratopic halogen bond donor to mediate the photodimerization of a bipyridine.[8] In that report, the resulting photoproduct was devoid of halogen atoms. If the preparation of a photoproduct containing halogen atoms could be achieved, the scope of template-directed syntheses of molecules in the solid state could be significantly expanded. The ability to generate photoproducts functionalized with halogen atoms in the solid state has thus been recognized as an important challenge.[4]

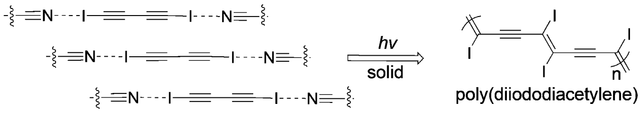
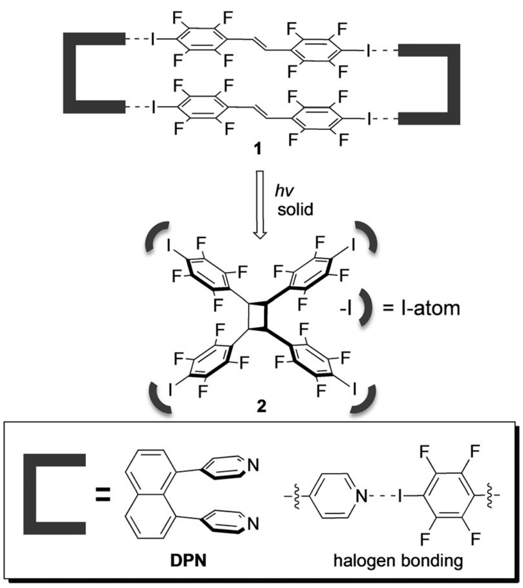


Figure 1. Halogen-bond-directed topochemical polymerization.[7]

Herein, we report 1,8-di(4-pyridyl)naphthalene (**DPN**) acting as a template to assemble *trans*-1,2-bis(4-iodotetrafluorophenyl)ethene (**1**) to form a co-crystal of composition 2(**DPN**)·2(**1**). Assembly within this co-crystal is mediated by N···I halogen bonds that facilitate an intermolecular [2+2] photodimerization of two stilbene molecules. We demonstrate that the halogenated olefin adopts a face-to-face π-stacked geometry within a discrete, or zero-dimensional (0D), four-component assembly and undergoes a photodimerization to generates *rctt*-1,2,3,4-tetrakis(4-iodo-2,3,5,6-tetrafluorophenyl)cyclobutane (**2**) stereoselectively and in quantitative yield. The resulting cyclobutane photoproduct is functionalized at the periphery with I atoms, an intrinsic feature key of the halogen bonds between the olefin and bipyridine (Scheme 1). We also show that halogenated photoproduct **2** self-assembles in the solid state to exhibit an extremely rare form of self-inclusion, wherein 1D channels defined by **2** are occupied by either solvent or molecules that make up the host itself.[9] The resulting isoskeletal frameworks and the self-inclusion of **2** are facilitated, in part, by halogen-bond interactions.[10]

To generate a photoproduct functionalized with halogen atoms, we set out to form a co-crystal based on a rigid ditopic template that assembles and stacks two halogenated olefins



Scheme 1. Templated solid-state photodimerization to form halogenated product **2**.

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Supporting information for this article is available on the WWW under http://dx.doi.org/10.1002/anie.201510912.

within a discrete halogen-bonded structure. We expected **DPN**, with a rigid naphthalene core and approximately parallel 4-pyridyl groups, to direct the assembly of **1** to form a 0D structure.[11] Although **1** has not been studied in terms of solid-state reactivity, the molecule has been reported to act as a building block for the formation of crystalline self-assembled frameworks.[12]

Initially, we focused on the reactivity of compound **1** alone in the solid state. The olefin was synthesized by a Wittig reaction between 2,3,4,5-tetrafluorobenzaldehyde and triphenyl(2,3,5,6-tetrafluorobenzyl)phosphonium bromide followed by iodination.[12] Pale-yellow single crystals of **1** in the form of plates were obtained by slow evaporation of a saturated MeOH solution over a period of one day.

An X-ray diffraction analysis revealed that **1**, which crystallized in the monoclinic space group $P21/c$, self-assembled to form 2D sheets driven by type II I···I interactions (I(1)···I(1) = 3.901(5) Å; C-I(1)···I(1) = 95.1(2)°; Figure 2 a,b).[18] Adjacent sheets interact through F···F interactions (F(1)···F(2) = 2.866(4) Å; F(1)···F(3) 2.815(5) Å; Figure 2 c).[13] As a consequence of the assembly process, the C=C bonds of the diiodoperfluorinated olefin are separated by 5.00 Å, which places the C=C bonds of **1** at a distance greater the limit, reported Schmidt, for a photodimerization reaction to occur.[14] Compound **1** in its crystalline form was determined to be photostable upon exposure to UV radiation (450 W, medium-pressure Hg lamp), as demonstrated by ^{1}H NMR spectroscopy.

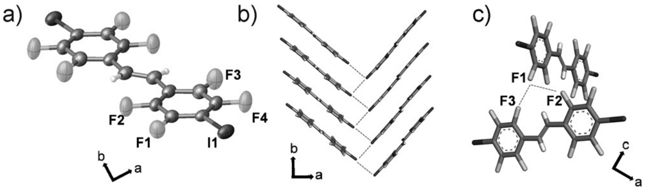

Figure 2. X-ray crystal structure of **1**, showing a) the ORTEP view, b) the formation of sheets held together by I···I interactions, and c) F···F contacts.

To orient **1** into a geometric arrangement suitable for a photodimerization reaction, we attempted to co-crystallize the olefin with **DPN** (1:1 ratio) in MeOH. Colorless prismatic crystals formed upon slow solvent evaporation after a period of 1 day. The formulation of 2(**DPN**)·2(**1**) was confirmed by ^{1}H NMR spectroscopy, as well as single-crystal and powder X-ray diffraction experiments.

Compound 2(**DPN**)·2(**1**) crystallizes in the monoclinic space group $C2/c$ (Figure 3).[18] The asymmetric unit consists of one half of a four-component 0D molecular assembly that sits around a center of inversion and is held together by four N···I halogen bonds (N(1)···I(1)−C: $d = 2.869(8)$ Å, $\theta = 177.3(3)°$; N(2)···I(2)−C: $d = 2.937(7)$ Å, $\theta = 178.3(3)°$; calc. 81 % and 83 % of the sum of the van der Waals radii).[15] In the arrangement, **DPN**, which is disordered over two sites (site occupancies: 0.51 and 0.49), assembles **1** in a face-to-face π-stacked geometry with the two C=C bonds of the stacked olefins being parallel and separated by 3.68 Å. The geometry, in contrast to pure **1**, satisfies the criteria of Schmidt for a photodimerization reaction to occur.[14] The four-component assemblies pack face-to-face and are offset by F···F (F(6)···F(6′) = 2.688(9) Å) and C−H···F interactions, with adjacent olefins between two four-component assemblies separated by 7.18 Å.

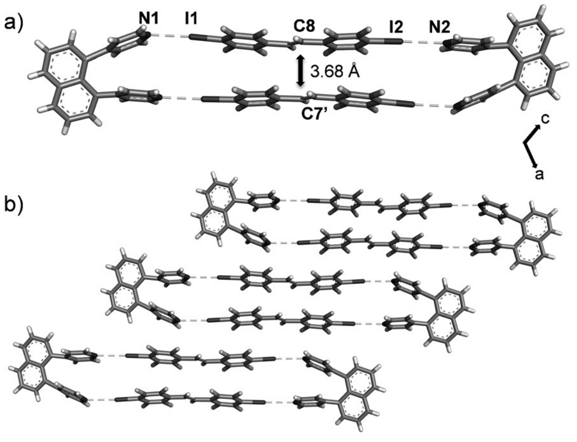

Figure 3. The X-ray crystal structure of 2(**DPN**)·2(**1**), showing a) the halogen bonds facilitating the formation of the four-component 0D assembly and b) extended packing. The highest occupancy of **DPN** is shown.

To determine the photoreactivity of 2(**DPN**)·2(**1**), a powdered crystalline sample was exposed to broadband UV radiation for a period of 20 h. ^{1}H NMR spectroscopy revealed that photodimerization occurred stereoselectively and in quantitative yield. The formation of a cyclobutane ring was evidenced by the disappearance of the olefinic resonance signal at $\delta = 7.32$ ppm in the ^{1}H NMR spectrum ([D$_6$]DMSO) and the appearance of a signal for cyclobutane at $\delta = 5.24$ ppm (Figure S2).

To confirm the structure of the photoproduct, the cyclobutane-containing compound was isolated using silica gel chromatography (hexanes:CH$_2$Cl$_2$ 2:1 v/v as eluent). The resulting solid was then recrystallized in hexane to give colorless prisms suitable for X-ray crystallographic analysis.

Photoproduct **2** crystallizes in the monoclinic space group $C2/c$ (Figure 4).[18] A single full cyclobutane sits in the asymmetric unit with the *p*-iodotetrafluorophenyl (C_6F_4I) moieties having an *rctt* geometry (C−C distances: C(25)−C(26) = 1.57(7) Å, C(26)−C(27) = 1.57(7) Å, C(27)−C(28) = 1.57(7) Å, C(28)−C(25) = 1.55(7) Å). The C_6F_4I rings of the photoproduct are distributed about the cyclobutane ring, with two of the angles between the aryl rings being 71.1° and 79.3°, respectively. The stereochemistry of **2** supports the intermolecular [2+2] photodimerization of **1** being dictated by the four-component halogen-bonded structure.

In addition to the stereochemistry of **2**, the X-ray crystal structure shows that compound **2** undergoes self-assembly to form a channel-type inclusion compound in the solid state (Figure 5). Specifically, **2** self-assembles by "pinching" of one C_6F_4I ring by two adjacent rings of a neighboring cyclobutane (Figure 5 a) to form 1D ribbons (Figure 5 b). Antiparallel ribbons interdigitate in a "tongue-and-groove" fit (Figure 5 c) by face-to-face π stacking, as well as through F···F and C···F

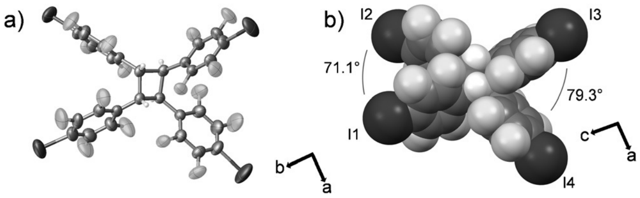

Figure 4. X-ray crystal structure of **2** showing a) the ORTEP view and b) a space-filling model.

interactions (see the Supporting Information). The interdigitation gives rise to the formation of columns that pack by means of F···I interactions (F(6)···I(3) = 3.29(3) Å, F(8)···I(3) = 3.43(4) Å) to form 1D channels of dimensions 3.26 × 7.58 Å (Figure 5 d). The I atoms from the photodimerization line the inner walls of the channels. Highly disordered electron density consistent with hexane as the solvent was located in the channels and modeled as diffuse electron density by using SQUEEZE.[16] A combination of ^{1}H NMR spectral and TGA-FTIR data confirmed that the solid compound had a composition of (**2**)·(hexanes).

In addition to the incorporation of hexanes as the guest molecules, **2** exhibits an unusual ability to host itself through a very rare form of self-inclusion. Specifically, when (**2**)·(hexanes) was heated at 125 °C under ambient pressure for 24 h, colorless single crystals in the form of well-defined needles formed from the melt (Figure 5 e). A single-crystal X-ray diffraction study revealed that **2** assembled in the triclinic space group $P\bar{1}$ to give the inclusion framework $(\mathbf{2h})_4\cdot(\mathbf{2g})$ (h = host, g = guest), a structure that is isoskeletal to (**2**)·(hexanes) (Figure 5 f).[18] A molecule of **2** resides in the channels supported by F···I and I···I interactions between different molecules of cyclobutane **2** comprising the host framework (Figure 5 g; F(18)···F(18) = 2.937(5) Å, I(3A)···I(1A) = 3.921(4) Å, F(10A)···I(5) = 3.223(9) Å, F(5A)···I(6) = 3.43(1) Å, I(2A)···(I8A) = 3.716(2) Å, I(2A)···(I8B) = 3.24(2) Å).[17] As in (**2**)·(hexanes), the host molecules of **2** interact by pinching of C_6F_4I groups and a tongue-and-groove fit to form channels of dimensions 9.68 × 1.25 Å (see the Supporting Information). The channels underwent a significant distortion to accommodate **2** as a guest. In 2006, Barbour et al. reported the rare form of self-inclusion exhibited by **2** in studies of a hydrogen-bonded diol-diyne.[9] Cyclobutane **2** is, to our knowledge, only the second example of a such a truly self-included structure[10] and the first to be based on halogen-bonding interactions.

In conclusion, we have employed halogen bonds to direct the formation of a halogenated photoproduct in the solid state. The product forms in a [2+2] photodimerization that occurs stereoselectively and in quantitative product yield. The resulting product **2** self-assembles to exhibit a rare form of true self-inclusion.[10] We are now focused to direct the assembly and reactivity of additional olefins substituted with halogen atoms and to explore the use of halogenated products to afford systems that exhibit unique host–guest and related materials properties.

Acknowledgements

We thank the National Science Foundation (LRM DMR-1408834) for financial support, Prof. Tori Z. Forbes for use of a TGA-FTIR, and Prof. Mishtu Dey for use of a digital-imaging optical microscope.

Keywords: dimerization · halocarbon compounds · halogen bonding · molecular recognition · self-assembly

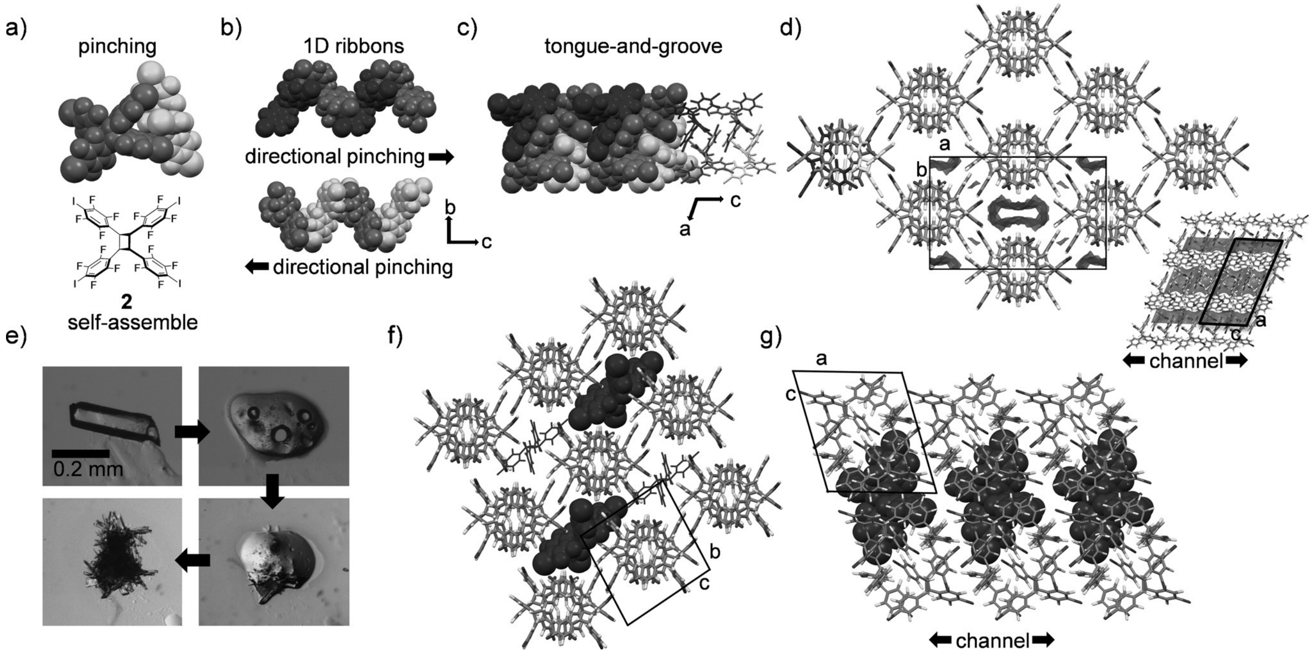

Figure 5. X-ray crystal structure of compound **2**·(hexanes), showing a) pinching, b) 1D ribbons, c) columns (viewed along the *c*-axis), and d) 1D channels. Crystal structures of $(\mathbf{2h})_4\cdot(\mathbf{2g})$, showing e) heating of (**2**)·(hexanes) at 125 °C (clockwise from top left: $t = 0$ h, $t = 1$ h, $t = 12$ h, and $t = 5$ d), f) the isoskeletal framework (with guest **2** shown as a space-filling model), and g) 1D channels showing the inclusion of **2**.

How to cite: *Angew. Chem. Int. Ed.* **2016**, *55*, 3477–3480
Angew. Chem. **2016**, *128*, 3538–3541

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[18] CCDC 1436471 (**1**), 1436472 (2(**DPN**)·2(**1**)), 1436473 (**2**)·(hexanes), and 1436474 $(\mathbf{2}_{h})_4\cdot(\mathbf{2}_{g})$ contain the supplementary crystallographic data for this paper. These data are provided free of charge by The Cambridge Crystallographic Data Centre.

Received: November 24, 2015