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Dawn E. Barry, Chris S Hawes, Salvador Blasco, and Thorfinnur Gunnlaugsson

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Structure direction, solvent effects and anion influences in halogen-bonded

adducts of 2,6-bis(iodoethynyl)pyridine

Dawn E. Barry, Chris S. Hawes,* Salvador Blasco & Thorfinnur Gunnlaugsson*

School of Chemistry & Trinity Biomedical Sciences Institute, Trinity College Dublin, Dublin 2, Ireland. Email: gunnlaut@tcd.ie

new divergent and self-complementary halogen bond donor-acceptor molecule 2,6-А bis(iodoethynyl)pyridine L has been prepared and structurally characterized, and used to generate a series of extended halogen-bonded adducts with tetrabutylammonium halide salts. The reaction between L and either tetrabutylammonium bromide or chloride gives the one-dimensional polymeric species {L·TBABr} or {L·TBACl}, respectively, which contain helical strands linked by C-I···X⁻ halogen bonds which partially encapsulate the associated organic cations. Varying the reaction solvent from ethyl acetate to 5:95 methanol:ethyl acetate gives rise to another polymeric phase on combining L with tetrabutylammonium chloride, the one-dimensional looped chain structure $\{L_2, TBACl\}$ in which each chloride ion acts as a four-connected square planar node for halogen bonding interactions originating from L. Similar solvent effects are observed in the discrete macrocyclic species {L·TBAI}- α and {L TBAI}- β , both consisting of cyclic (L₂I₂)² species which vary in their extended structures to adopt different packing modes, resembling those observed in the chloride and bromide adducts. Reaction of L with tetrabutylammonium fluoride in the presence of methanol gives a one-dimensional polymeric assembly $\{L_2: TBAF \cdot MeOH\}$ containing a unique MeOH \cdots F node in which the strongly hydrogenbonded anionic species is supported solely by four halogen bonding interactions. Excluding hydrogen bond donors from the reaction mixture affords $\{L_3TBAF_2\}$, an overall two-dimensional polymeric assembly consisting of a mixture of one- and two-dimensional networks based on iodine-fluoride halogen bonds. In all cases, the strong interactions between the iodoethynyl groups and halide anions overcome the tendency for L to form the self-complementary halogen-bonded network, showing that synthetically accessible heterocyclic iodoethynyl compounds present exciting new directions in the structural chemistry field.



Contact Author: Prof. Thorfinnur Gunnlaugsson School of Chemistry and Trinity Biomedical Sciences Institute (TBSI) Trinity College Dublin Dublin 2, Ireland Phone: +353-1-896 3459 Emails: hawescs@tcd.ie and gunnlaut@tcd.ie https://thorrigunnlaugsson.wordpress.com/

Structure direction, solvent effects and anion influences in halogen-bonded adducts of 2,6bis(iodoethynyl)pyridine

Dawn E. Barry, Chris S. Hawes, * Salvador Blasco & Thorfinnur Gunnlaugsson*

School of Chemistry and Trinity Biomedical Sciences Institute (TBSI), Trinity College Dublin,

The University of Dublin, Dublin 2, Ireland. Email: gunnlaut@tcd.ie

Abstract

A new divergent and self-complementary halogen bond donor-acceptor molecule 2.6bis(iodoethynyl)pyridine L has been prepared and structurally characterized, and used to generate a series of extended halogen-bonded adducts with tetrabutylammonium halide salts. The reaction between L and anions such as either bromide or chloride gives the one-dimensional polymeric species $\{L \cdot TBABr\}$ or $\{L \cdot TBACl\}$, respectively, which contain helical strands linked by C-I \cdots X⁻ halogen bonds which partially encapsulate the associated organic cations. Varying the reaction solvent from ethyl acetate to 5:95 methanol:ethyl acetate gives rise to another polymeric phase on combining L with tetrabutylammonium chloride, the one-dimensional looped chain structure $\{L_2, TBAC\}$ in which each chloride ion acts as a four-connected square planar node for halogen bonding interactions originating from L. Similar solvent effects are observed in the discrete macrocyclic species {L·TBAI}- α and {L·TBAI}- β , both consisting of cyclic $(L_2I_2)^{2-}$ species which vary in their extended structures to adopt different packing modes. resembling those observed in the chloride and bromide adducts. Reaction of L with tetrabutylammonium fluoride in the presence of methanol gives a one-dimensional polymeric assembly $\{L_2 \cdot TBAF \cdot MeOH\}$ containing a unique MeOH...F node in which the strongly hydrogen-bonded anionic species is supported solely by four halogen bonding interactions. Excluding hydrogen bond donors from the reaction mixture affords $\{L_3TBAF_2\}$, an overall twodimensional polymeric assembly consisting of a mixture of one- and two-dimensional networks based on iodine-fluoride halogen bonds. In all cases, the strong interactions between the iodoethynyl groups and halide anions overcome the tendency for L to form the selfcomplementary halogen-bonded network, showing that synthetically accessible heterocyclic iodoethynyl compounds present exciting new directions in the structural chemistry field.

Introduction

The directed and reversible assembly of multi-component architectures has long been an area of significant interest in coordination and materials chemistry.¹⁻² Many supramolecular structures and assemblies have been designed and constructed based on robust, directional and reversible interactions, principal among them the coordination bond and the hydrogen bond.³⁻⁴ More recently, more subtle intermolecular interactions have been employed as reliable synthons in the construction of supramolecular assemblies, such as π - π interactions and halogen bonding.⁵⁻⁸ The latter phenomenon has attracted intense interest in recent years, and is sometimes considered as an analogue to hydrogen bonding in strength, although with a much greater degree of directionality.⁹⁻¹² Since the phenomenon was first identified and methodically harnessed.¹³ many elegant examples have emerged of the use of halogen bonding interactions in the formation of multi-component organic or metal-organic assemblies, in the gaseous and solution states as well as in the solid state.¹⁴⁻²⁰ Now that substantial progress has been made towards adoption of the halogen bond as an accessible supramolecular synthon, many new examples of halogen bond donors are continually being discovered, alongside new applications for these materials in materials science.²¹⁻²⁴ In particular, halogen bonding constitutes an important aspect to pharmaceutical polymorph screening, where the presence of such interactions can play an important role in the nature and quantity of potential polymorphs of electron deficient haloarenes.25-28

To date, much of the research into halogen-bonded adducts has focused on iodoperfluoroaryl compounds such as 1,4-diiodo-2,3,5,6-tetrafluorobenzene and related isomers, and iodoperfluoroalkanes.²⁹⁻³³ These compounds make for attractive starting materials based on their ready availability and good stability, and possess the requisite σ -hole electronic nature to allow

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for robust interactions with various Lewis-basic groups. Other electron withdrawing substituents such as nitro and trifluoromethyl are also becoming increasingly widespread, to increase the Lewis acidity of jodine groups leading to stronger halogen bonding interactions.³⁴⁻³⁵ Other molecular platforms for halogen bonding are somewhat less common, but include the notably reactive halogenated dialkynes 1.4-diiododiacetylene and 1.4-dibromodiacetylene. Both compounds have been stabilized in the solid state through strong halogen bonding interactions with pyridine donors, allowing for their controlled topochemical polymerization.³⁶⁻³⁸ Although unsubstituted bis-haloalkynes are challenging to handle due to their tendencies towards violent polymerization. alkvneand haloalkyne-substituted aromatics and heterocycles are comparatively stable and are used as precursors in a wide variety of organic transformations.³⁹⁻⁴⁰ In several reports, Resnati, Aakeröy and others have used phenyl iodoalkynes to great effect in the formation of halogen bonded adducts with various Lewis bases.⁴¹⁻⁴⁴ Herein we report the synthesis and structural chemistry of a new bis(iodoalkyne)-substituted pyridine species 2,6bis(iodoethynyl)pyridine L, which represents an unusual example of a molecule containing both strong halogen bond donor and acceptor sites, and probe its behavior as a ditopic halogen bond donor in the presence of halide anions.

Experimental

Materials & Methods

All reagents, solvents and starting materials were purchased from Sigma-Aldrich, Merck or Fisher Scientific, were of reagent grade or better, and were used as received. 2,6-Diethynylpyridine was prepared according to literature procedures, and characterization data

were consistent with that previously reported.⁴⁵ ESI mass spectra were acquired using a Micromass time of flight mass spectrometer (tof), interfaced to a Waters 2690 HPLC. The instrument was operated in positive or negative mode as required. Leucine Enkephalin was used as an internal lock mass. Masses were recorded over the range 100-1000 m/z. Operating conditions were as follows: ESI capillary voltage 2500V, cone voltage 25V, desolvation temperature 300 °C, source temperature 100 °C. The ESI gas was nitrogen. MassLynx 4.0 software was used to carry out the analysis. Elemental analyses were carried out at the Microanalytical Laboratory, School of Chemistry and Chemical Biology, University College Dublin. NMR data were recorded in commercially available deuterated solvents on a Bruker Spectrospin DPX-400 spectrometer which operates at 400.13 MHz for ¹H NMR and 100.6 MHz for ¹³C NMR. Tetramethylsilane (TMS) was used as an internal standard and shifts were referenced relative to the internal solvent signals with chemical shifts expressed in parts per million (ppm / δ). Infrared spectra were recorded on a Perkin Elmer Spectrum 100 FTIR spectrometer with universal ATR sampling accessory, in the range 4000 - 550 cm⁻¹. X-ray powder diffraction patterns were collected using a Bruker D2 Phaser instrument with Cu Ka radiation ($\lambda = 1.5418$ Å). Samples were ground and mounted on silicon sample holders, and data were collected in the 2 θ range 5 – 55° at room temperature while rotating φ at a speed of 1 RPM. Sample background due to fluorescence was subtracted and the patterns were compared with those simulated from the single crystal data collected at 100 K.

Synthesis of 2,6-bis(iodoethynyl)pyridine L

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The title compound was prepared by a modification to a reported procedure for the synthesis of the mono-substituted equivalent 2-iodoethynylpyridine.⁴⁶ To a solution of 2,6-diethynylpyridine (0.9 g, 6.8 mmol) and potassium iodide (2.5 g, 15 mmol, 2.2 equiv.) in CH₃OH (60 mL) a solution of 70% aqueous tert-butyl hydroperoxide (2.84 mL, 20.4 mmol, 3 equiv.) was added drop-wise over a period of 30 mins with stirring at RT. The reaction mixture was stirred at RT for a further 24 hrs and was then quenched with sat. aq. Na₂S₂O₃, washed with brine and the product extracted into ethyl acetate. The organic layer was dried over MgSO₄ and solvent removed *in vacuo*, affording the pure product as a brown microcrystalline solid. Yield 1.467 g (57%). Single crystals suitable for X-ray diffraction were prepared by recrystallization from ethyl acetate, and X-ray powder diffraction confirmed that the original microcrystalline material matches this phase. m.p. 189-196 °C (decomp.); Found C, 28.66; H, 0.67; N, 3.50; Calculated for $C_{0}H_{3}NI_{2}C$, 28.53; H, 0.80; N, 3.70%; ¹H NMR (400 MHz, CDCl₃) $\delta_{H_{2}}$ 7.62 (1H, t, J = 7.8 Hz, pyridine-H), 7.34 (2H, d, J = 7.8 Hz, pyridine-H); ¹³C NMR (100 MHz, CDCl₃) δ_{C} 143.23, 136.51, 127.07, 93.33, 60.40; HRMS (m/z) (ESI⁺) Calculated for C₉H₄NI₂⁺ m/z = 379.8433 [M + H_{1}^{+} . Found m/z = 379.8429; v_{max} (ATR, cm⁻¹) 3057w, 2959m sh, 2871w, 2153m, 1574s, 1552s, 1436s, 1381w, 1242m, 1210w, 1155w, 1079w, 992w, 984w, 953w, 800s, 749w, 733m, 609m. Phase purity was confirmed by X-ray powder diffraction (Supporting Information).

Synthesis of halogen-bonded adducts

Synthesis of {L·TBABr}

A solution of L (20 mg, 53 μ mol) was prepared in 2 mL of ethyl acetate with the aid of sonication and gentle heating. This solution was added to a solution of tetrabutylammonium

bromide (17 mg, 53 µmol) in ethyl acetate (2 mL). A white suspension formed immediately on mixing. The mixture was sealed and left to stand for 24 hours, at which time the colourless crystals were isolated by filtration, washed with ethyl acetate, and dried in air. Yield 12 mg (30 %). m.p. 155-157 °C (decomp); Found C, 42.39; H, 5.50; N, 3.86; Calculated for $C_{25}H_{39}N_2BrI_2$ C, 42.82; H, 5.61; N, 3.99%; v_{max} (ATR, cm⁻¹) 3055w, 2961m sh, 2872m, 2158m, 1563s, 1553s, 1480m sh, 1460m, 1431s, 1380m, 1343w, 1297w, 1268m, 1238m, 1206m, 1149m, 1079m, 1028w, 1003w, 980m, 947m, 877m sh, 824s, 742s. Phase purity was confirmed by X-ray powder diffraction (Supporting Information).

Synthesis of {L·TBACl}

The title compound was prepared through an identical procedure to {L·TBABr}, using 15 mg (54 μ mol) of tetrabutylammonium chloride. Yield 6 mg (17 %). m.p. 151-154 °C (decomp); Found C, 45.71; H, 6.02; N, 4.12; Calculated for C₂₅H₃₉N₂ClI₂ C, 45.71; H, 5.98; N, 4.26%; v_{max} (ATR, cm⁻¹) 3058w, 2962m sh, 2872m, 2157m, 1563s, 1551s, 1479m sh, 1463m, 1430s, 1380m, 1342w, 1300w, 1269m, 1236m, 1205s, 1149s, 1079m, 1030w, 1004w, 980m, 946m, 878m sh, 825s, 742s. Phase purity was confirmed by X-ray powder diffraction (Supporting Information).

Synthesis of $\{L_2: TBACl\}$

A solution of L (20 mg, 53 μ mol) in 2 mL of 5:95 methanol:ethyl acetate was added to a solution of tetrabutylammonium chloride (8 mg, 29 μ mol) in 2 mL of 5:95 methanol:ethyl acetate. The mixture was allowed to concentrate by slow evaporation, yielding colourless crystals after 12

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hours. The crystals were isolated by filtration, washed with ethyl acetate, and dried in air. Yield 21 mg (75 %). m.p. 139-142 °C (decomp); Found C, 39.35; H, 4.04; N, 3.90; Calculated for $C_{34}H_{42}N_3CII_4$ C, 39.43; H, 4.09; N, 4.06%; v_{max} (ATR, cm⁻¹) 3057w, 2962m sh, 2873m, 2153m, 1574s, 1553s, 1480m sh, 1437s, 1379w, 1281m, 1241m, 1210s, 1156m, 1079w, 1027w, 981m, 950m, 877m, 809s, 743m, 733m. Phase purity was confirmed by X-ray powder diffraction (Supporting Information).

Synthesis of $\{L \cdot TBAI\}$ - α

A solution of L (20 mg, 53 µmol) in 2 mL of ethyl acetate was prepared with brief sonication and gentle heating. This mixture was added to a suspension of tetrabutylammonium iodide (20 mg, 54 µmol) in ethyl acetate (5 mL), and the mixture was heated at reflux for 30 minutes. On cooling to room temperature a white suspension formed, and the solution was left to stand overnight, giving colourless crystals which were isolated by filtration, washed several times with ethyl acetate, and dried in air. Yield 11 mg (28 %). m.p. 116-119 °C (decomp.); Found C, 40.00; H, 5.19; N, 3.63; Calculated for C₂₅H₃₉N₂I₃ C, 40.13; H, 5.25; N, 3.74%; v_{max} (ATR, cm⁻¹) 3057w, 2958m sh, 2872m, 2153m, 1574s, 1551s, 1485m, 1467m sh, 1433s, 1378m, 1293w, 1267m, 1242m, 1205s, 1145m, 1108w, 1075m sh, 1031m, 982m, 945s, 921m, 881s, 820s, 736s. Phase purity was confirmed by X-ray powder diffraction (Supporting Information).

Synthesis of $\{L \cdot TBAI\}$ - β

Solutions of L (20 mg, 53 µmol) and tetrabutylammonium iodide (20 mg, 54 µmol) were prepared, each dissolved in 2 mL of 5:95 methanol:ethyl acetate, and combined. The resulting clear solution was left to evaporate to dryness, yielding a pale yellow oil which crystallised over the course of two days. The crystalline material was triturated with ethyl acetate, and the crystals isolated by filtration, washed with ethyl acetate, and dried in air. Yield 16 mg (40 %). m.p. 120-123 °C (decomp.); Found C, 40.54; H, 5.42; N, 3.58; Calculated for $C_{25}H_{39}N_2I_3$ C, 40.13; H, 5.25; N, 3.74%; v_{max} (ATR, cm⁻¹) 3051w, 2959m sh, 2872m, 2154m, 1572m, 1553s, 1467m sh, 1433s, 1380m, 1287w, 1266w, 1240w, 1205m, 1149m, 1077w, 1031w, 982m, 946m, 881m sh, 821s, 739s. Phase purity was confirmed by X-ray powder diffraction (Supporting Information).

Synthesis of $\{L_2 \cdot TBAF \cdot MeOH\}$

Solutions of L (20 mg, 53 µmol) and tetrabutylammonium fluoride trihydrate (17 mg, 54 µmol) were prepared, each dissolved in 2 mL of 5:95 methanol:ethyl acetate, and combined. The resulting clear solution was allowed to concentrate by evaporation overnight, yielding colourless crystals after 12 hours. The crystals were isolated by filtration, washed with ethyl acetate, and dried in air. Yield 15 mg (42 %). m.p. 116-119 °C (decomp.); Found C, 40.27; H, 4.43; N, 3.88; Calculated for $C_{35}H_{46}N_3OFI_4$ C, 39.98; H, 4.41; N, 4.00%; v_{max} (ATR, cm⁻¹) 3056w, 2963m sh, 2874m, 2823w, 2524w br, 2157m, 1574s, 1556s, 1470m, 1437s, 1380w, 1342w, 1281m, 1241m, 1210m, 1155m, 1081w, 1025s, 981m, 951m, 926w, 880m sh, 805s, 732s sh. Phase purity was confirmed by X-ray powder diffraction (Supporting Information).

Synthesis of $\{L_3(TBAF)_2\}$

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To a warmed solution of L (20 mg, 53 μ mol) in 2 mL of ethyl acetate was added a solution of tetrabutylammonium fluoride trihydrate (12 mg, 38 μ mol) in 1 mL of ethyl acetate, causing immediate formation of a white suspension. The solution was sealed and allowed to stand overnight, and the resulting colourless crystals were isolated by filtration, washed with ethyl acetate, and dried in air. Yield 17 mg (58 %). m.p. 149-153 °C (decomp.); Found C, 42.60; H, 4.95; N, 4.07; Calculated for C₅₉H₈₁N₅F₂I₆ C, 42.70; H, 4.92; N, 4.22%; v_{max} (ATR, cm⁻¹) 3049w, 2963m sh, 2874m, 2147m, 1572m, 1552s, 1480m sh, 1436s, 1380m, 1281w, 1238m, 1209m, 1156w, 1081w, 1029w, 981m, 947m, 887w br, 815s sh, 737s sh. Phase purity was confirmed by X-ray powder diffraction (Supporting Information).

X-ray crystallography

Structural and refinement parameters are presented in Table 1. All diffraction data were collected using a Bruker APEX-II Duo dual-source instrument using graphite-monochromated Mo K α (λ = 0.71073 Å) or microfocus Cu K α (λ = 1.54178 Å) radiation. Datasets were collected using ω and φ scans with the samples immersed in oil and maintained at a constant temperature of 100 K using a Cobra cryostream. The data were reduced and processed using the Bruker APEX suite of programs.⁴⁷ Multi-scan absorption corrections were applied using SADABS.⁴⁸ The diffraction data were solved using SHELXT and refined by full-matrix least squares procedures using SHELXL-2015 within the OLEX-2 GUI.⁴⁹⁻⁵¹ The functions minimized were $\Sigma w(F_0^2 - F_c^2)$, with $w = [\sigma^2(F_0^2) + aP^2 + bP]^{-1}$, where $P = [max(F_0)^2 + 2F_c^2]/3$. All non-hydrogen atoms were refined with anisotropic displacement parameters. All carbon-bound hydrogen atoms were placed in calculated positions and refined with a riding model, with isotropic displacement parameters

equal to either 1.2 or 1.5 times the isotropic equivalent of their carrier atoms. Where appropriate and as discussed in the text, the positions of hydrogen atoms involved in hydrogen bonding interactions were refined to provide the best fit for the residual Fourier peaks and assigned a Uiso value equal to 1.5 times that of the nearest associated atom, with the appreciation that the exact positions of these atoms cannot be meaningfully inferred from X-ray diffraction data. The strongly hydrogen-bonded hydrogen atoms in the structure of $\{L_2 \cdot TBAF \cdot MeOH\}$ were modelled to coincide with the largest Fourier residual peak between the two possible donor atoms, which provided the best crystallographic fit (Supporting Information). However, the exact positions of these hydrogen atoms cannot be unambiguously inferred from the X-ray diffraction data, nor are their exact positions intended to be strongly implied by the model. Several of the datasets displayed minor disorder affecting the tetrabutylammonium cations; where appropriate, the positions of outer carbon atoms were split across multiple orientations and the occupancy of each disordered contributor refined as a free variable, and then fixed to an appropriate value. Restraints on bond lengths or U_{ii} tensors were only employed when a meaningful improvement in the ability of the structural model to describe the true chemical behavior was obtained. Despite repeated attempts, all isolated crystals of compound $\{L_3(TBAF)_2\}$ suffered from substantial nonmerohedral twinning and displayed poor diffraction characteristics, necessitating the use of microfocus Cu K α radiation for the data collection. Presumably due to the high absorption inherent to this wavelength in the presence of heavy atoms ($\mu_{calc} = 22.2 \text{ mm}^{-1}$), the crystals suffered decomposition by beam damage after several hours of irradiation. A structure model was obtained by merging two datasets collected before the crystal decomposition became untenable, using least-squares scaling and merging procedures in XPREP⁵²; although the structure model necessarily displays poor refinement statistics, the atomic connectivity is

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unambiguous and supported by FTIR, elemental analysis and X-ray powder diffraction data. Particular refinement strategies for each structure, including the specific use of restraints, are provided in the refine_special_details sections of the combined crystallographic information file. CCDC 1480733-1480739



Scheme 1: Synthesis of 2,6-bis(iodoethynyl)pyridine L. Reagents and conditions: (i) Trimethylsilylacetylene, CuI, Pd(PPh₃)₂Cl₂, NEt₃, THF; (ii) silica gel, DCM/Hexane; (iii) KI, TBHP, MeOH.

Results

Synthesis and structure of 2,6-bis(iodoethynyl)pyridine L

The title compound 2,6-bis(iodoethynyl)pyridine L was prepared in three steps from 2,6dibromopyridine with an overall yield of 31% as demonstrated in Scheme 1. Single crystals of 2,6-bis(iodoethynyl)pyridine L were prepared by slow cooling and evaporation of a hot ethyl acetate solution, yielding colourless crystals within several hours. The crystals were analysed by single crystal X-ray diffraction, and a structure model was generated in the orthorhombic space group $P2_12_12_1$. The asymmetric unit of L contains the molecule in its entirety, with no associated solvent or guest molecules. The structural parameters, particularly the C=C bond lengths of 1.207(4) and 1.210(4) Å, and C-I bond lengths of 1.979(3) and 2.011(3) Å, are consistent with the expected values. The statistically significant discrepancy in lengths for the two carbon-iodine bonds can be ascribed to the differences in intermolecular interactions between the two groups. Iodine atom I1 acts as a halogen bond donor in an interaction with the pyridine nitrogen atom of an adjacent molecule, with an I…N distance of 2.901(2) Å and angle C-I…N of 175.1(1)°. This interaction most likely leads to lengthening of the C-I bond due to the electron donation into the iodine σ -hole. Conversely, due to the lack of any other available groups of significant Lewis basicity, and crystal packing constraints preventing any possible iodine-iodine interactions, the iodine atom I2 does not engage in any meaningful intermolecular interactions within the structure, and as a consequence, exhibits the shorter of the two C-I bond lengths. The structure of L is shown in Figure 1.



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Figure 1. (Top) Structure of L with heteroatom labelling scheme. (Bottom) Halogen bonding $I \cdots N$ interactions in the structure of L

The halogen bonding interaction present in L propagates a one-dimensional chain parallel to the crystallographic *b* axis. The interactions between adjacent chains are limited to minor π - π interactions, although the degree of overlap is limited by the undulating geometry of each chain and the low symmetry and relatively compact π -surface of each molecule of L.

Structure of {L·TBABr}

Reaction of L with one equivalent of tetrabutylammonium bromide in ethyl acetate gave a white oily suspension immediately upon mixing. On standing for several hours, colourless crystals of $\{L \cdot TBABr\}$ deposited which were isolated and subjected to single crystal X-ray diffraction. The structure model obtained in the triclinic space group *P*-1 reveals an asymmetric unit containing two unique molecules of L, two tetrabutylammonium cations and two associated bromide counterions. The structure of $\{L \cdot TBABr\}$ is shown in Figure 2. Both molecules of L engage in halogen bonding interactions with the two unique bromide ions; each of which interacts with two iodine atoms, from crystallographically unique L molecules. The I···Br distances for these interactions fall in the range 3.1604(4) – 3.2280(4) Å, and C-I···Br angles in the range 174.4(1) - 176.0(1) °. For the two unique bromide ions, the angles I···Br···I are comparable, at 77.36(1) and 78.92(1)° for Br1 and Br2, respectively. Each of the four unique C-I bond lengths lie in the range 2.021(4) – 2.037(4) Å.



Figure 2. Structure of {L·TBABr} with heteroatom labelling scheme. Hydrogen atoms are omitted for clarity. Symmetry codes used to generate equivalent atoms: i) 1+x, +y, +z.

The bridging connectivity of both the L molecules and bromide anions imparts a onedimensional polymeric character to the extended structure of {L·TBABr} in which alternating L…Br…L chains proceed in a helical fashion parallel to the *a* axis. The helical nature of the chain is imparted by the dihedral angles (measured 11-12…13-14) of 28.485(3)° for binding to Br1 and 27.214(3)° for binding to Br2. The helical pitch distance of 8.3829(2) Å is equivalent to the length of the crystallographic *a* axis and allows for two complete molecules of L and two bromide anions per revolution. The central cavity of each helicate is occupied by one of the two unique tetrabutylammonium cations, while the other cation is associated with the external helical groove. Myriad weak C-H… π interactions occur between these cations and the pyridine groups comprising each helix, adding to the Coulombic attractions between the cationic and anionic species. Permitted by the rhombic outer shape of the helices, adjacent chains pack in offset layers, with handedness conserved along the *c* axis and alternating along the *b* axis. No

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substantial void space or solvent guest molecules were observed within the structure of {L·TBABr}.



Figure 3. *Top:* Representation of one helical chain within the structure of { $L \cdot TBABr$ }. Hydrogen atoms and tetrabutylammonium cations omitted for clarity. *Bottom:* Representation of the helical chain in { $L \cdot TBABr$ }, rendered as space-filling, and the relationship with the tetrabutylammonium cations located within the helical cavity (coloured yellow), and those associated with the external groove (coloured green).

Synthesis and Structure of $\{L \cdot TBACl\}$ and $\{L_2 \cdot TBACl\}$

The reaction of L with tetrabutylammonium chloride in ethyl acetate under similar conditions to those employed in the synthesis of {L·TBABr} gave a similar white oily deposit on mixing, which slowly deposited colourless microcrystals. Although the crystals obtained by this method were not of sufficient quality to allow structure determination by single crystal X-ray diffraction, both X-ray powder diffraction and infrared spectroscopy of the solid showed an equivalent structure to $\{L \cdot TBABr\}$, and microanalysis was consistent with a formulation of $\{L \cdot TBACl\}$ for the material obtained. However, repeating the reaction in a 5% methanol:ethyl acetate solvent system gave a clear solution on mixing of the two components, which deposited large colourless crystals after concentrating by evaporation overnight. Analysis of the crystals by single crystal X-ray diffraction provided a structural model of $\{L_2:TBACl\}$ in the triclinic space group P-1. The asymmetric unit contains two complete molecules of L, with one chloride ion and associated tetrabutylammonium cation. Both molecules of L are geometrically equivalent within error, and differ only by their relative orientations. Interestingly, no evidence of the helicate phase was observed when carrying out the reaction in this solvent system, regardless of whether a 1:1 or 2:1 L:TBACl ratio was used.

Here, the chloride ion is engaged in halogen bonding interactions with each of the four unique iodine atoms, at Cl…I distances in the range 3.0839(5) - 3.1196(5) Å in an approximately square-planar geometry. The geometry of these interactions is surprisingly regular, with all I…Cl…I *cis* angles falling within the range $83.424(12) - 94.506(15)^{\circ}$ and the two *trans* angles

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 $162.27(2)^{\circ}$ and $164.32(2)^{\circ}$ demonstrating a slight deviation from planarity, consistent with the Cl...(I₄ mean plane) distance of 0.45 Å. The structure of {L₂·TBACl} is shown in Figure 4.



Figure 4. Structure of the repeating unit of $\{L_2 \cdot TBACl\}$ with heteroatom labelling scheme. Hydrogen atoms are omitted for clarity. Symmetry codes used to generate equivalent atoms: i) +x, -1+y, -1+z.

With each chloride ion acting as a four-connected node, the extended structure of { $L_2 \cdot TBACl$ } consists of a one-dimensional chain comprised of planar L_2Cl_2 loops; oriented parallel to the [0,1,1] vector. The chains are grouped into pairs through offset face-to-face π - π interactions on one face, with minimum interatomic distance 3.359(3) Å for C4…C16, while the opposite face is interrupted by layers of tetrabutylammonium cations. Each loop is defined by two inwards-directed pyridine nitrogen atoms separated by 8.195(3) Å; these loops are occupied by two butyl chains of the nearby tetrabutylammonium cations. In the orthogonal direction, the chains align in an offset edge-to-edge fashion to give a densely packed layered structure as shown in Figure 5.



Figure 5. The extended structure of $\{L_2 \cdot TBACl\}$, viewed perpendicular (top) and near-parallel (bottom) to the direction of propagation. Hydrogen atoms are omitted for clarity.

Structure of $\{L \cdot TBAI\}$ - α

 Combining L with a suspension of tetrabutylammonium iodide in ethyl acetate, followed by heating at reflux for 30 minutes to account for the low room temperature solubility of the iodide salt, gave a white suspension after cooling to room temperature, which slowly crystallised on standing overnight. Analysis of the colourless crystals by single crystal X-ray diffraction provided a structural model in the orthorhombic space group *Pccn*. Equivalent crystals could also be prepared, albeit containing unreacted tetrabutylammonium iodide as an impurity, by mixing the two components at room temperature, equivalent to the procedure used for the bromide and chloride adducts. The asymmetric unit of $\{L \cdot TBAI\}$ - α contains one molecule of L, one iodide anion and halves of two non-equivalent tetrabutylammonium cations. The iodide anions act as

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acceptors for two halogen bonding interactions originating from the iodoalkyne groups of L, at I···I distances 3.3654(5) and 3.4027(5) Å for I1···I3 and I2···I3, respectively. The I···I angle of 80.338(12) is intermediate between the equivalent angles in {L TBABr} and {L₂ TBACl}. However, unlike the extended chains observed in those systems, in $\{L, TBAI\}$ -a two iodide ions act as caps to form a discrete cyclic assembly of the form L_2I_2 . These assemblies adopt a saddletype geometry, with a 49° angle between the mean planes of the two pyridine rings. Similarly to the previous cases, these loops encapsulate a tetrabutylammonium cation within the internal volume, defined by a distance between inwards-facing pyridine nitrogen atoms of 8.155(8) Å. Unlike the case of $\{L_2, TBAC\}$, however, the cation is centred on the pocket with butyl chains extending outwards, rather than occupying the central volume with butyl chains from an external position. The remaining tetrabutylammonium cation resides in a poorly-localised position on the periphery of the assembly, electrostatically bound by the nearby iodide anions. The difference in cation ordering between the encapsulated and free tetrabutylammonium groups can be seen by comparing the average freely refined U_{eq} values for the carbon and nitrogen atoms of each cation, which increases from 0.036 for the encapsulated cation to 0.124 for the unconfined. No meaningful disorder model could be beneficially applied to this group, and so the atom sites were allowed to freely refine at full occupancy with no ADP restraints to provide the most realistic depiction of the poorly localised group.



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Figure 6. The structure of {L·TBAI}- α with heteroatom labelling scheme. Hydrogen atoms are omitted for clarity. Symmetry codes used to generate equivalent atoms: i) 3/2-x, 1/2-y, +z.

Interestingly, when viewed parallel to the crystallographic *c* axis, the large-scale structure of $\{L \cdot TBAI\}$ - α bears a striking resemblance to the helical assembly of $\{L \cdot TBABr\}$. The L_2I_2 assemblies align into columns parallel to the *c* axis, with a distance of 8.1407(3) Å between equivalent iodide anions comparable to the helical pitch of 8.3829(2) Å observed in $\{L \cdot TBABr\}$. The rhombic shape and offset layer packing of the columns is also comparable between the two compounds, as is the alignment of the tetrabutylammonium cations. The two structures can be contrasted only by considering the relative twisting of each pair of **L** molecules within an essentially fixed matrix of tetrabutylammonium halides, as is demonstrated in Figure 7.



Figure 7. Overlaid structures of {L·TBABr} (yellow) and {L·TBAI}- α (red) using the halide ions as anchor points.

Structure of { $L \cdot TBAI$ }- β

Given the similarities between {L·TBAI}- α and {L·TBABr}, the reaction between L and tetrabutylammonium iodide was repeated under conditions comparable to those which formed $\{L_2, TBAC\}$, to test for the presence of any other phases with different packing motifs. Reaction of L with tetrabutylammonium iodide in a solution of 5% methanol in ethyl acetate gave a clear solution on mixing, from which colourless crystals deposited after concentration by evaporation overnight. Analysis of these crystals by single crystal X-ray diffraction gave a structure model for {L·TBAI}- β in the triclinic space group P-1, with an asymmetric unit containing two molecules of L, two iodide ions, and two tetrabutylammonium cations. The halogen bonding connectivity of $\{L \cdot TBAI\}$ - β is directly comparable to that observed in the α phase, in that two L molecules and two iodide anions comprise a cyclic assembly with I...I distances in the range 3.3090(3) - 3.4052(3) Å and I···I···I angles $74.506(6)^{\circ}$ and $77.026(6)^{\circ}$ for I5 and I6, respectively. The halogen-bonded macrocycles in the β phase are more planar than those in the α phase, with an angle between pyridine mean planes of 36° in the β phase compared to 49° in the α phase. The distance between the inwards-facing pyridine nitrogen atoms from each loop is reduced by *ca.* 0.5 Å in the β phase, to a value of 7.617(4) Å, and consequently only a single butyl chain from one tetrabutylammonium cation is observed occupying the free volume within each loop.





Figure 8. *Top:* The asymmetric unit of $\{L \cdot TBAI\}$ - β with heteroatom labelling scheme. Hydrogen atoms are omitted for clarity. *Bottom:* Overlaid structures of the α (red) and β (blue) phases of $\{L \cdot TBAI\}$.

Adjacent loops are aligned in a corner-to-corner fashion in the [1,1,0] direction, with a distance of 5.1194(3) Å between iodide anions. The extended structure of {L·TBAI}- β bears a resemblance to that of {L₂·TBACl} in this respect, where iodide anions alternate between halogen bonding L linkages and no linking interactions, rather than the continuous chain formed in the chloride case, as is evident from Figure 9. The arrangement of these chains relative to one another was also similar to that observed in {L₂·TBACl}, with lateral groups oriented approximately parallel to one another and forming an undulating 2-dimensional layer, interspersed by layers of tetrabutylammonium cations. Intermolecular interactions in the structure of {L·TBAI}- β are largely limited to various C-H··· π interactions between the

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tetrabutylammonium cations and the L moieties. Attempts were made to induce the formation of an isostructural chain to {L₂·TBACl} using tetrabutylammonium iodide at other stoichiometries, however the α and β phases of the cyclic species were the only crystalline materials isolated.



Figure 9. Extended structure of $\{L \cdot TBAI\}$ - β showing the offset packing between adjacent macrocycles. Hydrogen atoms are omitted for clarity.

Structure of $\{L_2 \cdot TBAF \cdot MeOH\}$

The reaction of **L** with tetrabutylammonium fluoride in 5% methanol/ethyl acetate gave colourless crystals after concentration by slow evaporation. Analysis of the crystals by single crystal X-ray diffraction provided a structural model in the triclinic space group *P*-1. The asymmetric unit of { L_2 ·TBAF·MeOH} contains four unique molecules of **L**, two fluoride anions, two tetrabutylammonium cations and two methanol molecules. Most strikingly, a strong hydrogen bonding interaction can be seen between the fluoride ions and the methanol molecules, with F··O distances 2.504(3) and 2.511(3) Å for the two unique interactions. The position of the hydrogen atom in this interaction cannot be unambiguously determined by X-ray diffraction techniques, particularly due to the presence of heavy atoms nearby. Nonetheless, the large residual Fourier peaks between the pairs of F··O atoms reside consistently closer to the mid-

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point between the possible donors than the corresponding O site, seemingly consistent with an $F \cdots H \cdots O$ ionic hydrogen bonding mode rather than either extreme case of O-H \cdots F or F-H \cdots O. A notable improvement in refinement statistics was obtained by modelling this hydrogen atom to coincide with the Fourier residual located part-way between the two atoms, rather than adopting a calculated position bonded to either of the possible donors (See Supporting Information).

Infrared spectroscopy of the material shows a very broad absorbance in the range 3500-2400 cm⁻¹ with maximum *ca*. 2500 cm⁻¹, consistent with an ionic hydrogen bonding interaction.⁵³ Repeating the reaction with CD₃OD in the place of methanol within the solvent mixture effected a detectable shift of the symmetric CH₃ stretching band from 2822 cm⁻¹ to 2062 cm⁻¹ for the CD₃ equivalent. However, due to the highly hygroscopic nature of the starting material and reaction conditions no meaningful difference in the hydrogen-bonded stretching frequency was observed. While methanol-fluoride adducts have been studied theoretically and in the gas and solution phases,^{54,55} typically as clusters with multiple hydrogen bond donors, structurally characterised examples of discrete [F···H···OMe] anions are less common. Such species can exist in the presence of supporting polydentate hydrogen bonding hosts or coordinated to metal ions,^{56,57} but to our knowledge {L₂·TBAF·MeOH} is unique as a crystallographically characterised example of such an adduct supported purely by halogen bonding interactions.

The strongly hydrogen-bonded [F···H···OMe] anionic species act as halogen bond acceptors within the structure of {L₂·TBAF·MeOH}, with each anionic unit interacting with four iodine atoms, two per fluoride ion and two per oxygen atom (Figure 10). Each of the four unique F···I distances lie in the range 2.585(2) – 2.595(2) Å, while the four O···I interactions exhibit slightly longer distances, in the range 2.725(2) – 2.751(2) Å. The I···F···I and I···O···I angles are

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comparable, with values of 119.56(7)°, 120.38(7)°, 114.73(8)° and 115.44(8)° for the two pairs of angles involving F and O acceptors, respectively.



Figure 10. *Top:* One of the two crystallographically unique looped motifs in the structure of $\{L_2 \cdot TBAF \cdot MeOH\}$ with partial atom labelling scheme; *Bottom:* extended structure of the polymeric chain in $\{L_2 \cdot TBAF \cdot MeOH\}$ showing the associated tetrabutylammonium cation. Hydrogen atoms are omitted for clarity. Symmetry codes used to generate equivalent atoms: i) +x, y-1, +z; ii) +x, y+1, +z.

With each $F \cdots H \cdots OMe$ anion interacting with four iodine atoms, the extended structure of $\{L_2 \cdot TBAF \cdot MeOH\}$ consists of a series of one-dimensional looped chains oriented parallel to the *b* axis, resembling those observed in the structure of $\{L_2 \cdot TBACl\}$. The polyatomic nature of the halogen bond accepting anionic species in $\{L_2 \cdot TBAF \cdot MeOH\}$ lends a stepped property to each

chain in the *c* direction, with the two facing **L** units no longer occupying coplanar orientations across the breadth of the chains. The loops defined by these groups, with distances between pyridine nitrogen atoms of 7.306(4) and 7.257(4) Å for the two unique pairs, are occupied by butyl chains from nearby tetrabutylammonium cations. The long-range structure of $\{L_2 \cdot TBAF \cdot MeOH\}$ is also closely related to that of $\{L_2 \cdot TBACl\}$, with chains aligned in an offset parallel fashion in the *b* direction and combined into alternating double-layers of anionic chains and tetrabutylammonium cations in the *a* direction.

Structure of $\{L_3(TBAF)_2\}$

Reaction of L with tetrabutylammonium fluoride in pure ethyl acetate gave a white suspension immediately on mixing, and colourless crystals were deposited after the mixture was allowed to stand at room temperature overnight. Despite numerous attempts to optimise the crystallisation of this material, every crystalline batch examined suffered from severe non-merohedral twinning and displayed poor diffraction characteristics. As such, the only sensible data collection strategy required the use of microfocus Cu K α radiation, which subsequently caused beam damage to the crystals within several hours of irradiation, presumably due to the particularly high absorption expected due to the presence of multiple heavy atoms. A connectivity model was established by merging datasets from two partial collections, providing a structural model of unambiguous connectivity, but nonetheless we refrain from a detailed analysis of interatomic distances or angles due to the difficulties with data quality. Analysis of the material by X-ray powder diffraction, elemental analysis and ATR-IR spectroscopy all strongly corroborate the suggested structure. The asymmetric unit of {L₃(TBAF)₂}, solved and refined in the monoclinic space

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group $P2_1/c$, contains three unique molecules of L, two fluoride anions, and two associated tetrabutylammonium cations. Unlike the case of {L₂·TBAF·MeOH}, no solvent molecules or guests were detected within the structure.

Two different modes of halogen bonding interactions take place in the structure of $\{L_3(TBAF)_2\}$, shown in Figure 11. One fluoride atom F1 engages in two halogen bonding interactions with one unique L group within the structure, interacting with the two unique iodine atoms at F...I distances of 2.40(2) and 2.47(2) Å and I···F···I angle of 113.9(7)°. Fluorine atom F2 participates in four halogen bonding interactions, involving each of the four iodine atoms from the remaining two of the three unique L groups within the asymmetric unit. The geometry of halogen bond donors around F2 is best described as trigonal pyramidal, in which three iodine atoms I3, I5 and I6 define the basal plane, at F...I distances 2.531(13), 2.613(13) and 2.591(13) Å respectively, and a distance F...(I₃ mean plane) of 0.51 Å. The axial I...F distance is marginally longer at 2.689(13) Å, and the corresponding F...I vector is near-parallel to the normal vector of the I_3 basal plane (angle $1.1(3)^{\circ}$). These inter-atomic distances are considerably shorter than those observed in the structure of $\{L_2 \cdot TBAF \cdot MeOH\}$, although the larger estimated standard deviations must be considered. The relative shortening of the inter-atomic distances in the case of F1 compared to F2 is most likely a consequence of the low coordination number and the increased efficiency of electron donation as a result.



Figure 11. Chemical environment of the two unique fluoride ions and the associated L molecules in the structure of $\{L_3(TBAF)_2\}$ with halogen atom labelling scheme. Hydrogen atoms are omitted for clarity. Symmetry codes used to generate equivalent atoms: i) +x, y+1, +z; ii) +x, y-1, +z; iii) +x, y-2, +z; iv) x-1, +y, +z; v) -x, y-1/2, 3/2-z; vi) -x, 1/2+y, 3/2-z; vii) 1+x, +y, +z.

Each of the two unique fluoride ions acts as a linker in two distinct non-entangled extended networks. Fluoride ion F1 connects two equivalent molecules of L into a one-dimensional zigzag chain oriented parallel to the crystallographic a axis. Fluoride ion F2 acts as a four-connected node connected to four divergent linkers, giving an undulating 2-dimensional (4,4) network in the ab plane. The complementary zig-zag shapes of both networks, imparted by the linker geometry, allows for efficient tongue-in-groove type packing between the one-dimensional and two-dimensional networks, as shown in Figure 12. The arrangement of the two networks leaves rectangular tubes oriented parallel to the a axis, within which reside the tetrabutylammonium cations.





Figure 12. *Top:* The 2-dimensional halogen bonded network associated with fluoride ion F2; *Bottom:* Association of adjacent F1 (blue) and F2 (red) networks in the structure of $\{L_3TBAF_2\}$. Tetrabutylammonium cations and hydrogen atoms are omitted for clarity.

Discussion

From the results presented above, it is clear that the iodoethynyl substituent represents a potent halogen bond donor, which in the solid state consistently forms structures in which all halogenbond donors strongly interact with Lewis bases, without the need for perfluorination of the organic backbone. Although the crystal structure of L itself contains a non-interacting iodoethynyl group due to the mismatch of halogen bond donors and acceptors within the

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molecule, the drive towards crystallisation of the one-dimensional halogen bonded chain is sufficient to render the molecule surprisingly poorly soluble in non-polar solvents. Attempts were made to generate halogen bonding adducts of L with a range of neutral ditopic Lewis bases, such as various ethers, pyridines and alcohols, however recrystallization of L was the only reproducible outcome. This implies that the dense L phase constitutes a thermodynamic sink in the absence of any opportunity to form stronger charge-assisted halogen bonds. The comparative strengths of the halogen bonds within the structures presented can be summarised using the 'normalised contact' N_c parameter discussed by Resnati *et al.*⁸, defined as $d_{xy}/(r_x + r_y)$, where d_{xy} is the crystallographically determined halogen bonding distance and r_x and r_y are the appropriate van der Waals or ionic radii for the involved atoms or ions, respectively (Figure 13). This analysis reveals a trend following the expected pattern of relatively shorter contacts for either lower coordination numbers or higher charge density of the halogen bond receptor. The only exception is the similarities of the contact distances in the I⁻ and Br⁻ systems – in this case, the geometric constraints of the tightly bound macrocyclic L_2I_2 species may lead to relatively shorter contacts than those seen in the extended helicate phase. The relatively strong I...N interaction in the structure of L, comparably shorter than those of I, Cl⁻ and Br⁻, is presumably overcome by the formation of two equivalent interactions per L molecule in the adducts, rather than one in the structure of the free ligand. The seemingly exceptional I...O short contact is indicative the partly ionic character of the acceptor species; the van der Waals radius for oxygen was used in the calculation rather than the shorter ionic radius as the most appropriate description for the supposed oxygen behaviour in the MeOH \cdot F⁻ adduct.

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Figure 13. Normalised contact distances plotted against halogen bond acceptor type. The appropriate ionic radii were used in the calculation for the halide anions,⁵⁸ and van der Waals radii were used for N and O acceptors.⁵⁹ The following distinctions were made to separate the fluoride-involving interactions: (i) Four-connected F⁻; (ii) Hydrogen-bonded, two-connected F⁻; (iii) two-connected F⁻.

Although the tendency for halogen bonding interactions in iodoalkynes has been demonstrated to improve thermal stability,³⁶⁻³⁸ no specific trends were observed in the decomposition temperatures of the halogen-bonded adducts of **L**. Indeed, the decomposition temperature of **L** was the highest of any of the materials at 189-196 °C, even in the presence of an unstabilised iodoalkyne, although an explosive polymerisation pathway is unlikely in the case of pyridine-separated iodoalkynes. The thermally destabilising effect of tetraalkylammonium cations is well known, and is most likely the cause of the earlier onset of decomposition in the halogen bonded adducts.^{60,61}

The solvent-dependence observed in the formation of halogen bonded adducts of L can most likely be ascribed to subtle differences in the energetics of crystallisation of each adduct. Whereas the compounds formed from pure ethyl acetate underwent immediate precipitation at room temperature, those containing 5% methanol deposited crystalline material only after an

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evaporation period. Presumably, this mixing time allowed for equilibration to the chain-type phases { L_2 ·TBACl} and {L·TBAI}- β . It is especially notable that { L_2 ·TBACl} and {L·TBACl} could be generated independent of reaction stoichiometry, and appear purely solvent dependent in their formation, with no evidence of the other phase by X-ray powder diffraction when repeating both experiments with the opposing stoichiometry. While the incorporation of a methanol molecule within the structure of { L_2 ·TBAF·MeOH} can be ascribed to the well-known strength of F⁻ as a hydrogen bond acceptor,^{62,63} the consistency of the helical structure for the TBABr adducts of L under both solvent conditions are most likely the result of a subtle balance of charge density for the bromide ion and the low solubility of the assembly as a whole.

Conclusions

We have prepared and structurally characterised a new bis-iodoalkynyl pyridine species L, and established its properties as a potent halogen-bond donor in the solid state by generating a series of halogen-bonded adducts with tetrabutylammonium halide salts. The free compound displays self-complementary halogen bonding interactions in the solid state between the pyridine nitrogen atom and one of the two iodoethynyl groups, forming a one-dimensional halogen-bonded chain. In the presence of tetrabutylammonium halides, a series of adducts of varying structural classes were prepared. Polymeric helices were generated from bromide or chloride ions in pure ethyl acetate, looped chains were observed from chloride or fluoride ions in an ethyl acetate/methanol mixture, polymorphic discrete macrocycles resulted from iodide ions in either solvent mixture, and a combination of linear chains and grids were the outcome from fluoride ions in the absence of methanol. The solvent-dependent outcomes of these reactions were rationalised on the basis of solubility and the irreversibility of the crystallisation process. Furthermore, we have observed the

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formation of a unique halogen-bond supported anionic methanol-fluoride adduct, to the best of our knowledge the first reported example of such, acting as a four-connected Lewis basic node in the generation of a halogen-bonded assembly. These results provide new directions in the field of halogen bonding, namely the potential for extended halogen-bonded networks from iodoalkynylsubstituted heterocycles containing complementary Lewis base character, without the need for backbone perfluorination or additional electron withdrawing groups, which are now being pursued further in our laboratory.

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Supporting Information

Ellipsoid plots for all compounds; X-ray powder diffraction patterns for all compounds; NMR spectra for L; additional figures for hydrogen atom treatment in $\{L_2 \cdot TBAF \cdot MeOH\}$. This material is available free of charge *via* the Internet at http://pubs.acs.org. CCDC 1480733-1480739.

Corresponding Authors

Email: hawescs@tcd.ie and gunnlaut@tcd.ie

Author Contributions

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Crystal Growth & Design

Table 1: Summary of cr	rystal and refinement para	meters for all compounds.
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Compound	L	L_TBABr	L ₂ _TBACl	L_TBAI_α	L_TBAI_β	L_TBAF_MeOH	$L_3_TBAF_2$
Empirical formula	C ₉ H ₃ I ₂ N	$C_{25}H_{39}BrI_2N_2$	C34H42ClI4N3	C25H39I3N2	C50H78I6N4	C ₃₅ H ₄₆ FI ₄ N ₃ O	$C_{59}H_{81}F_2I_6N_5$
Formula weight/ g.mol ⁻¹	378.92	701.29	1035.75	748.28	1496.56	1051.35	1659.68
Temperature/K	100	99.99	100	100.01	100	99.99	100.15
Crystal system	orthorhombic	triclinic	triclinic	orthorhombic	triclinic	triclinic	monoclinic
Space group	$P2_{1}2_{1}2_{1}$	<i>P</i> -1	<i>P</i> -1	Pccn	<i>P</i> -1	<i>P</i> -1	$P2_1/c$
a/Å	8.1995(2)	8.3829(2)	13.0024(4)	19.1066(6)	8.9908(3)	13.3942(4)	13.975(3)
b/Å	10.2881(2)	18.0105(5)	14.1473(4)	19.4063(5)	18.3163(5)	14.7293(5)	14.169(3)
c/Å	11.4882(3)	19.8922(5)	14.1906(4)	16.2814(5)	18.3312(6)	21.8988(7)	33.787(7)
α/°	90	84.5880(10)	119.2880(10)	90	93.9600(10)	89.5780(10)	90
β/°	90	83.5810(10)	91.2960(10)	90	96.6230(10)	75.5530(10)	90.58(3)
γ/°	90	76.9820(10)	116.1120(10)	90	90.9490(10)	75.5210(10)	90
Volume/Å ³	969.11(4)	2900.38(13)	1947.67(10)	6037.0(3)	2990.53(16)	4043.9(2)	6690(2)
Z	4	4	2	8	2	4	4
$\rho_{calc}/g.cm^{-3}$	2.597	1.606	1.766	1.647	1.662	1.727	1.648
μ/mm ⁻¹	6.433	3.56	3.294	3.12	3.149	3.115	22.207
F(000)	680	1376	992	2896	1448	2024	3224
Radiation	ΜοΚα	ΜοΚα	ΜοΚα	ΜοΚα	ΜοΚα	ΜοΚα	CuKa
2⊖ range for data collection/°	5.316 to 72.912	3.00 to 56.998	3.454 to 59.998	2.992 to 54.00	3.048 to 64.118	2.86 to 64.114	5.232 to 136.634
Index ranges	$\begin{array}{c} -13 \leq h \leq 11, -17 \\ \leq k \leq 17, -19 \leq l \leq \\ 19 \end{array}$	$\begin{array}{c} -10 \leq h \leq 11, -24 \\ \leq k \leq 24, -26 \leq l \leq \\ 26 \end{array}$	$\begin{array}{c} -17 \leq h \leq 18, -19 \\ \leq k \leq 19, -19 \leq l \leq \\ 19 \end{array}$	$\begin{array}{c} -24 \leq h \leq 23, -23 \\ \leq k \leq 24, -20 \leq l \leq \\ 20 \end{array}$	$\begin{array}{c} -13 \leq h \leq 13, -27 \\ \leq k \leq 27, -27 \leq 1 \\ \leq 27 \end{array}$	$\begin{array}{c} \textbf{-19} \leq h \leq 19, \textbf{-21} \leq k \\ \leq 21, \textbf{-32} \leq l \leq 32 \end{array}$	$\begin{array}{c} -16 \leq h \leq 16, -14 \\ \leq k \leq 17, -40 \leq l \leq \\ 38 \end{array}$
Reflections collected	21698	74809	52963	41408	134757	182618	40821
Independent reflections	$\begin{array}{c} 4736 \; [R_{int} = \\ 0.0351, \; R_{sigma} = \\ 0.0274] \end{array}$	$\begin{array}{c} 14708 [\mathrm{R_{int}} = \\ 0.0598, \mathrm{R_{sigma}} = \\ 0.0538] \end{array}$	$11344 [R_{int} = 0.0206, R_{sigma} = 0.0167]$	$\begin{array}{c} 6603 \; [R_{int} = \\ 0.0321, \; R_{sigma} = \\ 0.0213] \end{array}$	$20819 [R_{int} = 0.0670, R_{sigma} = 0.0523]$	$28098 [R_{int} = 0.0364, R_{sigma} = 0.0262]$	$\begin{array}{c} 11962 \; [R_{int} = \\ 0.1571, \; R_{sigma} = \\ 0.1870] \end{array}$
Reflns Obs. [I>=2 σ (I)]	4534	10985	9661	5251	13731	22016	6662
Data/restraints/parameters	4736/0/109	14708/20/577	11344/0/383	6603/0/276	20819/0/549	28098/0/803	11962/86/663
Goodness-of-fit on F ²	1.059	1.015	1.083	1.001	1.000	1.107	1.195
Final R indexes [I>= 2σ (I)]	$R_1 = 0.0196, wR_2$ = 0.0461	$R_1 = 0.0334, WR_2$ = 0.0519	$R_1 = 0.0212, WR_2$ = 0.0428	$R_1 = 0.0385, wR_2$ = 0.0810	$R_1 = 0.0356, wR_2$ = 0.0577	$R_1 = 0.0336, WR_2 = 0.0636$	$R_1 = 0.1483, WR_2$ = 0.3678
Final R indexes [all data]	$R_1 = 0.0216, WR_2$ = 0.0471	$R_1 = 0.0608, WR_2$ = 0.0578	$R_1 = 0.0294, WR_2$ = 0.0467	$R_1 = 0.0535, WR_2$ = 0.0894	$R_1 = 0.0789, wR_2$ = 0.0680	$R_1 = 0.0526, WR_2 = 0.0706$	$R_1 = 0.2023, WR_2$ = 0.4183
Flack parameter	-0.036(14)	n/a	n/a	n/a	n/a	n/a	n/a
CCDC no.	1480733	1480734	1480735	1480738	1480739	1480737	1480736

For Table of Contents Use Only

Structure direction, solvent effects and anion influences in halogen-bonded

adducts of 2,6-bis(iodoethynyl)pyridine

Dawn E. Barry, Chris S. Hawes, * Salvador Blasco & Thorfinnur Gunnlaugsson *



A new self-complementary halogen bond donor-acceptor molecule 2,6-bis(iodoethynyl)pyridine L has been prepared and structurally characterized in the crystalline phase and in the presence of tetrabutylammonium halide halogen bond acceptors. The resulting adducts display variation in dimensionality, connectivity and halogen bonding strength based on the nature of the Lewis basic halogen bond acceptor, and a consistent structural dependence on the solvent and crystallization conditions.



Scheme 1: Synthesis of 2,6-bis(iodoethynyl)pyridine L. Reagents and conditions: (i) Trimethylsilylacetylene, CuI, Pd(PPh3)2Cl2, NEt3, THF; (ii) silica gel, DCM/Hexane; (iii) KI, TBHP, MeOH.

84x59mm (300 x 300 DPI)



Figure 1. (Top) Structure of L with heteroatom labelling scheme. (Bottom) Halogen bonding I…N interactions in the structure of L

92x100mm (300 x 300 DPI)





Figure 2. Structure of {L·TBABr} with heteroatom labelling scheme. Hydrogen atoms are omitted for clarity. Symmetry codes used to generate equivalent atoms: i) 1+x, +y, +z.

68x54mm (300 x 300 DPI)





Crystal Growth & Design

Figure 3. Top: Representation of one helical chain within the structure of {L·TBABr}. Hydrogen atoms and tetrabutylammonium cations omitted for clarity. Bottom: Representation of the helical chain in {L·TBABr}, rendered as space-filling, and the relationship with the tetrabutylammonium cations located within the helical cavity (coloured yellow), and those associated with the external groove (coloured green).

85x169mm (300 x 300 DPI)





Figure 4. Structure of the repeating unit of {L2·TBACl} with heteroatom labelling scheme. Hydrogen atoms are omitted for clarity. Symmetry codes used to generate equivalent atoms: i) +x, -1+y, -1+z.

51x31mm (300 x 300 DPI)





Figure 5. The extended structure of {L2·TBACl}, viewed perpendicular (top) and near-parallel (bottom) to the direction of propagation. Hydrogen atoms are omitted for clarity.

83x81mm (300 x 300 DPI)





Figure 6. The structure of {L·TBAI}-a with heteroatom labelling scheme. Hydrogen atoms are omitted for clarity. Symmetry codes used to generate equivalent atoms: i) 3/2-x, 1/2-y, +z.

47x26mm (300 x 300 DPI)





Figure 7. Overlaid structures of {L·TBABr} (yellow) and {L·TBAI}-a (red) using the halide ions as anchor points.

83x81mm (300 x 300 DPI)

- 58 59
- 60



Figure 8. Top: The asymmetric unit of $\{L \cdot TBAI\}-\beta$ with heteroatom labelling scheme. Hydrogen atoms are omitted for clarity. Bottom: Overlaid structures of the a (red) and β (blue) phases of $\{L \cdot TBAI\}$.

85x101mm (300 x 300 DPI)





Figure 9. Extended structure of $\{L \cdot TBAI\}$ - β showing the offset packing between adjacent macrocycles. Hydrogen atoms are omitted for clarity.

38x17mm (300 x 300 DPI)



Figure 10. Top: One of the two crystallographically unique looped motifs in the structure of {L2·TBAF·MeOH} with partial atom labelling scheme; Bottom: extended structure of the polymeric chain in {L2·TBAF·MeOH} showing the associated tetrabutylammonium cation. Hydrogen atoms are omitted for clarity. Symmetry codes used to generate equivalent atoms: i) +x, y-1, +z; ii) +x, y+1, +z.

85x107mm (300 x 300 DPI)





Figure 11. Chemical environment of the two unique fluoride ions and the associated L molecules in the structure of {L3(TBAF)2} with halogen atom labelling scheme. Hydrogen atoms are omitted for clarity. Symmetry codes used to generate equivalent atoms: i) +x, y+1, +z; ii) +x, y-1, +z; iii) +x, y-2, +z; iv) x-1, +y, +z; v) -x, y-1/2, 3/2-z; vi) -x, 1/2+y, 3/2-z; vii) 1+x, +y, +z.

85x63mm (300 x 300 DPI)



Figure 12. Top: The 2-dimensional halogen bonded network associated with fluoride ion F2; Bottom: Association of adjacent F1 (blue) and F2 (red) networks in the structure of {L3TBAF2}. Tetrabutylammonium cations and hydrogen atoms are omitted for clarity.

85x110mm (300 x 300 DPI)





Figure 13. Normalised contact distances plotted against halogen bond acceptor type. The appropriate ionic radii were used in the calculation for the halide anions,58 and van der Waals radii were used for N and O acceptors.59 The following distinctions were made to separate the fluoride-involving interactions: (i) Fourconnected F-; (ii) Hydrogen-bonded, two-connected F-; (iii) two-connected F-.

85x51mm (300 x 300 DPI)