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Extended Self-complementary Halogen Bonded Dimers

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Abstract The X-ray structure of a series of 1,4-diethynylbenzene bridged pyridyl polyfluoroiodoand polyfluorobromophenyls designed to form self-complementary dimers in the solid state are reported. The compound 2-[[4-[(3-bromotetrafluorophenyl)ethynyl]phenyl]ethynyl] pyridine, 1, crystalized in the triclinic space group P-1 with unit cell parameters a = 6.3332(4) (Å), b =7.4288(4) (Å), c = 17.8897(10) (Å) and $\alpha = 91.0980$ $(10)^{\circ}$, $\beta = 90.8580(10)^{\circ}$ and $\gamma = 94.3830(10)^{\circ}$. The asymmetric unit contains a unique molecule as a self-complementary halogen bonded dimer. Compounds 2, 3-[[4-[(2bromotetrafluorophenyl)ethynyl]phenyl]ethynyl]pyridine and **3**, 3-[[4-[(2-iodotetrafluorophenyl)ethynyl]phenyl]ethynyl] pyridine both crystalized in the triclinic space group P-1 and are isostructural with unit cell parameters a = 6.1324(13) $(\text{\AA}), b = 11.264(2) (\text{\AA}), c = 13.064(3) (\text{\AA}), \alpha = 66.646(3)^{\circ},$ $\beta = 89.736(3)^{\circ}$, $\gamma = 87.726(3)^{\circ}$ for **2** and a = 6.1671(5)(Å), b = 11. 2571(9) (Å), c = 13.3083(11) (Å), $\alpha =$ $66.2870(10)^{\circ}, \beta = 88.1990(10)^{\circ}, \gamma = 87.3820(10)^{\circ}$ for **3**. In both structures the molecules assemble as essentially planar self-complementary halogen bonded dimers. In contrast 3-[[4-[(2-bromo-4,5-difluorophenyl)ethynyl]phenyl]ethynyl] pyridine, 4, crystalized in the monoclinic space group P21/cwith unit cell parameters a = 18.7881(7) (Å), b =3.83820(10) (Å), c = 22.9321(9) (Å), $\alpha = \gamma = 90^{\circ}$, $\beta =$

Eric Bosch ericbosch@missouristate.edu; http://chemistry.missouristate.edu/EricBosch.aspx $102.6180(10)^\circ$ and featured a C–H…N hydrogen bonded dimer.

Graphical Abstract The formation of self-complementary halogen bonded dimers with a series of 1,4-diethynylbenzene bridged pyridyl polyfluoroiodo- and polyfluorobromophenyls is reported.



Keywords Halogen bonding · Self-complementary · Dimer

Introduction

Halogen bonding is now widely recognized as a useful tool in molecular recognition and the field of crystal engineering [1]. In this context we recently reported examples of self-complementary halogen bonded dimer formation with a series of polyfluoroiodo- and polyfluorobromophenylethynylpyridines [2]. The basic plan in that research was to prepare simple molecules containing both a pyridyl moiety as halogen bond acceptor and fluorine activated bromo or iodo halogen bond donor with a geometric arrangement that would favor dimer formation. van der Boom and co-workers had earlier

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established that 4-[(4-bromo-2,3,5,6-tetrafluorophenyl) ethynyl]pyridine forms one-dimensional halogen bonded ribbons of molecules [3, 4] and that 3,5-diiodo-2,4,6-trifluorostilbazole which does not have a linear arrangement of the donor and acceptor sites formed infinite helices [4]. In contrast we demonstrated that a simple positional switch led to the exclusive formation of self-complementary halogen-bonded dimers. For example, 3-[(2-bromo-3,4,5,6-tetrafluorophenyl) ethynyl]pyridine favored formation of the self-complementary dimer in the solid state as shown in Scheme 1 [2].

In this short paper we report the extension of that study to include the series of 1,4-diethynylbenzene bridged pyridyl polyfluoroiodophenyl and polyfluorobromophenyls shown in Scheme 2.

Experimental Section

Synthesis of 2-[(4-Iodophenyl)ethynyl]pyridine, 5

A mixture of 2-ethynylpyridine (2.193 g, 21 mmol), 1,4diiodobenzene (8.095 g, 25 mmol) and triethylamine (40 ml) were stirred under argon for ten minutes while palladium(II) bis(triphenylphosphine)dichloride (117 mg, 0.14 mmol) and copper(I) iodide (36 mg, 0.17 mmol) were added. The mixture was stirred under the inert atmosphere for two days at room temperature. The reaction mixture was dissolved in dichloromethane (200 ml) and washed twice with water (100 ml). The solution was dried over



Scheme 1 Self-complementary halogen bonded dimers [2]

Scheme 2 Target molecules used in this study

anhydrous sodium sulfate and the solvent evaporated. The crude product was purified using flash chromatography with silica gel primed with hexanes and eluted with a progressively polar eluant comprising mixtures of hexanes with ethyl acetate. Fractions were evaluated using TLC (2:1 hexanes:ethyl acetate mix). The fractions containing the desired compound were collected and the solvent evaporated. The product was a pale yellow solid (2.639 g, 41 %). ¹H NMR (CDCl₃, 400 MHz): δ 8.63 (d, J = 3.9 Hz, 1H), 7.70 (dt, J = 7.6, 1.9 Hz, 2H), 7.66 (dd, J = 6.1, 1.8 Hz, 1H), 7.52 (d, J = 7.8 Hz, 1H), 7.32 (td, J = 8.5, 1.9 Hz, 2H), 7.25 (ddd, J = 12.3, 2.7, 1.2 Hz, 1H). ¹³C NMR (100 MHz): 150.1, 143.1, 137.6, 136.2, 133.4, 127.2, 123.0, 121.7, 95.2, 89.9, 88.1.

Synthesis of 2-[(4-Ethynylphenyl)ethynyl]pyridine, 6

Trimethylsilyacetylene (1.601 g, 16 mmol), 2-[(4-iodophenyl)ethynyl]pyridine 5 (2.559 g, 8.4 mmol), and triethylamine (40 ml) were stirred under argon for ten minutes while palladium(II) bis(triphenylphosphine)dichloride (121 mg, 0.14 mmol) and copper(I) iodide (19 mg, 0.09 mmol) were added. The mixture was stirred under the inert atmosphere for two days at room temperature. The reaction mixture was dissolved in dichloromethane (200 ml) and washed twice with water (100 ml). The solution was dried over anhydrous sodium sulfate and the solvent evaporated. The crude product was purified using flash chromatography as described for compound 5. The TMS-protected intermediate crystalized as colorless needles from ethyl acetate (1.366 g, 59 %). ¹H NMR (CDCl₃, 400 MHz): δ 8.63 (d, J = 4.9 Hz, 1H), 7.69 (td, J = 7.8, 1.8 Hz, 1H), 7.53 (m, J =8.0 Hz, 3H), 7.45 (br d, J = 6.5 Hz, 2H), 7.26 (m, 1H), 0.261 (s, 9H). ¹³C NMR (100 MHz): 152.36, 148.86, 138.52, 132.08, 131.58, 123.63, 123.16, 122.60, 120.33, 104.52, 96.79, 92.33, 87.85, 0.10.

The TMS-protected intermediate (1.2331 g, 4.5 mmol) was added to a solution of potassium hydroxide (2.727 g) in absolute ethanol (100 ml) and the resultant mixture stirred at room temperature for 1 h and then poured into DI



water (100 ml). The mixture was extracted with dichloromethane (200 ml), washed once more with DI water (70 ml). The solution was dried over anhydrous sodium sulfate and the solvent was evaporated to yield **6** as a creamy-white solid (0.6479 g, 71 %). ¹H NMR (CDCl₃, 400 MHz): δ 8.64 (br d, J = 4.9 Hz, 1H), 7.69 (td, J = 7.6, 1.9 Hz, 1H), 7.55 (m, 3H), 7.48 (md, J = 6.6 Hz, 2H), 7.26 (m, 1H), 3.19 (s, 1H). ¹³C NMR (100 MHz): 150.1, 143.1, 136.2, 132.1, 131.9, 127.2, 122.9, 122.7, 122.6, 90.3, 88.5, 83.1, 79.2.

Synthesis of 2-[[4-[(3-Bromotetrafluorophenyl) ethynyl]phenyl]ethynyl]pyridine, 1

А mixture of 2-[(4-ethynylphenyl)ethynyl]pyridine (0.4043 g, 1.99 mmol), 1,3-dibromotetrafluorobenzene (0.7948 g, 2.5 mmol) and triethylamine (15 ml) were stirred under argon for ten minutes while palladium(II) bis(triphenylphosphine)dichloride (66.5 mg, 0.07 mmol) and copper(I) iodide (16.9 mg, 0.07 mmol) were added. The mixture was stirred under the inert atmosphere for seven days at 85 °C. The reaction mixture was dissolved in dichloromethane (100 ml) and washed twice with water (50 ml). The solution was dried over anhydrous sodium sulfate and the solvent evaporated. The crude product was purified using flash chromatography with silica gel primed with hexanes and eluted with a progressively polar eluant comprising mixtures of hexanes with ethyl acetate. Fractions were evaluated using TLC (2:1 hexanes:ethyl acetate mix). The fractions containing the desired compound were collected and the solvent evaporated. The product was crystallized in a screw-capped vial from CDCl₃ as colorless needles (0.2538 g, 30%). Melting point = 177.1–179.3 °C. ¹H NMR (CDCl₃, 400 MHz): δ 8.63 (br d, J = 4.9 Hz, 1H), 7.69 (dt, J = 7.6, 1.8 Hz, 1H), 7.53 (md, J = 8.0 Hz, 3H), 7.45 (md, J = 8.0 Hz, 2H), 7.26 (m, 1H). ¹⁹F NMR (376 MHz): -161.2 (td, J = 21.8, 9.2 Hz, 1F), -129.4 (dd, J = 21.2, 5.7 Hz, 1F), -123.0 (dd, J = 21.8, 5.8 Hz, 1F), -105.4 (d, J = 9.1 Hz, 1F). ¹³C NMR (100 MHz): 155.2 (md, J = 253 Hz), 150.5 (md, J =255 Hz), 150.2, 149 (md, J = 255 Hz), 143.1, 137.5 (md, J = 248 Hz), 136.3, 134.5 (m, J = 7 Hz), 132.1, 131.9, 128.1 (m, J = 5.0 Hz), 127.3, 123.5, 123.1, 122.1, 100.6 (d, J = 3.7 Hz), 95.3 (t, J = 3.0 Hz), 90.9, 88.4.

Synthesis of 3-[(4-Iodophenyl)ethynyl]pyridine, 7

A mixture of 3-ethynylpyridine (0.9683 g, 9.4 mmol), 1,4diiodobenzene (3.2908 g, 10 mmol) and triethylamine (40 ml) were stirred under argon for ten minutes while palladium(II) bis(triphenylphosphine)dichloride (125.3 mg, 0.15 mmol) and copper(I) iodide (26.2 mg, 0.13 mmol)

were added. The mixture was stirred under the inert atmosphere for two days at room temperature. The reaction mixture was dissolved in dichloromethane (200 ml) and washed twice with water (100 ml). The solution was dried over anhydrous sodium sulfate and the solution was evaporated. The crude product was purified using flash chromatography with silica gel primed with hexanes and a progressively polar eluant, ethyl acetate. Fractions were evaluated using TLC (2:1 hexanes:ethyl acetate mix). The fractions containing the desired compound were collected and the solvent was evaporated. The product was a peach colored flaky solid (1.4378 g, 63 %). ¹H NMR (CDCl₃, 400 MHz): δ 8.76 (d, J = 1.4 Hz, 1H), 8.56 (dd, J = 1.4, 4.7 Hz, 1H), 7.80 (dt, J = 8.0, 2.0 Hz, 1H), 7.72 (md, J = 8.3 Hz, 2H), 7.31 (ddd, J = 8.8, 4.9 Hz, 0.78 Hz 1H), 7.27 (m, 2H). ¹³C NMR (100 MHz): 152.2, 148.8, 138.5, 137.7, 133.1, 123.1, 122.1, 120.2, 94.9, 91.7, 87.3.

Synthesis of 3-[(4-Ethynylphenyl)ethynyl]pyridine, 8

Trimethylsilylacetylene (0.633 g, 6.4 mmol), 3-[(4-iodophenyl)ethynyl]pyridine 7 (1.389 g, 4.6 mmol), and triethylamine (30 ml) were stirred under argon for ten minutes while palladium(II) bis(triphenylphosphine)dichloride (156 mg, 0.18 mmol) and copper(I) iodide (29 mg, 0.14 mmol) were added. The mixture was stirred under the inert atmosphere for two days at room temperature. The reaction mixture was dissolved in dichloromethane (200 ml) and washed twice with water (100 ml). The solution was dried over anhydrous sodium sulfate and the solvent was evaporated. The crude product was purified using flash chromatography with silica gel as described before. The TMS protected intermediate was isolated as a pale yellow solid (1.366 g, 86 %). ¹H NMR (CDCl₃, 400 MHz): δ 8.76 (br d, J = 1.4 Hz, 1H), 8.56 (dd, J = 4.9, 1.8 Hz, 1H), 7.80 (dt, J = 7.6, 1.9 Hz, 1H), 7.47 (m, 4H), 7.29 (ddd,J = 8.0 Hz, 4.9 Hz, 1.0 Hz, 1H) 0.22 (s, 9H). ¹³C NMR (100 MHz): 152.4, 148.9, 138.5, 132.1, 131.6, 123.6, 123.2, 122.6, 120.3, 104.5, 96.8, 92.3, 87.9, 0.10.

The TMS protected intermediate (0.994 g, 3.6 mmol) was added to a solution of potassium hydroxide (2.816 g) in absolute ethanol (100 ml) and stirred at room temperature for 1 h. The reaction mixture was then poured into DI water (100 ml) and extracted with dichloromethane (200 ml). The organic solution was washed with DI water (70 ml). The solution was dried over anhydrous sodium sulfate and the solvent evaporated to yield the desired product as a brown solid (0.674 g, 92 %). ¹H NMR (CDCl₃, 400 MHz): δ 8.78 (s, 1H), 8.56 (brd, J = 4.9 Hz, 1H), 7.81 (dq, J = 7.8 Hz, 1.7 Hz, 1H), 7.53 (m, 4H), 7.30 (m, 1H), 3.20 (s, 1H). ¹³C NMR (100 MHz): 152.3, 148.8, 138.5, 132.5, 132.2, 131.6, 128.6, 123.1, 122.5, 92.0, 87.3, 83.1, 79.2.

Synthesis of 3-[[4-[(2-Bromotetrafluorophenyl)ethynyl] phenyl]ethynyl]pyridine, 2

A mixture of 3-[(4-ethynylphenyl)ethynyl]pyridine 8 (0.276 g, 1.4 mmol), 1,2-dibromotetrafluorobenzene (0.696 g, 2.3 mmol) and triethylamine (15 ml) were stirred under argon for ten minutes while palladium(II) bis(triphenvlphosphine)dichloride (56 mg, 0.06 mmol) and copper(I) iodide (15 mg, 0.07 mmol) were added. The mixture was stirred under the inert atmosphere for seven days at 85 °C. The reaction mixture was dissolved in dichloromethane (100 ml) and washed twice with water (50 ml). The solution was dried over anhydrous sodium sulfate and the solution was evaporated. The crude product was purified using flash chromatography as described before. Fractions were evaluated using TLC (2:1 hexanes:ethyl acetate mix). The desired compound was crystallized from ethyl acetate as flat, clear crystals (0.144 g, 16 %). Melting point = 164.7–167.3 °C. ¹H NMR (CDCl₃, 400 MHz): δ 8.78 (brdd, J = 2.1, 0.8 Hz, 1H), 8.57 (dd, J = 4.9, 1.8 Hz, 1H), 7.82 (dt, J = 8.0, 2.0 Hz, 1H), 7.58 (m, 4H), 7.33 (m, 1H). ¹⁹F NMR (376 MHz): -155.3 (td, J = 22.5 Hz, 3.0 Hz, 1F), -151.5 (td, J = 21.8, 3.4 Hz, 1F), -132.1 (ddd, J = 21.3 Hz, 9.5 Hz, 3.5 Hz, 1F), -128.2 (ddd, J = 21.8 Hz, 9.2 Hz, 3.5 Hz, 1F). ¹³C NMR (100 MHz): 152.3, 148.9, 148.5 (dm, J = 252 Hz), 145.8 (dddd, J = 248 Hz, 12 Hz, 4.8 Hz, 2.5 Hz), 141.3 (dddd, J)J = 260 Hz, 18 Hz, 13.3 Hz, 3.2 Hz), 140.1 (dddd, *J* = 260 Hz, 16 Hz, 12.8 Hz, 3.8 Hz), 138.5, 134.8, 134.5, 133.0, 131.5 (m), 129.1, 127.7 (m), 123.8, 120.1, 100.6 (d, J = 5.2 Hz), 91.9, 88.5, 81.1.

Synthesis of 3-[[4-[(2-Iodotetrafluorophenyl) ethynyl]phenyl]ethynyl]pyridine, 3

A mixture of 3-[(4-ethynylphenyl)ethynyl]pyridine 8 (0.326 g, 1.6 mmol), 1,2-diiodotetrafluorobenzene (0.810 g, 2.0 mmol) and triethylamine (10 ml) were stirred under argon for ten minutes while palladium(II) bis(triphenylphosphine)dichloride (88 mg, 0.09 mmol) and copper(I) iodide (20 mg, 0.09 mmol) were added. The mixture was stirred under the inert atmosphere for seven days at room temperature. The reaction mixture was dissolved in dichloromethane (100 ml) and washed twice with water (50 ml). The solution was dried over anhydrous sodium sulfate and the solution evaporated. The crude product was purified using flash chromatography as described above. The product was crystalized from CDCl₃ as clear plates (0.163 g, 21 %). Melting point = 226.2-228.9 °C. ¹H NMR (CDCl₃, 400 MHz): δ 8.79 (d, J = 1.6 Hz, 1H), 8.59 (dd, J = 4.8 Hz, 1.6 Hz, 1H), 7.83 (dt, J = 7.8 Hz, 2.1 Hz, 1H), 7.63 (m, 2H), 7.58 (m, 2H), 7.32(m, 1H). ¹⁹F NMR (376 MHz): -153.8 (td, J = 20.5 Hz, 4.0 Hz, 1F), -151.0 (ddd, J = 23 Hz, 19 Hz, 1F), -130.4 (ddd, J = 20.7 Hz, 10 Hz, 4.0 Hz, 1F), -113.4 (ddd, J = 22.5 Hz, 10 Hz, 4.0 Hz, 1F). ¹³C NMR (100 MHz): 152.3, 148.9, 147.4 (dm, J = 256 Hz), 138.6–148.0 (3 signals, each dm, $J = \sim 250$ Hz), 138.5, 131.8, 131.2, 134.3 (m), 127.8 (m), 123.8, 123.1, 121.9, 120.1, 99.7, 92.0, 88.5, 84.7.

Synthesis of 3-[[4-[(2-Bromo-4,5-difluorophenyl) ethynyl]phenyl]ethynyl]pyridine, 4

A mixture of 3-[(4-ethynylphenyl)ethynyl]pyridine 8 (0.2726 g, 1.3 mmol), 1,2-dibromo-4,5-difluorobenzene (0.4948 g, 1.8 mmol) and triethylamine (10 ml) were stirred under argon for ten minutes while palladium(II) bis(triphenylphosphine)dichloride (78 mg, 0.08 mmol) and copper(I) iodide (24 mg, 0.11 mmol) were added. The mixture was stirred under the inert atmosphere for seven days at 85 °C. The reaction mixture was dissolved in dichloromethane (100 ml) and washed twice with water (50 ml). The solution was dried over anhydrous sodium sulfate and the solution was evaporated. The crude product was purified using flash chromatography as described above. The product was crystallized from CDCl₃ as clear plates (0.258 g, 51 %). Melting point = 183.0-185.6 °C. ¹H NMR (CDCl₃, 400 MHz): δ 8.78 (br s, 1H), 8.57 (d, J = 4.0 Hz, 1H), 7.81 (d, J = 7.8 Hz, 1H), 7.54 (m, 4H), 7.44 (mt, J = 8.5 Hz, 1H), 7.37 (mt, J = 8.3 Hz, 1H), 7.39 (m, 1 H). ¹⁹F NMR (376 MHz): -137.8 (ddd, J = 21.2, 10.3, 7.5 Hz, 1F), -132.5 (dt, J = 21.2, 8.8 Hz, 1F). ¹³C NMR (100 MHz): 152.2, 150.0 (dd, J = 258, 13.7 Hz), 149.2 (dd, 250, 12.5 Hz), 148.8, 138.4, 134.9 (m, J = 5.9 Hz), 131.7, 131.6, 130.1, 127.9 (m), 123.1 (d, J = 20.6 Hz), 122.6, 121.8, 120.1, 119.9 (d, J = 20.3 Hz), 93.9, 92.1, 88.2, 88.0.

X-ray Structure Determination

For each complex a single crystal was mounted on a Kryoloop using viscous hydrocarbon oil. Data were collected using a Bruker Apex2 CCD diffractometer equipped with Mo K α radiation with $\lambda = 0.71073$ Å. Data collection at 100 K was facilitated by use of a Kryoflex system with an accuracy of ± 1 K. Initial data processing was carried out using the Apex II software suite [5]. Structures were solved by direct methods using SHELXS-2013 and refined against F2 using SHELXL-2013 [6] using the program X-Seed as a graphical interface [7]. Hydrogen atoms were located in the difference maps but were placed in idealized positions and refined with a riding model. Abbreviated crystallographic details are collected in Table 1.

	1	2	3	4
Formula	C ₂₁ H ₈ BrF ₄ N	C ₂₁ H ₈ BrF ₄ N	C ₂₁ H ₈ IF ₄ N	$C_{21}H_{10}BrF_2N$
CCDC	1413645	1413647	1413644	1413646
Formula weight	430.18	430.18	477.18	394.20
Crystal dim. (mm ³)	$0.20 \times .20 \times .02$	$0.02 \times .20 \times .40$	$0.06 \times .24 \times .53$	$0.02 \times .20 \times .40$
Crystal system	Triclinic	Triclinic	Triclinic	Monoclinic
Space group	<i>P</i> -1	<i>P</i> -1	<i>P</i> -1	P21/c
a (Å)	6.3332(4)	6.1324(13)	6.1671(5)	18.7781(7)
b (Å)	7.4288(4)	11.264(2)	11.2571(9)	3.83820(10)
c (Á)	17.8897(10)	13.064(3)	13.3083(11)	22.9321(9)
α (°)	91.0980(10)	66.646(3)	66.2870(10)	90
β (°)	90.8580(10)	89.736(3)	88.1990(10)	102.6180(10)
γ (°)	94.3830(10)	87.726(3)	87.3820(10)	90
Z	2	2	2	4
$V(\dot{A}^3)$	838.95(8)	827.8(3)	844.94(12)	1612.89(10)
$\rho_{calcd} \ (mg \ m^{-3})$	1.703	1.726	1.876	1.623
Т (К)	100	100	100	100
$\mu (mm^{-1})$	2.496	2.530	1.941	2.572
Reflections/unique	10988/3687	9964/3608	10646/3730	19674/3578
Data/restraints/parameters	3687/0/1244	3608/0/1244	3730/0/244	3578/0/226
Goodness of fit	1.045	1.065	1.071	1.059
R_1/wR_2	0.028/0.1065	0.035/0.095	0. 027/0. 064	0.020/0.050
R ₁ /wR ₂ (all data)	0.033/0.067	0.040/0.099	0.030/0. 066	0.022/0.051
Largest diff. peak/hole (eÅ ³)	0.40/-0.41	1.44/-0.83	0.86/-0.47	0.536/-0.23

 Table 1 Crystallographic data for complexes 1–4



Fig. 1 Synthetic scheme for the synthesis of compound 1, 2-[[4-[(3-bromotetrafluorophenyl)ethynyl]phenyl]phynyl]pyridine

Results and Discussion

The compounds 1–4 were prepared using three successive Sonogashira coupling reactions. The synthesis of compound 1 is outlined in Fig. 1. Initial coupling of 2-ethynylpyridine with 1,4-diiodobenzene yielded 2-(4-iodophenylethynyl) pyridine, 5. Subsequent reaction of 5 with trimethylsilylethyne followed by base promoted deprotection yielded terminal alkyne 6 in modest yield. Sonogashira coupling of 6 with 1,3-dibromotetrafluorobenzene yielded compound 1 in low overall yield. The reaction conditions and yields were not optimized.

Compounds 2, 3 and 4 were synthesized in a similar manner starting from 3-ethynylpyridine as shown in Fig. 2. All compounds were analyzed by a combination of 1 H, 13 C and 19 F NMR spectroscopy and the chemical shifts and



Fig. 3 View of the self-complementary halogen bonded dimer formed with 2-[[4-[(3-bromotetrafluorophenyl)ethynyl]phenyl]ethynyl]pyridine, 1, (a) along with an orthogonal view to emphasize slight twist of the molecule (b). Thermal ellipsoids drawn at the 50 % level

coupling constants of the halophenyl and pyridyl rings were consistent with related compounds reported in our earlier study [2].

Compound **1** was recrystallized from chloroform as needles. Self-complementary dimer formation in the solid state was confirmed on X-ray analysis of the crystalline solid. The dimeric unit of **1** is shown in Fig. 3.

The halogen bond is almost linear with a C–Br…N angle of $172.37(3)^{\circ}$ in accord with $n \rightarrow \sigma^*$ nature of the halogen bonding interaction [8, 9]. The pyridyl and fluorophenyl rings

are not however coplanar: the pyridyl ring is angled out of the plane of the fluorophenyl ring with an angle of approximately 151° . The N···Br distance in **1** is 3.003(4) Å which is 88 % of the sum of the van der Waals radii of 3.40 Å. [10] This is similar to the N···Br distance of 3.029(2) Å reported for 2-[(3-bromo-2,4,5,6-tetrafluorophenyl)ethynyl]pyridine [2]. The torsional angle between the pyridyl and phenyl rings is approximately 6.5° and the torsional angle between the central phenyl ring and the fluorophenyl ring is about 15° . The aromatic rings twist in the same direction relative to the



Fig. 4 View highlighting the weak intermolecular interactions, $F \cdots F$ and $C-H \cdots F$, between halogen bonded dimers of 2-[[4-[(3-bromotetrafluorophenyl]ethynyl]phenyl]phynyl]pyridine, 1



Fig. 5 Three dimensional packing of the halogen bonded dimers of 2-[[4-[(3-bromotetrafluorophenyl)ethynyl]phenyl]ethynyl]pyridine, 1, viewed along the b-axis

central phenyl ring as shown in Fig. 3b. There is a close F…F contact and a variety of weak C-H…F interactions and π -stacking that help stabilize the three-dimensional packing of dimeric units. While the F…F distance, F4…F4#1 denoted as (b) in Fig. 4, of 2.889 Å is only marginally less than the sum of the van der Waals radii of 2.94 Å, the C-H…F distances of 2.397, 2.511 and 2.601 Å for F1…H11, F3…H14 and F2…H19 are 89.8, 94 and 97.4 % of the sum of the van der Waals radii (2.67 Å) respectively. These interactions are labelled (c), (d) and (e) in Fig. 4. These C–H…F distances and angles compare favorably to those reported in the indepth study of weak phenyl C–H…F interactions observed in a series of polyfluorobenzenes reported by Thallandi et al. in 1998 [11].

The dimer units are offset π -stacked with the central phenyl ring and the halophenyl ring alternating in the stacks (Fig. 5). The closest centroid to centroid distance between these rings is 3.67 Å. with a closest atom to atom distance of about 3.5 Å. The pyridyl rings have no close contacts.

The structures of compounds 2 and 3 are isostructural with space group *P*-1 and Z = 2. Individual molecules of 2 and 3 are essentially planar with a distinct bent overall shape as shown in Fig. 5. As expected two complementary halogen bonds facilitate dimer formation. Both of the halogen bonds are almost linear in both structures with a C-Br...N angle of 171.58(3)° and a C-I...N angle of 171.73(4)°. The N...Br distance in 2 is 2.986(4) Å, 85 % of



Fig. 6 View of the self-complementary halogen bonded dimer formed with 3-[[4-[(2-iodotetrafluorophenyl)ethynyl]phenyl]ethynyl]pyridine, 3, (a) along with two orthogonal views to show the planarity of the molecule (b, c). Thermal ellipsoids drawn at the 50 % level

the sum of the van der Waals radii, while the N···I distance in **3** is 2.905(6) Å, 82 % of the sum of the van der Waals radii, is slightly shorter in accord with the more intense sigma hole on iodine as compared to bromine [12]. The obvious bend of the molecules (Fig. 6a) is similar for compound **2** and **3**. For **2** the average angle around the alkynyl carbons is 174.9° while the average angle about the alkynyl carbons in **3** is 175.3° (see Fig. 6a angles C5–C6–C7, C6–C7–C8, C11–C14–C15 and C14–C15–C16). It is noteworthy that in the structure of compound **1** this bend is not observed. This lack of bend in **1** is likely a consequence of the internal fluorine atom (F1 in Fig. 3) which is involved in supportive C–H…F interactions on the interior of the halogen-bonded dimer.



Fig. 7 View along (110) of a portion of the two-dimensional sheet comprising self-complementary dimers of **3** showing the unit cell with labels and the four weak C-H···F interactions (d, e, f and g)



Fig. 8 a View of the hydrogen bonded dimer formed with 3-[[4-[(2-bromo-4,5-difluorophenyl]ethynyl]phenyl]pyridine, 4, with the asymmetric unit labeled and thermal ellipsoids drawn at the 50 % level. b Orthogonal view corresponding to a

Compounds 2 and 3 form two-dimensional sheets that are π -stacked to form the three-dimensional structure. A portion of the two-dimensional sheet formed from close packed dimeric units of 3 is shown in Fig. 7.

The dimeric units of **3** are close packed with two pyridyl C–H…F interactions (d and e in Fig. 6) and two phenyl C–H…F interactions (f and g in Fig. 7) that serve to stabilize the two-dimensional sheets. The distances F1...H3



Fig. 9 View of a one-dimensional sheet of the hydrogen bonded dimer formed with 3-[[4-[(2-bromo-4,5-difluorophenyl)]ethynyl]phenyl] ethynyl]pyridine 4

(d), F3...H4 (e), F3...H9 (f), and F4...H9 (g) are 2.458, 2.674, 2.697 and 2.462 Å respectively as compared to the sum of the van der Waals radii of 2.67 Å which compare favorably to those reported by Thallandi et al. [11].

In contrast to compounds **1–3** the difluoro compound **4**, 3-(2-bromo-4,5-difluorophenylethynyl) pyridine, formed twisted C–H…N hydrogen bonded dimeric units interlinked with a C–Br alkyne interaction as shown in Fig. 8. The formation of a hydrogen bonded dimer was also observed with the shorter difluoro analogue 3-[[2-bromo-4,5-difluorophenyl]ethynyl]pyridine [2].

The non-conventional C–H···N hydrogen bond has an N···H distance of 2.426 Å compared to the sum of the van der Waals radii of 2.75 Å with a C–H···N angle of 160.64°. The individual molecules are essentially planar with torsional angles between the central phenyl group and the halophenyl ring and the pyridyl ring less than 1°. The bromine atom has a close contact to one of the alkynes with distances Br1-C6#1 and Br1-C7#1 of 3.387 and 3.402 Å respectively. These interactions lead to the formation of a corrugated one dimensional sheet shown in Fig. 9.

Conclusions

The results described here follow those previously reported for shorter phenylethynylpyridines [2] with similar halogen bond distances and angles and demonstrate that the concept of self-complementary halogen bonded dimers can be extrapolated to larger and potentially more complex molecules. The observation of competing C-H…N hydrogen bonding has been explored separately [13].

Supplementary Material

CCDC 1413644-1413647 contain the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.

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