ARTICLE

OBC
www.rsc.org/obc

An exploration of Suzuki aryl cross coupling chemistry involving [2.2]paracyclophane derivatives†

Alex J. Roche* and Belgin Canturk

Rutgers, The State University of New Jersey, Department of Chemistry, 315 Penn St, Camden, NJ, 08102-1411, USA. E-mail: alroche@crab.rutgers.edu

Received 13th October 2004, Accepted 17th November 2004
First published as an Advance Article on the web 22nd December 2004

Suzuki aryl cross coupling reactions using derivatives of [2.2]paracyclophane were examined. A variety of aryl boronic acids and pinacolate esters were successfully cross coupled with 4-bromo[2.2]paracyclophane under standard Suzuki conditions. Whilst an excellent tolerance for electron donating and withdrawing groups was observed, cross coupling reactions with highly sterically demanding borates (*e.g.* mesityl) were unsuccessful. The preparation and stability of the previously unreported [2.2]paracyclophanyl-4-boronic acid, -pinacolate ester and -dimethyl ester are described, along with the utility of these systems in Suzuki aryl cross coupling reactions. Application of this methodology led to a dicyclophane containing two [2.2]paracyclophane units separated by a 4–4′connected biphenyl spacer group.

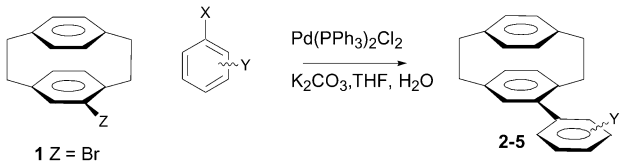
Introduction

Even though [2.2]paracyclophane (PCP)[1] was first prepared more than half a century ago, the chemistry and utility of this compound and its derivatives are still active fields of research.[2] PCP compounds find application in a multitude of areas, including unique polymers[3] and materials,[4] and catalysts with planar chirality.[5] As part of the ongoing development of the chemistry of 1,1,2,2,9,9,10,10-octafluoro[2.2]paracyclophane (OFP),[6–8] we had previously described the preparation of the boronic acid of OFP,[9] and studied its potential in Suzuki aryl cross coupling reactions.[9,10] In order to probe the influence that the octafluorinated bridges impart on such systems, we had to compare the preparation and reactivity of the boronic acids (and esters) of PCP and OFP. We were slightly surprised to find no literature reports concerning the boronic acid of PCP. Indeed at outset of this project, there were no literature reports of either substituted or unsubstituted PCP boronic acids/esters, or even Suzuki aryl cross coupling reactions on a PCP skeleton, although Heck couplings have been reported.[11] However, last year Rozenberg and coworkers reported Suzuki coupling reactions of several hetero- and homo-annularly substituted PCP systems *en route* to a selection of planar chiral bidentate ligands.[12] Our interest lay in the use of Suzuki aryl cross coupling methodology to introduce a variety of functionalized aryl groups into the 4-position of paracyclophanes to prepare more exotic monomers for Parylene type polymers and also with the aim of generating dicyclophanes (compounds containing two paracyclophane units connected through an aryl–aryl linkage).

Results and discussion

In order to examine the scope of Suzuki aryl cross coupling reactions on the [2.2]paracyclophane skeleton, coupling reactions using 4-bromo[2.2]paracyclophane **1** and a selection of aryl boronic acids (method A) and pinacolate esters (method B) were performed.

As shown in Table 1, an excellent tolerance of electronically different substituents on the phenyl group was observed. We observed that an *ortho* tolyl group could be cross coupled successfully (Table 1, entry 2), but that the sterically larger mesityl could not be cross coupled onto PCP using these conditions (Table 1, entry 5). The results from reactions employing either aryl boronic acids (method A) or boronic acid pinacol esters (method B) displayed no considerable differences. The same protocol was followed for all the aryl cross couplings; the reagents and catalyst were added into the reaction vessel under a counter-current of dry nitrogen, the solvent was added *via* syringe and then the reaction mixture was warmed to reflux for 48 h. TLC was used to monitor the reaction progress and then ether/water workup was followed by product isolation using column chromatography on silica gel. After establishing this ground work, we sought to compare the effectiveness of the same cross coupling transformations, but with interchanged functionalities, *i.e.* reacting PCP–$B(OH)_2$, **7**, with a selection of aryl bromides.



The synthesis of boronic acid **7** is not reported in the literature and our initial attempts to prepare and isolate **7** using standard synthetic methods met with disappointment. Compound **7** appears to be unstable in air and exposure to silica gel led to the production of PCP–OH **8**[13] and PCP. However, the formation of **8** was taken as evidence that the desired boronic acid was generated at least to some extent. Indeed, following the established literature preparation of **8**,[13] deliberate oxidation (using alkaline hydrogen peroxide) of our reaction mixture afforded product **8** in 79% isolated yield (Scheme 1). This can be taken as a lower limit for the yield of formation of **7**. The instability of boronic acid **7** is in contrast to its octafluorinated bridge analogue, with the latter being oxidatively stable in air and able to be stored and used in reactions without special precautions.[9] Our inability to isolate compound **7** left us with two alternatives; try to prepare a more stable analogue (such as boronate ester), or try to generate and react the boronic acid *in situ*.

Both the dimethyl and diisopropyl borate esters of PCP were found to be similarly unstable. However, the boronic acid pinacol ester of PCP **9** which was easily prepared by the reaction of **1** with butyllithium and bis(pinacolato)diboron, was found to be

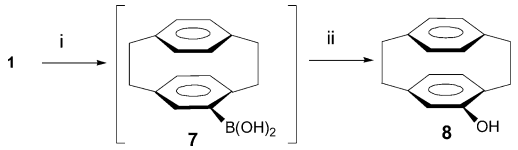
† Electronic supplementary information (ESI) available: ^{13}C and ^{1}H NMR spectra of compounds **3**–**5**, **9** and **11**. See http://www.rsc.org/suppdata/ob/b4/b415764h/

DOI: 10.1039/b415764h

Table 1 Suzuki reactions leading to aryl-substituted cyclophanes

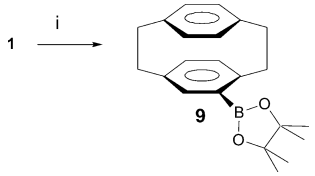
			Isolated yields		
Entry	Y	Product	Method A/%	Method B/%	Method C/%
1	H	**2**	84	87	79
2	2-Me	**3**	81	86	82
3	4-CN	**4**	87	83	87
4	3-OH	**5**	80	88	85
5	2,4,6-Me_3	**6**	0	0[a]	0

[a] Bis(pinacol) ester used.



Scheme 1 Reaction conditions: (i) BuLi, $B(OMe)_3$, ether, then H_3O^+; (ii) air, or H_2O_2, NaOH, THF, H_2O.[13]

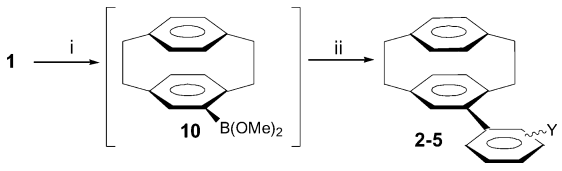
stable in air and could be isolated in 71% yield as a colorless solid using column chromatography on silica gel (Scheme 2). Product **9** could also be formed by transesterification of the initially formed dimethyl boronate, using pinacol.



Scheme 2 Reaction conditions: (i) BuLi, bis(pinacolato)diboron, THF.

The enhanced stability of **9** was demonstrated by exposure to alkaline hydrogen peroxide, which resulted in only a 10% conversion to **8** after 24 h, with 2 weeks required for full conversion. However, this extra stability unfortunately precluded the efficient use of **9** in Suzuki cross coupling experiments, as the reaction of **9** with aryl bromides under standard Suzuki conditions gave only low conversions (<10%) to desired products after one week under reflux.

Alternatively, as shown in Scheme 3, the *in situ* formation and reaction of PCP–$B(OMe)_2$, **10** with aryl bromides was much more productive (Table 1, method C). These two-step, one-pot Suzuki reactions gave cross coupled products in high yields comparable to the yields of the arylboronic acid/PCP–Br approach.

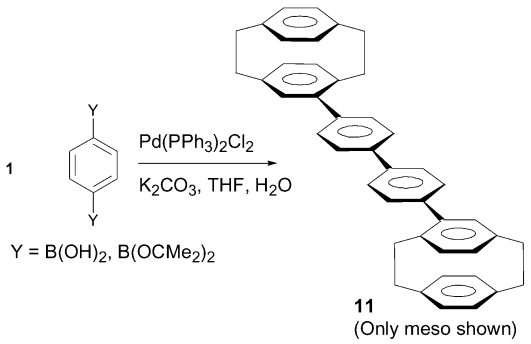


Scheme 3 Reaction conditions: (i) BuLi, $B(OMe)_3$; (ii) BrC_6H_4-Y, $Pd(PPh_3)_2Cl_2$, K_2CO_3, THF, H_2O.

The various aryl-substituted paracyclophanes prepared were identified and confirmed from their ^1H and ^{13}C NMR data.[14] In the ^1H NMR spectrum of compounds **2**–**5** it was observed that the aryl substituents did not exert either a significant *ortho* or *geminal* shift on the cyclophane aryl hydrogens. Thus compounds **2**–**5** displayed their substituent aryl C–H signals at much lower field than the cyclophane aryl C–H resonances. For example, compound **3** displayed δ_H = 7.2–7.7 ppm for the substituent and δ_H = 6.5–6.7 ppm for the cyclophane aryl signals.[15] The ^{13}C NMR spectra of these systems were fully consistent with the product structures, but spectroscopically unremarkable, as indeed were the mass spectra which displayed the characteristic cyclophane–xylylene fragmentation patterns.[2]

There are a variety of dicyclophane compounds where two cyclophanes are linked through an aryl–aryl linkage, including the parent system diPCP,[16] its bridge fluorinated analogue,[8] and a number of systems containing organic, inorganic[17] and transition metal[18] spacer groups. Due to the planar chirality of mono-substituted [2.2]paracyclophanes,[2] there is interest in the diastereoselectivity of dicyclophane formation and in NMR chemical shift differences between diastereomers of this type. Such compounds are also of interest as they serve as monomers for cross linked Parylene type polymers.[19]

Our initial attempts to use the above Suzuki methodology to prepare diPCP, or PCP–OFP dicyclophanes were not successful, with sterics being the most likely cause. So we turned our attention to the formation of a dicyclophane with a spacer group. In an attempt to prepare a dicyclophane with a phenyl spacer group, we reacted *p*-phenyldiboronic acid with an excess of **1** under Suzuki conditions. Surprisingly, the only dicyclophane product observed in the reaction was identified as **11**, in 44% isolated yield (Scheme 4). It is presumed that this product arises from a homocoupling of boronic acids. The same product with similar yield (33%) was also observed employing the dipinacolate ester. Such homocouplings of arylboronic acids (and esters) during Suzuki reactions are known to occur when the cross coupling reaction is very slow.[20] A similar product was also reported in the case of the bridge-fluorinated analogue.[9]



Scheme 4

Product **11** showed analytical data characteristically similar to the aryl derivatives **2**–**5** described above. In the ^1H NMR spectrum, the biphenyl hydrogens appeared as a doublet of doublets at δ_H = 7.7 and 7.9 ppm and the cyclophane aryl hydrogens were clustered together around δ_H = 6.6 ppm. We were not able to convincingly resolve the *meso* and (DL) diastereomers of **11** by any GC or HPLC techniques available to us. Such diminutive diastereomeric differences imply that the planar chiral units are significantly alienated from each other by the large distance and orientation away from one another, as dictated by the 4,4′ biphenyl spacer group.

Further investigations into the syntheses of other related cyclophane and dicyclophane systems, including their diastereoselectivity of formation, spectroscopic properties and applications, are ongoing in our laboratory.

Experimental

General details

All NMR spectra were obtained on a Varian Mercury Plus 300 MHz spectrometer with 5 mm ATB probe at ambient temperature. Coupling constants are given in Hz. All products were colorless solids, except where specified otherwise in the text. All reagents, unless otherwise specified, were used as purchased from Aldrich or Fisher. Column chromatography was performed using chromatographic silica gel 200–425 mesh, as supplied by Fisher. Melting points are uncorrected. Low-resolution mass spectrometry was performed at the Center for Advanced Food Technology, New Brunswick, NJ and high-resolution mass spectrometry was performed at the University of Pennsylvania, Philadelphia, PA.

The aryl bromides, boronic acids and boronic acid pinacol esters used were purchased from commercial sources except for the following: 4-bromo[2.2]paracyclophane, **1**, was prepared from PCP according to a literature method.[21] 2-Phenyl-4,4,5,5-tetramethyl-1,3-dioxaborolane, 2-(2-methylphenyl)-4,4,5,5-tetramethyl-1,3-dioxaborolane and 2,2′-(1,4-phenylene)bis[4,4,5,5-tetramethyl-1,3-dioxaborolane] were prepared as described previously.[9]

[2.2]Paracyclophanyl-4-boronic acid pinacol ester (9)

4-Bromo[2.2]paracyclophane, **1**, (1.47 g, 5.10 mmol) in THF (47 mL) was cooled to −78 °C under a dry N_2 atmosphere. *n*-Butyllithium (4.7 mL of 1.6 M in hexane, 7.52 mmol) was added dropwise and the solution was stirred for 1 h at this temperature. A solution of bis(pinacolato)diboron (2.55 g, 10.04 mmol) in THF (10 mL) was slowly syringed into the reaction mixture and the mixture was left to stir for an additional 1 h at this temperature. The reaction mixture was then allowed to warm to room temperature overnight. The mixture was extracted with ether (3 × 20 mL), the extracts were dried ($MgSO_4$) and evaporated under reduced pressure. The solid residue was subjected to column chromatography (hexane–chloroform 1 : 1) to give (R_f = 0.55) **9** (1.21 g, 71%); mp 104–106 °C (from chloroform); δ_H (300 MHz; d_6-acetone; Me_4Si) 6.86 (1 H, d, ^4J 1.5), 6.43 (1 H, d, ^3J 9.9), 6.28–6.34 (4 H, m), 6.23 (1H, d, ^3J 7.8) (aryl C–Hs); 2.71–2.89 (8 H, m, bridge CH_2s) 1.27 (12 H, s, CH_3s); δ_C (75 MHz; d_6-acetone; Me_4Si) 139.60, 134.51, 133.18, 132.52, 132.30, 131.84, 131.45 (aryl C–Hs); 34.93, 34.72, 34.59, 34.45 (CH_2s); 146.37, 138.93, 138.75, 137.44 (cyclophane bridgeheads); 82.37 (quaternary); 23.95, 23.76 (CH_3s); *m/z* (EI) 334 (M^+, 90%), 83 (40), 130 (60), 229 (40), 203 (100). HRMS (CI+) 334.2089 (M^+. $C_{22}H_{27}BO_2$ requires 334.2104).

4-Hydroxy[2.2]paracyclophane (8)

4-Bromo[2.2]paracyclophane, **1**, (0.50 g, 1.77 mmol) and ether (22 mL) were cooled to −78 °C under an atmosphere of dry N_2. *n*-Butyllithium (2.31 mL of 1.6 M in hexane, 3.70 mmol) was added dropwise and the solution was stirred as it warmed to room temperature for 20 min. The temperature of the reaction mixture was brought down to 0 °C and then trimethyl borate (0.39 mL, 3.46 mmol) was syringed into the solution and the mixture was left to stir for an additional 1 h. To the reaction mixture was added an aqueous solution of 0.5 M sodium hydroxide (0.86 mL, 0.43 mmol) and 30% hydrogen peroxide (0.74 mL, 6.49 mmol) and the mixture was heated at 40 °C for 2 h. The solution was acidified with dilute HCl, extracted with ether (3 × 20 mL) and the extracts were dried ($MgSO_4$) and evaporated under reduced pressure. The solid residue was subjected to column chromatography (chloroform) to give (R_f = 0.29) **8** (0.31 g, 79%): δ_H (300 MHz; $CDCl_3$; Me_4Si) 6.98 (1 H, dd, ^3J 7.8, ^4J 1.9), 6.44–6.35 (4 H, m), 6.24 (1 H, dd, ^3J 7.7, ^4J 1.6), 5.54 (1 H, d, ^4J 1.6) (aryl C–Hs); 4.40 (1 H, br s, OH); 3.39 (1 H, m), 2.66–3.27 (6 H, m), 2.59 (1 H m) (bridge CH_2s); *m/z* (EI) 224 (M^+, 50%), 104 (50), 120 (100). Such characterization is in excellent agreement with literature values.[13]

4-(3-Hydroxyphenyl)[2.2]paracyclophane (5)

Method A. Under a counter-current of nitrogen gas, a round-bottomed flask was charged with 4-bromo[2.2]paracyclophane, **1**, (0.20 g, 0.70 mmol), 3-hydroxyphenylboronic acid (0.13 g, 0.94 mmol), bis(triphenylphosphine)palladium(II) chloride (23 mg, 0.04 mmol), potassium carbonate (0.26 g, 1.88 mmol), THF (6 mL) and water (1.5 mL). The vessel was thoroughly flushed with N_2 and the mixture heated under reflux for 48 h. The reaction mixture was then cooled to room temperature, extracted with ether (3 × 20 mL), the extracts were dried ($MgSO_4$) and evaporated under reduced pressure. The crude product was chromatographed (hexane–ether 1 : 1, R_f = 0.46) to give **5** (168 mg, 80%); mp = 185–189 °C (from ether); δ_H (300 MHz; d_6-acetone; Me_4Si) 8.40 (1 H, s), 7.30 (1 H, t, ^3J 7.4), 6.97 (1 H, d, ^3J 7.4), 6.85 (1 H, d, ^3J 7.4), 6.68–6.52 (7 H, m) (aryl C–Hs); 3.37–3.50 (m, 2H), 2.83–3.21 (m, 4H), 2.58–2.70 (m, 2H) (bridge CH_2s); δ_C (75 MHz; d_6-acetone; Me_4Si) 136.00, 133.25, 132.75, 132.35, 132.28, 132.17, 129.94, 129.59, 121.09, 116.70, 13.90 (aryl C–Hs); 157.79 (C–OH); 140.00, 139.83, 139.68, 139.59, 137.38, 137.01 (quaternary); 35.46, 35.16, 34.92, 34.26 (CH_2s); *m/z* (EI) 300 (M^+, 90%), 181 (90), 195 (100). HRMS (CI+) 300.1511 (M^+. $C_{22}H_{20}O$ requires 300.1515).

Method B. Under a counter-current of nitrogen gas, a round-bottomed flask was charged with 4-bromo[2.2]paracyclophane, **1**, (0.20 g, 0.70 mmol), 3-hydroxyphenylboronic acid pinacol ester (0.23 g, 1.05 mmol), bis(triphenylphosphine)-palladium(II) chloride (23 mg, 0.04 mmol), potassium carbonate (0.26 g, 1.88 mmol), THF (6 mL) and water (1.5 mL). The vessel was thoroughly flushed with N_2 and the mixture heated under reflux for 48 h. The reaction mixture was then cooled to room temperature, extracted with ether (3 × 20 mL), the extracts were dried ($MgSO_4$) and evaporated under reduced pressure. The crude product was chromatographed (hexane–ether 1 : 1, R_f = 0.46) to give **5** (185 mg, 88%) spectroscopically identical with the sample prepared above.

Method C. 4-Bromo[2.2]paracyclophane, **1**, (0.20 g, 0.70 mmol) and ether (30 mL) were cooled to −78 °C under an N_2 atmosphere. *n*-Butyllithium (0.86 mL of 1.6 M in hexane, 1.38 mmol) was added and the solution was stirred at this temperature for 1 h. Trimethyl borate (0.17 mL, 1.39 mmol) was syringed into the solution and the solution was left to stir for an additional hour whilst warming to 0 °C. Through a pressure-equalizing dropping funnel, a THF (6 mL) solution of 3-bromophenol (0.24 g, 1.39 mmol) and bis(triphenyl-phosphine)palladium(II) chloride (23 mg, 0.04 mmol) were added, followed by an aqueous solution (1.5 mL) of potassium carbonate (0.26 g, 1.88 mmol). The vessel was thoroughly flushed with N_2 and the mixture was heated under reflux for 48 h. The reaction mixture was then cooled to room temperature, extracted with ether (3 × 20 mL) and the extracts were dried ($MgSO_4$) and evaporated under reduced pressure. The crude product was chromatographed (hexane–ether 1 : 1, R_f = 0.46) to give **5** (179 mg, 85%) spectroscopically identical with the sample prepared above.

4-(4-Cyanophenyl)[2.2]paracyclophane (4)

At the same scale and according to the same procedure as described in method A, 4-cyanophenylboronic acid, after column chromatography (hexane–dichloromethane 1 : 1), gave (R_f = 0.44) **4** (188 mg, 87%); mp = 107–108 °C (from dichloromethane); δ_H (300 MHz; d_6-acetone; Me_4Si) 7.87 (2 H, dd, ^3J 6.0 and ^4J 1.5), 7.74 (2 H, dd, ^3J 6.6 and ^4J 2.1), 6.53

(1 H, d, ^3J 8.1), 6.60 (1 H, d, ^3J 7.5), 6.62 (1 H, d, ^3J 9.3), 6.66–6.69 (4 H) (aryl C–Hs); 3.39 (1 H, m), 2.76–3.20 (6 H, m), 2.53–2.62 (1 H m) (bridge CH_2s); δ_C (75 MHz; d_6-acetone; Me_4Si) 136.44, 133.50, 133.39, 132.92, 132.50, 132.26, 132.23, 130.77, 129.76 (aryl C–Hs); 34.47, 34.27, 33.98, 33.21 (CH_2s); 139.51, 139.34, 138.85, 138.65 (cyclophane bridgeheads); 147.18, 145.10, 109.61 (quaternary); 117.78 (CN); *m/z* (EI) 309 (M^+, 34%), 104 (42), 105 (100). HRMS (CI+) 309.1519 (M^+. $C_{23}H_{19}N$ requires 309.1518).

Method B using 4-cyanophenylboronic acid pinacol ester gave **4** in 83%; Method C using 4-bromobenzonitrile gave **4** in 87%.

4-Phenyl[2.2]paracyclophane (2)

At the same scale and using the same procedure as described in method A with phenylboronic acid, after column chromatography (hexane–chloroform 8 : 1), gave ($R_f = 0.35$) **2** (167 mg, 84%); δ_H (300 MHz; d_6-acetone; Me_4Si) 7.46 (2 H, d, ^3J 7.5), 7.35 (2 H, t, ^3J 7.2), 7.29 (1 H, t, ^3J 7.4), 6.59–6.91 (7 H, m) (aryl C–Hs); 2.66–3.20 (7 H, m) 3.40–3.51 (1 H, m) (bridge CH_2s); *m/z* (EI) 284 (M^+, 27%), 180 (100), 104 (76). Such data is in agreement with previously reported data.[22,23]

Method B using phenylboronic acid pinacol ester gave **2** in 87%; Method C using bromobenzene gave **2** in 79%.

4-(2-Methylphenyl)[2.2]paracyclophane (3)

At the same scale and using the same procedure as described in method A, 2-methylphenylboronic acid, after column chromatography (hexane–chloroform 7 : 1), gave (R_f = 0.33) **3** (169 mg, 81%); mp = 105–110 °C (from chloroform) (lit.[23] = 114–116 °C); δ_H (300 MHz; d_6-acetone; Me_4Si) 7.71 (1 H, d, ^3J 7.5), 7.41 (1 H, d, ^3J 7.2), 7.23 (1 H, d, ^3J 7.5), 7.29 (1 H, d, ^3J 7.5), 6.72 (1 H, d, ^3J 7.8), 6.60–6.67 (3 H, m), 6.50–6.57 (3 H, m) (aryl C–Hs); 3.02–3.16 (6 H, m), 2.75–2.89 (2 H, m) (bridge CH_2s), 2.09 (3 H, s, CH_3); δ_C (75 MHz; d_6-acetone; Me_4Si) 133.65, 132.44, 132.20, 131.68, 131.59, 131.55, 129.14, 129.14, 129.01, 126.18, 125.37 (aryl C–Hs); 34.52, 34.35, 34.31, 32.66 (CH_2s); 140.62, 139.90, 138.86, 138.78, 127.58, 136.30, 135.26 (quaternary); 18.93 (CH_3); *m/z* (EI) 298 (M+, 50%), 104 (40), 178 (50), 179 (70), 193 (100). HRMS (CI+) 298.1718 (M^+. $C_{23}H_{22}$ requires 298.1722). Such data agrees with and expands upon, the reported spectroscopic data.[23]

Method B using 2-methylphenylboronic acid pinacol ester gave **3** in 86%; Method C using 2-bromotoluene gave **3** in 82%.

4,4′-Bis([2.2]paracyclophan-4-yl)biphenyl (11)

Under a counter-current of nitrogen gas, a round-bottomed flask was charged with 4-bromo[2.2]paracyclophane **1** (0.24 g, 0.84 mmol), phenylene-1,4-diboronic acid (34 mg, 0.20 mmol), bis(triphenylphosphine)palladium(II) chloride (14 mg, 0.02 mmol), potassium carbonate (0.32 g, 2.32 mmol), THF (8.5 mL) and water (1.5 mL). The vessel was thoroughly flushed with N_2 and the mixture was heated under reflux for 48 h. The reaction mixture was then cooled to room temperature, extracted with ether (3 × 20 mL) and the extracts were dried ($MgSO_4$) and evaporated under reduced pressure. The crude product was subjected to column chromatography (hexane–chloroform 2 : 1) to give ($R_f = 0.59$) **11** (25 mg, 44%); mp = 103–106 °C (from chloroform); δ_H (300 MHz; d_6-acetone; Me_4Si) 7.79 (4 H, d, ^3J 8.4), 7.59 (4 H, d, ^3J 8.4), 6.53–6.66 (14 H, m) (aryl C–Hs); 3.53 (2 H, m), 2.67–3.22 (12 H, m), 2.58–2.63 (2 H, m) (bridge CH_2s); δ_C (75 MHz; d_6-acetone; Me_4Si) 135.27, 132.38. 131.93, 131.61, 131.42, 131.28. 129.53. 128.97, 126.12 (aryl C–Hs); 141.53, 140.70, 140.67, 140.05 (cyclophane bridgeheads); 139.70, 139.67. 137.13 (quaternary); 34.54, 34.27, 33.99, 33.44 (CH_2s). *m/z* (EI) 566 (M^+, 100%), 119 (40), 357 (50). HRMS (CI+) 566.3002 (M^+. $C_{44}H_{38}$ requires 566.2974).

Using phenylene-1,4-diboronic acid bis-pinacol ester gave **11** in 33%.

Acknowledgements

The National Science Foundation is gratefully acknowledged for allowing the purchase of an NMR system through a Major Research Instrumentation grant (NSF CHE-0116145). Rutgers, The State University of New Jersey, Campus at Camden, is also acknowledged for generously providing startup funds. Additionally, Shirin Modarai is thanked for her laboratory assistance.

References

1 C. J. Brown and A. C. Farthing, *Nature*, 1949, **164**, 915.

2 (*a*) B. H. Smith, *Bridged Aromatic Compounds*, Academic Press, New York, 1964; (*b*) L. Rossa, F. Vögtle, V. Boekelheide, I. Tabushi and K. Yamamura, *Top. Curr. Chem.*, 1983, 113; (*c*) F. Vögtle, *Top. Curr. Chem.*, 1983, 115; (*d*) F. Diederich, *Cyclophanes*, Royal Society of Chemistry, London, 1991; (*e*) F. Vögtle, *Cyclophane Chemistry*, Wiley, New York, 1993; (*f*) E. Weber, in *Topics in Current Chemistry*, Springer, Heidelberg, 1994, vol. 172; (*g*) V. V. Kane, W. H. de Wolf and F. Bickelhaupt, *Tetrahedron*, 1994, **50**, 4575; (*h*) G. J. Bodwell, *Angew. Chem.*, 1996, **108**, 2221; (*i*) A. de Meijere and B. König, *SYNLETT*, 1997, 1221; (*j*) G. J. Bodwell, *Organic Synthesis Highlights IV*, ed. H. G. Schmalz, Wiley-VCH, New York, 2000, p. 289; (*k*) H. Hopf, *Classics in Hydrocarbon Chemistry*, Wiley-VCH, Weinheim, 2000; (*l*) G. Gleiter and H. Hopf, *Modern Cyclophane Chemistry*, Wiley-VCH, Weinheim, 2004.

3 (*a*) D. A. Loy, R. A. Assink, G. M. Jamison, W. F. McNamara, S. Prabakar and D. A. Schneider, *Macromolecules*, 1995, **28**, 5799; (*b*) G. N. Gerasimov, E. L. Popova, E. V. Nikolaeva, S. N. Chvalun, E. I. Grigoriev, L. I. Trakhtenberg, V. I. Rozenberg and H. Hopf, *Macromol. Chem. Phys.*, 1998, **199**, 2179.

4 (*a*) J. Zyss, I. Ledoux, S. Volkov, V. Chernyak, S. Mukamel, G. P. Bartholomew and G. C. Bazan, *J. Am. Chem. Soc.*, 2000, **122**, 11956; (*b*) E. L. Popova, V. I. Rozenberg, Z. A. Starikova, S. Keuker-Baumann, H. S. Kitzerow and H. Hopf, *Angew. Chem. Int. Ed.*, 2002, **41**, 3411.

5 (*a*) S. E. Gibson and J. D. Knight, *Org. Biomol. Chem.*, 2003, **1**, 1256; (*b*) S. Dahmen and S. Bräse, *Chem. Commun.*, 2002, **1**, 26, and references contained within.

6 (*a*) Syntheses of OFP: S. W. Chow, L. A. Pilato and W. L. Wheelwright, *J. Org. Chem.*, 1970, **35**, 20; (*b*) W. R. Dolbier, Jr., J. X. Duan and A. J. Roche, *US Pat.*, 5841005, 1998; (*c*) W. R. Dolbier, Jr., J. X. Duan and A. J. Roche, *Org. Lett.*, 2000, **2**, 1867; (*d*) H. Amii, H. Y. Hatamoto, M. Seo and K. Uneyama, *J. Org. Chem.*, 2001, **66**, 7216.

7 (*a*) A. J. Roche and W. R. Dolbier, Jr., *J. Org. Chem.*, 1999, **64**, 9137; (*b*) A. J. Roche and W. R. Dolbier, Jr., *J. Org. Chem.*, 2000, **65**, 5282; (*c*) W. R. Dolbier, Jr., J. X. Duan, K. Abboud and B. Ameduri, *J. Am. Chem. Soc.*, 2000, **122**, 12083; (*d*) L. Guyard, P. Audebert, W. R. Dolbier and J. X. Duan, *J. Electroanal. Chem.*, 2002, **537**, 189; (*e*) W. R. Dolbier, Jr., J. X. Duan and A. J. Roche, *US Pat.* , 6392097, 2002; (*f*) W. R. Dolbier, Jr. and W. F. Beach, *J. Fluorine Chem.*, 2003, **122**, 97; (*g*) M. A. Battiste, J. X. Duan, Y. A. Zhai, I. Ghiviriga, K. Abboud and W. R. Dolbier, Jr., *J. Org. Chem.*, 2003, **68**, 3078.

8 A. J. Roche, J. X. Duan, W. R. Dolbier, Jr. and K. A. Abboud, *J. Org. Chem.*, 2001, **66**, 7055.

9 A. J. Roche and B. Canturk, *J. Fluorine Chem.*, DOI: 10.1016/j.jfluchem.2004.11.008.

10 (*a*) Recent excellent reviews include: S. Kotha, K. Lahiri and D. Kashinath, *Tetrahedron*, 2002, **58**, 9633; (*b*) J. Hassan, M. Sévignon, C. Gozzi, E. Schulz and M. Lemaire, *Chem. Rev.*, 2002, **102**, 1359; (*c*) N. Miyaura, *Top. Curr. Chem.*, 2002, **219**, 11; (*d*) N. Miyaura and A. Suzuki, *Chem. Rev.*, 1995, **95**, 2457.

11 B. Konig, B. Knieriem and A. de Meijere, *Chem. Ber.*, 1993, **126**, 1643.

12 V. I. Rozenberg, D. Y. Antonov, R. P. Zhuravsky, E. V. Vorontsov and Z. A. Starikova, *Tetrahedron Lett.*, 2003, **44**, 3801.

13 (*a*) V. V. Kane, A. Gerdes, W. Grahn, L. Ernst, I. Dix, P. G. Jones and H. Hopf, *Tetrahedron Lett.*, 2001, **42**, 373; (*b*) K. Krohn, H. Rieger, H. Hopf, D. Barrett, P. G. Jones and D. Doering, *Chem. Ber.*, 1990, **123**, 1729.

14 For an excellent review of cyclophane NMR spectroscopy see: L. Ernst, *Prog. Nucl. Magn. Reson. Spectrosc.*, 2000, **37**, 47.

15 This convenient "separation" of substituent and cyclophane aryl C–H NMR signals was useful since it assisted us in the elucidation of the corresponding ^{1}H NMR spectra from the bridge fluorinated OFP analogues. In these cases, the electron withdrawing fluorines force the OFP hydrogens to lower field, which often overlapped with the substituent aryl C–H resonances. See ref. 9.

16 (*a*) P. G. Jones and P. Kus, *Pol. J. Chem.*, 1998, **72**, 1106; (*b*) P. Kus, *Pol. J. Chem.*, 1994, **68**, 1983.
17 (*a*) L. Ernst and L. Wittkowski, *Eur. J. Org. Chem.*, 1999, **7**, 1653; (*b*) P. G. Jones, L. Ernst, I. Dix and L. Wittkowski, *Acta Crystallogr., Sect C: Cryst. Struct. Commun.*, 2000, **C56**, 239; (*c*) Y. Ma, C. Song, C. Ma, Z. Sun, Q. C. Chai and M. B. Andrus, *Angew. Chem. Int. Ed.*, 2003, **42**, 5871; (*d*) E. S. Baker, J. W. Hong, J. Gidden, G. P. Bartholomew, G. C. Bazan and M. T. Bowers, *J. Am. Chem. Soc.*, 2004, **126**, 6255; (*e*) V. I. Rozenberg, D. Y. Antonov, R. P. Zhuravsky, E. V. Vorontsov, V. N. Khrustalev, N. S. Ikonnikov and Y. N. Belokon, *Tetrahedron: Asymmetry*, 2000, **11**, 2683; (*f*) A. A. Aly, *Tetrahedron*, 2003, **59**, 1739.
18 H. Hopf, S. Sankararaman, I. Dix, P. G. Jones, H. G. Alt and A. Licht, *Eur. J. Inorg. Chem.*, 2002, **1**, 123.
19 E. Popova, D. Antonov, E. Sergeeva, E. Vorontsov, A. Stash, V. Rozenberg and H. Hopf, *Eur. J. Inorg. Chem.*, 1998, **11**, 1733.
20 (*a*) E. M. Campi, W. R. Jackson, S. M. Marcuccio and C. G. M. Naeslund, *J. Chem. Soc., Chem. Commun.*, 1994, 2395; (*b*) T. Gillman and T. Weeber, *SYNLETT*, 1994, 649; (*c*) Z. Z. Song and H. N. C. Wong, *J. Org. Chem.*, 1994, **59**, 33.
21 D. J. Cram and A. C. Day, *J. Org. Chem.*, 1966, **31**, 1227.
22 S. C. Dickerman and N. Milstein, *J. Org. Chem.*, 1967, **32**, 852.
23 P. Kus and A. Zemanek, *Pol. J. Chem.*, 1985, **59**, 281.