

# Influence of fluorine substituents on the NMR properties of phenylboronic acids

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The paper presents results of a systematic NMR studies on fluorinated phenylboronic acids. All possible derivatives were studied. The experimental  $^1\text{H}$ ,  $^{13}\text{C}$ ,  $^{19}\text{F}$ ,  $^{11}\text{B}$ , and  $^{17}\text{O}$  spectral data were compared with the results of theoretical calculations. The relation between the calculated natural bond orbital parameters and spectral data (chemical shifts and coupling constants) is discussed. The first examples of  $^{10}\text{B}/^{11}\text{B}$  isotopic effect on the  $^{19}\text{F}$  spectra and  $^4J_{\text{FO}}$  scalar coupling in organic compounds are reported. Copyright © 2014 John Wiley & Sons, Ltd.

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## Introduction

Arylboronic acids have attracted increasing interest because of their new applications in organic synthesis, catalysis, supramolecular chemistry, and material engineering.<sup>[1–3]</sup> Moreover, their biomedical applications are intensively studied. Boronic acids make a most promising group of chemoreceptors for sensing of glucose and other biologically important diols<sup>[1,4–6]</sup> as well as bacterial or animal cells.<sup>[7]</sup> They are also important drugs,<sup>[8–11]</sup> showing various biological activities (antibacterial,<sup>[12–14]</sup> antiviral,<sup>[13,15–17]</sup> antifungal,<sup>[12]</sup> and anticancer<sup>[13,18]</sup>). Boron group-containing molecules are studied as a drug delivery systems of a low cytotoxicity and immunogenicity.<sup>[15,19,20]</sup> The compounds containing  $^{10}\text{B}$  isotope are used in the so-called boron neutron-capture therapy of cancer. Various boronic acids are used as boron-carrying molecules for this purpose.<sup>[21–24]</sup>

Boronic acids can be regarded as Lewis acids. Their acidity depends on the substituents in phenyl ring. Introduction of electron-withdrawing substituents increases the acidity of boronic acids and has been observed for fluorine substituents. Thus, fluorinated boranes were investigated as additives to polymer electrolytes as the anion binding species enhancing the mobility of lithium cations and increasing the cation transference number.<sup>[25–27]</sup>

Cyclic esters of fluoro-substituted phenylboronic acids have been recently investigated. It has been established that introduction of a fluorine substituent into the phenyl ring resulted in increased Lewis acidity of the catechol esters, with the highest effect for 2-fluoro derivative. However, no correlation between the Gutmann acceptor number and the number of fluorine atoms in the molecule has been observed. The pentafluoro-substituted derivative was the strongest Lewis acid among the ones studied, with acidity comparable to that of tris(pentafluorophenyl)borane, considered as one of the strongest organoboron acids.<sup>[28]</sup> Other cyclic esters of this acid were also investigated. The differences in Lewis acidity have been discussed on the basis of electronic and geometric parameters.<sup>[29]</sup>

Fluoride sensing by boronic acids can also be enhanced by the introduction of fluorine substituent into phenyl ring.<sup>[30,31]</sup>

Molecular and crystal structures of fluoro-substituted phenylboronic catechol esters have been recently investigated.<sup>[32]</sup> It was found that the substitution does not influence the molecular geometry very much, and that this geometry is alike in the isolated species and crystals. In all species investigated, weak interactions play the key role in determining their geometry. There has been no systematic investigation of spectral properties of these compounds. One fluoroarylboronic acid (**4**) has been studied by solid-state NMR,<sup>[33]</sup> while for 2,3-difluorophenylboronic acid, the experimental and calculated NMR spectra have been reported.<sup>[34]</sup> The paper presents a comprehensive NMR spectroscopic characterization ( $^1\text{H}$ ,  $^{11}\text{B}$ ,  $^{13}\text{C}$ ,  $^{19}\text{F}$ , and  $^{17}\text{O}$ ) of all fluoro-substituted phenylboronic acids (Fig. 1) and is a continuation of our previous NMR studies on boronic acids and its derivatives.<sup>[35–38]</sup>

## Experimental

### Materials

All studied boronic acids were commercial products of Sigma-Aldrich and CombiBlocks companies. Deuterated solvents (Sigma-Aldrich) used for measurements were dehydrated, deoxygenated, and distilled before use. Labeling of boronic acids was made by dissolving of 50 mg of a given acid in

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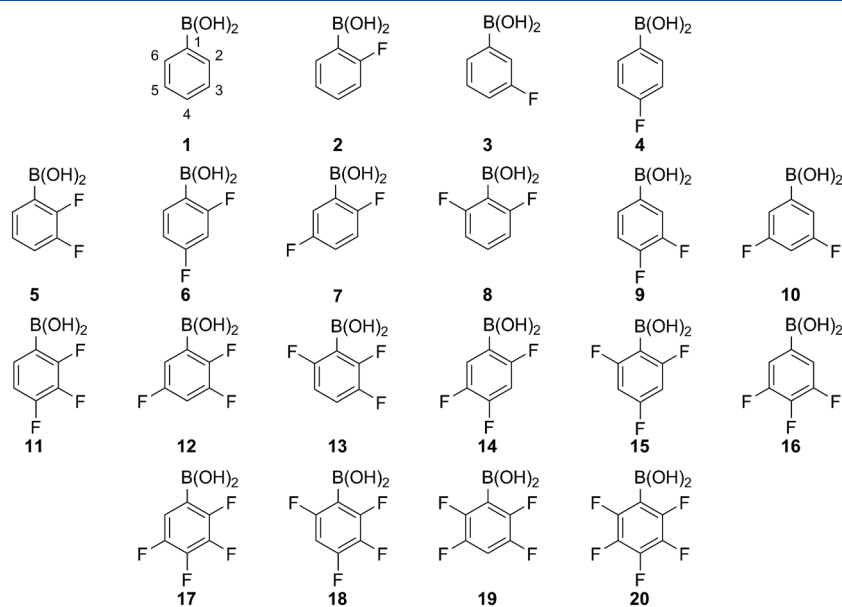


Figure 1. Structures of the compounds studied.

dry, freshly distilled acetonitrile, followed by the addition of 20  $\mu\text{l}$  of  $\text{H}_2^{17}\text{O}$  (20% enriched; CortecNec, France). The mixture was stirred overnight, and the solvent was evaporated. All compounds were crystallized before use and dried in vacuum at room temperature. Their purity was checked by  $^1\text{H}$  NMR and HPLC methods. The only impurities detected in the samples used for NMR measurements were the corresponding cyclic anhydrides (boroxines), formed on crystallization and/or on drying. For monofluorinated, difluorinated, and trifluorinated acids, the content of the corresponding anhydrides in final samples was less than 10%. Tetrafluorophenylboronic and pentafluorophenylboronic acids undergo dehydration during crystallization. In consequence, the solid material obtained as a result of their purification contains only anhydrides. In order to prepare samples for NMR measurements, the stoichiometric amount of water was added to the solution of these compounds to convert them into acids.

### Nuclear magnetic resonance measurements

All spectra were recorded at 298 K. All samples were prepared using a vacuum-line method under dry, deoxygenated argon. If not mentioned otherwise, the samples concentration was 0.01 M. The  $^{17}\text{O}$  NMR measurements were performed on Agilent DD2 800 spectrometer (Agilent Technologies, Santa Clara CA, USA), operating at frequency 108.442 MHz, equipped with a 5-mm probehead (BB/ $^1\text{H}$ ; 90°  $^{17}\text{O}$  pulse width 8  $\mu\text{s}$ ) using a simple one-pulse sequence (*s2pul*) with increased acquisition delay (30  $\mu\text{s}$ ) to reduce the distortion of baseline. The acquisition parameters were as follows: spectral width 52 kHz, acquisition time 0.5 s, 90° flip angle. Between 100 and 1000 transients were recorded to obtain satisfactory signal-to-noise ratio (total acquisition time *ca.* 2–15 min). Line broadening factor of 10 Hz was used. The signal-to-noise ratio for all spectra recorded was better than 20:1 before line broadening and 150:1 after applying the window function. The  $^{11}\text{B}$  NMR spectra were recorded on Bruker Avance DRX 600 spectrometer (Bruker GmbH, Karlsruhe, Germany) at frequency 192.577 MHz, using 5-mm direct detection probehead (BB/ $^1\text{H}$ ; 90°  $^{11}\text{B}$  pulse width 15  $\mu\text{s}$ ) and a standard one-pulse sequence with broadband  $^1\text{H}$  decoupling

(*zgpg*). The spectral width was 25 kHz, acquisition time = 2 s, line broadening factor 10 Hz. The  $^1\text{H}$ ,  $^{13}\text{C}$ , and  $^{19}\text{F}$  NMR spectra were recorded on Varian VNMR-S 400 (Varian Inc., Palo Alto CA, USA) at frequencies 402.643, 101.254, and 378.816, respectively, using BB/ $^{19}\text{F}/^1\text{H}$  PFG ATB probehead (90° pulse width:  $^1\text{H}$  = 13.6,  $^{13}\text{C}$  = 6.9, and  $^{19}\text{F}$  = 20.0  $\mu\text{s}$ ). Standard one-pulse sequence (*s2pul*) and acquisition parameters were used. The  $^{13}\text{C}$  NMR spectra were recorded with broadband  $^1\text{H}$  decoupling. For measurements of coupling constants, increased digital resolution of  $^1\text{H}$ ,  $^{13}\text{C}$ , and  $^{19}\text{F}$  NMR spectra was needed. It was achieved by using of gaussian multiplication. The  $^{19}\text{F}$  spectra with  $^1\text{H}$  decoupling were recorded on Bruker Avance II 400 equipped with ATM BBO BB(F)/ $^1\text{H}$  5-mm probehead, operating at frequency 376.498 MHz for  $^{19}\text{F}$ . The *zgpg30* sequence from Bruker library was used.

The  $^{17}\text{O}$  NMR spectra were referred to external doubly distilled water, inserted in 1 mm coaxially capillary into NMR tube (0.00 ppm), the  $^{11}\text{B}$  NMR spectra were referred to external  $\text{BF}_3 \cdot (\text{C}_2\text{H}_5)_2\text{O}$  in  $\text{CDCl}_3$  (15%; 0.00 ppm). The  $^{11}\text{B}$  and  $^{17}\text{O}$  chemical shifts measured were corrected for magnetic susceptibility of the solvent. The  $^1\text{H}$  and  $^{13}\text{C}$  chemical shifts were measured against internal TMS (0.02%; v/v) while  $^{19}\text{F}$  chemical shift against internal  $\text{CFCl}_3$  (0.01%; v/v). The accuracy of  $^{17}\text{O}$  NMR shifts was better than 0.1 ppm. The  $^{11}\text{B}$  chemical shifts accuracy was *ca.* 0.02 ppm. For  $^1\text{H}$ ,  $^{13}\text{C}$ , and  $^{19}\text{F}$ , the accuracy of chemical shifts measurements was better than 0.01 ppm.

The coupling constants for non-first order spin systems were obtained from spin simulation with MestReNova 6.0.<sup>[39]</sup>

### DFT calculations

Starting structures were pre-optimized by the HF/3–21g method. Conformational search was performed by examining of all torsion angles along acyclic bonds using CAChe 5.0. One conformer was found in the range of 4 kcal/mol, apart from the molecules containing *ortho* substituent. The pre-optimized input structures were then fully optimized by the density functional theory (DFT) method at the B3LYP/6–311++G(2d, 2p) level of theory with Gaussian03.<sup>[40]</sup> Molecules were allowed to relax concurrently and without any enforcement of symmetry restrictions. The

optimized structures were used for calculations of NMR shifts. These calculations were also performed using DFT, at the same level of theory, which provided a good correlation with experimental results. The calculated oxygen-17 chemical shieldings ( $\sigma(^{17}\text{O})$ ) were converted to chemical shifts scale ( $\delta(^{17}\text{O})$ ) by  $\delta(^{17}\text{O})_X = \sigma(^{17}\text{O})_{\text{CO}} - \sigma(^{17}\text{O})_X + 350.1$ , where  $\sigma(^{17}\text{O})_{\text{CO}}$  is the shielding of the oxygen atom in carbon monoxide molecule, calculated in the same base as the other molecules ( $\sigma(^{17}\text{O})_{\text{CO}} = -69.7$  ppm), 350.1 ppm is the experimental chemical shift of CO in gas phase measured versus liquid  $\text{H}_2\text{O}$  (0.0 ppm).<sup>[41]</sup> The calculations of geometry-optimized TMS,  $\text{CFCl}_3$ , and  $\text{BF}_3$  gave the shielding values  $\sigma(^1\text{H})_{\text{TMS}} = 31.81$  ppm,  $\sigma(^{13}\text{C})_{\text{TMS}} = 183.77$  ppm,  $\sigma(^{19}\text{F})_{\text{CFCl}_3} = 156.59$  ppm, and  $\sigma(^{11}\text{B})_{\text{BF}_3} = 89.19$  ppm; thus, the calculated values of the chemical shifts of studied arylboronic acids are expressed as  $\delta(^1\text{H})_X = 31.81 - \sigma(^1\text{H})_X$ ;  $\delta(^{13}\text{C})_X = 183.77 - \sigma(^{13}\text{C})_X$ ;  $\delta(^{19}\text{F})_X = 156.59 - \sigma(^{19}\text{F})_X$ ; and  $\delta(^{11}\text{B})_X = 89.19 - \sigma(^{11}\text{B})_X$ , respectively. The natural bond orbital (NBO) calculations were performed with NBO Version 3.1 program from Gaussian software packet.<sup>[42]</sup>

## Results and Discussion

Structures of the compounds studied are presented in Fig. 1. The NMR measurement results are collected in Tables 1–4. The calculated values of the chemical shifts are presented as Supporting Information (Table S1–S4).

### $^1\text{H}$ NMR

Signals of C–H hydrogen atoms have chemical shifts typical of aromatic compounds (6.82–7.93 ppm). The chemical shift of boronic group (7.1–8.3 ppm) is strongly affected by sample concentration, impurities (water), and temperature. The proton–proton coupling constants are typical of aromatic compounds. Slight increase in their values upon substitution of the other hydrogen atoms by fluorine ones is observed.

The  $^3J_{\text{HF}}$  values recorded for mono-fluorophenyl boronic acids are slightly higher than that obtained for fluorobenzene (8.8 Hz). The observed effects are *ca.* 1.1 ppm for *ortho*, 0.0, and 1.0 for *meta* and 0.6 Hz for *para* derivatives. These effects are smaller for oligosubstituted analogs (e.g., 11.0 Hz for **5** vs 10.8 for 2,3-difluorobenzene or 10.8 Hz for **18** vs 10.4 Hz for 1,2,3,5-tetrafluorobenzene). The effect of  $\text{B}(\text{OH})_2$  substituent on  $^4J_{\text{HF}}$  is generally small ( $<1$  Hz), but in some compounds, it is enormously high (e.g., +4.3 Hz in **17** vs 1,2,3,4-tetrafluorobenzene or –3.8 Hz in **5** vs 2,3-difluorobenzene). The reasons for such behavior are not clear. No splitting due to coupling to boron nucleus or  $^{10}\text{B}/^{11}\text{B}$  was observed.

The  $^1\text{H}$  NMR chemical shifts of Ar–H protons are well reproduced by DFT calculations (Eqn (1);  $R^2 = 0.91$ ). The  $\delta$  values for BOH hydrogen atoms do not correlate with calculated ones.

$$\delta_{\text{obs}}^{\text{H}} = (0.58 \pm 0.03) \delta_{\text{calcd}}^{\text{H}} + (2.90 \pm 0.24) \quad (1)$$

### $^{13}\text{C}$ NMR

The  $^{13}\text{C}$  NMR chemical shifts of the studied group of compounds are affected mainly by the fluorine substituents. The chemical shifts range is 67.8 ppm (from 100.91 to 168.68 ppm). The shifts caused by boronyl group are rather small. The  $\text{C}^1$  signal is very difficult to observe. In the carbon spectra, it appears as a very

broad (*ca.* 200 Hz) peak of a low intensity (about 0.3% of that of C–H ones; Fig. 2). For many compounds studied, it overlaps with other signals in  $^{13}\text{C}$  NMR spectra. Its chemical shift varies from 110 to 139 ppm. The boronyl substituent effects calculated on the basis of the measurements for the series studied are  $\sigma_i(^{13}\text{C}) = 7.1 \pm 1.9$  ppm. The shape of this signal is determined by fast relaxation, caused by the proximity of quadrupolar boron-10/11 nuclei and the splitting of the signal due to scalar spin–spin interactions with both boron isotopes as well as fluorine atoms. For the carbon atoms in other positions, the  $\text{B}(\text{OH})_2$  substituent effects are  $\sigma_o(^{13}\text{C}) = 6.0 \pm 1.9$  ppm,  $\sigma_m(^{13}\text{C}) = -0.3 \pm 1.2$  ppm and  $\sigma_p(^{13}\text{C}) = 2.5 \pm 1.2$  ppm, respectively. No splittings caused by the coupling of  $\text{C}^2$ ,  $\text{C}^3$ , or  $\text{C}^4$  atoms with boron-10/11 are observed in the series of boronic acids studied; however, these signals are split due to interactions of carbon atoms with fluorine nuclei.

The  $^1J_{\text{CF}}$  values vary between 239.6 and 252.9 Hz, but no relationship between the calculated structural parameters and  $^1J_{\text{CF}}$  has been found. The values observed for monosubstituted phenylboronic acid (244.2, 243.7, and 246.4 Hz for *ortho*-derivative, *meta*-derivative, and *para*-derivative, respectively) indicate a small influence of  $\text{B}(\text{OH})_2$  group on one-bond  $^{13}\text{C}$ – $^{19}\text{F}$  scalar coupling (245.6 Hz for fluorobenzene).<sup>[43]</sup> The effect of subsequent fluorine substituents on this value is between –4 to +10 Hz; however, it is not systematic, contrary to the examples published earlier.<sup>[44]</sup>

Similarly to the relation reported for vicinal C–H scalar couplings,<sup>[45]</sup> the values of  $^3J_{\text{CF}}$  correlate well with the vicinal NBO interaction between CC bond and C–F antibond ( $\pi_{\text{C}=\text{C}} \rightarrow \sigma_{\text{C}^*\text{F}}^*$ ;  $\Delta E_{\pi\sigma^*}$ ; for  $\Delta E_{\pi\sigma^*}$  values see Supporting Information). Different relations were found for C–H (Eqn (2);  $R^2 = 0.95$ ) and C–F (Eqn (3);  $R^2 = 0.92$ ) carbon atoms:

$$^3J_{\text{CF}} = (1.58 \pm 0.08) \Delta E_{\pi\sigma^*} - (21.6 \pm 1.3) \quad (2)$$

$$^3J_{\text{CF}} = (2.36 \pm 0.15) \Delta E_{\pi\sigma^*} - (28.8 \pm 2.5) \quad (3)$$

For the coupling between C-6 and F-2 (or C-2 and F-6), no correlation of  $J$  value and  $\Delta E_{\pi\sigma^*}$  (Fig. 3) has been found. It is probably a result of the interaction between  $\pi$ -electron system and  $p_z$  orbitals of boron atom connected to C-1 position. This interaction has a strong influence on the electron interactions in the  $\text{C}=\text{C}$ – $\text{C}^1\text{F}$  unit. The B–C  $\pi$ -bonding is shown by NBO calculations. The stabilization energy of interaction between  $\text{C}^1=\text{C}^2$   $\pi$ -orbital as a donor and ‘empty’  $p_z$  orbital ( $\text{LP}^*$ ) of B-atom is high (*ca.* 84 kJ mol $^{-1}$ ). This value is close to the energy of interaction between  $\text{C}=\text{C}$   $\pi$  electrons and  $\pi^*$  antibond in the phenyl ring of the studied molecules (90–100 kJ mol $^{-1}$ ). In consequence, the occupancy of  $p_z$  orbital of the boron atom is quite high (0.3–0.4). The B–C  $\pi$ -bonding has been also evidenced on the basis of UV and photoelectron spectroscopy as well as X-ray crystallography for various arylboronic and alkenylboronic acids.<sup>[1]</sup>

No simple correlation between  $^2J_{\text{CF}}$  and the calculated NBO and molecules geometry parameters has been found. A crude relation ( $R^2$  *ca.* 0.65) between  $^2J_{\text{CF}}$  and the chemical shift of the coupled carbon is observed, indicating the influence of the total electric charge at this atom on the  $J$  value. Similar trends have been reported earlier for other fluorinated aromatic compounds.<sup>[43]</sup>

For C-2 of **1**, the  $^{10}\text{B}/^{11}\text{B}$  isotopic effect is observed ( $\Delta(^{10}\text{B}/^{11}\text{B}) = 1.5$  Hz). On C-4, this effect has the opposite sign and is much smaller ( $\Delta(^{10}\text{B}/^{11}\text{B}) = -0.9$  Hz). For the other compounds studied, boron-10/11 isotopic effect was not observed.

**Table 1.**  $^1\text{H}$  NMR chemical shifts and coupling constants for studied arylboronic acids in  $[\text{D}_6]\text{-acetone}$  (298 K)

Compound	Chemical shifts (ppm) and coupling constants (Hz)					
	BOH	H-2	H-3	H-4	H-5	H-6
<b>1</b>	7.2; br	7.89; pseudod <sup>a</sup> $^3J_{\text{H2H3}} = 7.9$ $^4J_{\text{H2H4}} = 1.4$ $^4J_{\text{H2H6}} = 2.0$ $^5J_{\text{H2H5}} = 0.8$	7.35; pseudod <sup>a</sup> $^3J_{\text{H2H3}} = 7.9$ $^3J_{\text{H3H4}} = 7.4$ $^4J_{\text{H3H5}} = 1.7$ $^5J_{\text{H3H6}} = 0.8$	7.42; pseudod <sup>a</sup> $^3J_{\text{H3H4}} = ^3J_{\text{H4H5}} = 7.4$ $^4J_{\text{H2H4}} = ^4J_{\text{H4H6}} = 1.4$	7.35; pseudod <sup>a</sup> $^3J_{\text{H5H6}} = 7.9$ $^3J_{\text{H4H5}} = 7.4$ $^4J_{\text{H3H5}} = 1.7$ $^5J_{\text{H2H5}} = 0.8$	7.89; pseudod <sup>a</sup> $^3J_{\text{H5H6}} = 7.9$ $^4J_{\text{H4H6}} = 1.4$ $^4J_{\text{H2H6}} = 2.0$ $^5J_{\text{H3H6}} = 0.8$
<b>2</b>	7.2; br	—	7.06; ddd $^3J_{\text{H3F2}} = 9.9$ $^3J_{\text{H3H4}} = 8.3$ $^4J_{\text{H3H5}} = 1.8$	7.46; dddd $^3J_{\text{H3H4}} = 8.3$ $^3J_{\text{H4H5}} = 7.4$ $^4J_{\text{H4F2}} = 5.4$ $^4J_{\text{H4H6}} = 1.9$	7.19; tt $^3J_{\text{H4H5}} = ^3J_{\text{H5H6}} = 7.4$ $^4J_{\text{H3H5}} = 1.8$ $^5J_{\text{H5F2}} = 1.8$	7.76; ddd $^3J_{\text{H5H6}} = 7.4$ $^4J_{\text{H6F2}} = 6.4$ $^4J_{\text{H4H6}} = 1.9$
<b>3</b>	7.1; br	7.57; dd $^3J_{\text{H2F3}} = 9.9$ $^4J_{\text{H2H4}} = 2.8$	—	7.18; ddd $^3J_{\text{H4F3}} = 8.8$ $^3J_{\text{H4H5}} = 7.9$ $^4J_{\text{H2H4}} = 2.8$	7.41; td $^3J_{\text{H4H5}} = ^3J_{\text{H5H6}} = 7.9$ $^4J_{\text{H5F3}} = 5.6$	7.70; d $^3J_{\text{H5H6}} = 7.9$
<b>4</b>	7.4; br	7.93; m <sup>a</sup> $^3J_{\text{H2H3}} = 8.6$ $^3J_{\text{H2F4}} = 6.3$ $^4J_{\text{H2H6}} = -1.6$	7.11; m <sup>a</sup> $^3J_{\text{H3F4}} = 9.4$ $^3J_{\text{H2H3}} = 8.6$ $^4J_{\text{H3H5}} = -1.8$	—	7.11; m <sup>a</sup> $^3J_{\text{H5F4}} = 9.4$ $^3J_{\text{H5H6}} = 8.6$ $^4J_{\text{H3H5}} = -1.8$	7.93; m <sup>a</sup> $^3J_{\text{H5H6}} = 8.6$ $^4J_{\text{H6F4}} = 6.3$ $^4J_{\text{H2H6}} = -1.6$
<b>5</b>	7.5; br	—	—	7.35; ddd $^3J_{\text{H4F3}} = 11.0$ $^3J_{\text{H4H5}} = 8.4$ $^4J_{\text{H4F2}} = 8.1$ $^4J_{\text{H4H6}} = 1.7$	7.18; dddd $^3J_{\text{H4H5}} = 8.4$ $^3J_{\text{H5H6}} = 7.7$ $^4J_{\text{H5F3}} = 4.3$ $^5J_{\text{H5F2}} = 1.1$	7.50; ddt $^3J_{\text{H5H6}} = 7.7$ $^4J_{\text{H6F2}} = 5.0$ $^4J_{\text{H4H6}} = ^5J_{\text{H6F3}} = 1.7$
<b>6</b>	7.3; br	—	6.93; td $^3J_{\text{H3F2}} = ^3J_{\text{H3F4}} = 9.8$ $^4J_{\text{H3H5}} = 2.3$	—	7.00; td $^3J_{\text{H5F4}} = ^3J_{\text{H5H6}} = 8.4$ $^4J_{\text{H3H5}} = 2.3$	7.91; dt $^3J_{\text{H5H6}} = 8.4$ $^4J_{\text{H6F2}} = ^4J_{\text{H6F4}} = 7.6$
<b>7</b>	7.6; br	—	7.11; ddd $^3J_{\text{H3F2}} = 8.8$ $^3J_{\text{H3H4}} = 8.0$ $^4J_{\text{H3F5}} = 4.0$	7.22; dddd $^3J_{\text{H4F5}} = 8.8$ $^3J_{\text{H3H4}} = 8.0$ $^4J_{\text{H4F2}} = 5.0$ $^4J_{\text{H4H6}} = 3.5$	—	7.41; ddd $^3J_{\text{H6F5}} = 8.2$ $^4J_{\text{H6F2}} = 4.3$ $^4J_{\text{H4H6}} = 3.5$
<b>8</b>	7.8; br	—	6.91; m <sup>a</sup> $^3J_{\text{H3F2}} = 9.0$ $^3J_{\text{H3H4}} = 8.3$ $^4J_{\text{H3H5}} = -2.0$	7.41; m <sup>a</sup> $^3J_{\text{H3H4}} = ^3J_{\text{H4H5}} = 8.3$ $^4J_{\text{H4F2}} = ^4J_{\text{H4F6}} = 6.9$	6.91; m <sup>a</sup> $^3J_{\text{H5F6}} = 9.0$ $^3J_{\text{H4H5}} = 8.3$ $^4J_{\text{H3H5}} = -2.0$	—
<b>9</b>	7.4; br	7.70; m <sup>b</sup> $^3J_{\text{H2F3}} = 8.6$ $^4J_{\text{H2F4}} = 5.5$ $^4J_{\text{H2H6}} = 1.5$	—	—	7.30; m <sup>b</sup> $^3J_{\text{H5F4}} = 11.0$ $^3J_{\text{H5H6}} = ^4J_{\text{H5F3}} = 8.1$	7.74; m <sup>b</sup> $^3J_{\text{H5H6}} = 8.1$ $^4J_{\text{H6F4}} = 6.7$ $^4J_{\text{H2H6}} = 1.5$
<b>10</b>	7.6; br	7.43; m <sup>a</sup> $^3J_{\text{H2F3}} = 9.0$ $^4J_{\text{H2H4}} = 2.5$ $^4J_{\text{H2H6}} = 0.8$	—	7.06; m <sup>a</sup> $^3J_{\text{H4F3}} = ^3J_{\text{H4F5}} = 9.3$ $^4J_{\text{H2H4}} = ^4J_{\text{H4H6}} = 2.5$	—	7.43; m <sup>a</sup> $^3J_{\text{H6F5}} = 9.0$ $^4J_{\text{H6H4}} = 2.5$ $^4J_{\text{H2H6}} = 0.8$
<b>11</b>	7.5; br	—	—	—	7.17; dddd $^3J_{\text{H5F4}} = 10.5$ $^3J_{\text{H5H6}} = 8.6$ $^4J_{\text{H5F3}} = 6.7$ $^5J_{\text{H5F2}} = 1.9$	7.54; dtd $^3J_{\text{H5H6}} = 8.6$ $^4J_{\text{H6F2}} = ^4J_{\text{H6F4}} = 6.7$ $^5J_{\text{H6F3}} = 2.5$
<b>12</b>	7.6; br	—	—	7.26; dddd $^3J_{\text{H4F3}} = 10.6$ $^3J_{\text{H4F5}} = 8.3$ $^4J_{\text{H4F2}} = 6.3$ $^4J_{\text{H4H6}} = 3.2$	—	7.22; dtd $^3J_{\text{H6F5}} = 8.3$ $^4J_{\text{H4H6}} = ^4J_{\text{H5F2}} = 3.2$ $^5J_{\text{H6F3}} = 2.0$
<b>13</b>	8.1; br	—	—	7.33; dtd $^3J_{\text{H4F3}} = 10.2$	6.94; dddd $^3J_{\text{H4H5}} = 9.1$	—

(Continues)

Table 1. (Continued)

Compound	Chemical shifts (ppm) and coupling constants (Hz)					
	BOH	H-2	H-3	H-4	H-5	H-6
<b>14</b>	7.4; br	—	7.17; ddd $^3J_{\text{H3F4}} = 10.9$ $^3J_{\text{H3F2}} = 8.8$ $^4J_{\text{H3F5}} = 6.2$	$^3J_{\text{H4H5}} = ^4J_{\text{H4F2}} = 9.1$ $^3J_{\text{H4F6}} = 5.2$	$^3J_{\text{H5F6}} = 7.6$ $^4J_{\text{H5F3}} = 3.2$ $^5J_{\text{H5F2}} = 1.9$	7.60; ddd $^3J_{\text{H6F5}} = 10.9$ $^4J_{\text{H6F2}} = 10.1$ $^4J_{\text{H6F4}} = 5.5$
<b>15</b>	7.8; br	—	6.82; m <sup>a</sup> $^3J_{\text{H3F2}} = 9.3$ $^3J_{\text{H3F4}} = 8.9$ $^4J_{\text{H3H5}} = 1.7$ $^5J_{\text{H3F6}} = -0.7$	—	6.82; m <sup>a</sup> $^3J_{\text{H5F6}} = 9.3$ $^3J_{\text{H5F4}} = 8.9$ $^4J_{\text{H3H5}} = 1.7$ $^5J_{\text{H5H2}} = -0.7$	—
<b>16</b>	7.5; br	7.57; m <sup>a</sup> $^3J_{\text{H2F3}} = 8.6$ $^4J_{\text{H2F4}} = 7.7$ $^4J_{\text{H2H6}} = -2.0$	—	—	—	7.57; m <sup>a</sup> $^3J_{\text{H6F5}} = 8.6$ $^4J_{\text{H6F4}} = 7.7$ $^4J_{\text{H2H6}} = -2.0$
<b>17</b>	7.5; br	—	—	—	—	7.41; dddd $^3J_{\text{H6F5}} = 10.6$ $^4J_{\text{H6F4}} = 8.8$ $^4J_{\text{H6F2}} = 4.7$ $^5J_{\text{H6F3}} = 2.7$
<b>18</b>	8.0; br	—	—	—	7.03; dddd $^3J_{\text{H5F4}} = 10.8$ $^3J_{\text{H5F6}} = 8.2$ $^4J_{\text{H5F3}} = 5.4$ $^5J_{\text{H5F2}} = 2.4$	—
<b>19</b>	8.2; br	—	—	7.54; m <sup>a</sup> $^3J_{\text{H4F3}} = ^3J_{\text{H4F5}} = 10.1$ $^4J_{\text{H4F2}} = ^4J_{\text{H4F6}} = 7.6$	—	—
<b>20</b>	8.3; br	—	—	—	—	—

<sup>a</sup>AA'MM'X spin system.<sup>b</sup>Second-order spin system.

The experimental values of the  $^{13}\text{C}$  NMR chemical shifts are excellently reproduced by DFT calculations, but if the values for C-1 carbon atom are not used for statistical analysis. For C-2 to C-6 carbon atoms,  $R^2$  is better than 0.99 (Eqn (4)), while for all carbon atoms (C-1 to C-6),  $R^2$  is 0.91 (Eqn (5)). The errors in the calculation of C-1 chemical shifts may be a result of the interactions of B(OH)<sub>2</sub> moiety with environment (solvent, impurities, and other solute molecules), influencing strongly the  $\delta$  values on the closest carbon atom. Moreover, the great line width of C-1 signal results in errors in chemical shifts measurements.

$$\delta_{\text{obs}}^{13\text{C}} = (0.874 \pm 0.007) \delta_{\text{calcd}}^{13\text{C}} + (10.7 \pm 1.2) \quad (4)$$

$$\delta_{\text{obs}}^{13\text{C}} = (0.81 \pm 0.2) \delta_{\text{calcd}}^{13\text{C}} + (19.9 \pm 3.6) \quad (5)$$

### $^{19}\text{F}$ NMR

The  $^{19}\text{F}$  signals of the fluorine atoms were observed in the range typical of fluorinated arenes (−100.1 to −168.1 ppm). Comparison with the data published for various fluorobenzenes<sup>[46]</sup> permits determination of the effect of boronyl substituent on  $^{19}\text{F}$  NMR chemical shift in substituted fluorobenzenes. These values are  $\sigma_{\text{ortho}} = 7.0 \pm 1.1$ ,  $\sigma_{\text{meta}} = -1.4 \pm 0.5$ , and  $\sigma_{\text{para}} = 1.4 \pm 1.5$ .

The  $^3J_{\text{FF}}$  coupling constants vary in the range from −19.5 to −22.5 Hz. The boronyl group in the *ortho* position to FCCF unit (series of 2,3-fluorosubstituted derivatives) causes an increase in the absolute value of the  $^3J_{\text{FF}}$  by 0.8–2.0 Hz (in comparison with the value for the corresponding fluorobenzene). This is the effect of the overlapping of the  $p_z$  orbitals of boron atom with delocalized  $\pi$ -electron system of benzene ring, resulting in an increase in electron density between C<sup>2</sup> and C<sup>3</sup> carbon atoms. For the *meta* position, these effects are smaller, between −0.25 and 0.45 Hz. The  $^4J_{\text{FF}}$  values are smaller (2.2–10.0 Hz). The effect of the boronyl substituent is the highest for compounds with 1,2,4 substitution mode (e.g., **11** or **17**). For these compounds, the presence of B(OH)<sub>2</sub> group increases the value  $^4J_{\text{FF}}$  by ca. 1.0–2.9 Hz (comparing to that for unsubstituted fluorobenzenes). The other derivatives show a smaller increase in  $^4J_{\text{FF}}$  coupling constant values (e.g., 0.2 Hz for **15**) or even its decrease (e.g., of −1.5 Hz for **8**). The *para* F–F coupling ( $^5J_{\text{FF}}$ ) has a value of 10.0–20.2 Hz. For all compounds studied, the  $^5J_{\text{FF}}$  values are by 0.6–2.6 Hz higher than for the parent fluorobenzenes.

Neither of compounds studied show the inter space coupling with −OH hydrogen atoms. Also, the couplings with  $^{10}\text{B}$  or  $^{11}\text{B}$  nuclei are not observed. Surprisingly, distinct  $^{10/11}\text{B}$  isotope effect

**Table 2.**  $^{19}\text{F}$  NMR chemical shifts and coupling constants for studied arylboronic acids in  $[\text{D}_6]\text{acetone}$  (298 K)

Compound	Chemical shifts (ppm) and coupling constants (Hz)				
	F-2	F-3	F-4	F-5	F-6
<b>1</b>	—	—	—	—	—
<b>2</b>	−105.99; dddd $^3J_{\text{F}_2\text{H}_3} = 9.9$ $^4J_{\text{F}_2\text{H}_4} = 7.4$ $^4J_{\text{F}_2\text{H}_6} = 6.4$ $^5J_{\text{F}_2\text{H}_5} = 1.8$	—	—	—	—
<b>3</b>	—	−115.01; dddd $^3J_{\text{F}_3\text{H}_2} = 9.9$ $^3J_{\text{F}_3\text{H}_4} = 8.8$ $^4J_{\text{F}_3\text{H}_5} = 5.6$ $^5J_{\text{F}_3\text{H}_6} = 0.8$	—	—	—
<b>4</b>	—	—	−111.07; m <sup>a</sup> $^3J_{\text{F}_4\text{H}_3} = ^3J_{\text{F}_4\text{H}_5} = 9.3$ $^4J_{\text{F}_4\text{H}_2} = ^4J_{\text{F}_4\text{H}_6} = 6.3$	—	—
<b>5</b>	−132.59; dddd $^3J_{\text{F}_2\text{F}_3} = 21.6$ $^4J_{\text{F}_2\text{H}_4} = 8.1$ $^4J_{\text{F}_2\text{H}_6} = 5.0$ $^5J_{\text{F}_2\text{H}_5} = 1.1$	−140.54; ddd $^3J_{\text{F}_2\text{F}_3} = 21.6$ $^3J_{\text{F}_3\text{H}_4} = 10.9$ $^4J_{\text{F}_3\text{H}_5} = 4.3$	—	—	—
<b>6</b>	−101.7; ddd $^3J_{\text{F}_2\text{H}_3} = 9.8$ $^4J_{\text{F}_2\text{H}_6} = 7.6$ $^4J_{\text{F}_2\text{F}_4} = 6.5$	—	−107.7; dddd $^3J_{\text{F}_4\text{H}_3} = 9.8$ $^3J_{\text{F}_4\text{H}_5} = 8.4$ $^4J_{\text{F}_4\text{H}_6} = 7.6$ $^4J_{\text{F}_2\text{F}_4} = 6.5$	—	—
<b>7</b>	−112.2; dddd $^5J_{\text{F}_2\text{F}_5} = 20.2$ $^3J_{\text{F}_2\text{H}_3} = 8.8$ $^4J_{\text{F}_2\text{H}_4} = 5.0$ $^4J_{\text{F}_2\text{H}_6} = 4.3$	—	—	−120.8; dddd $^5J_{\text{F}_2\text{F}_5} = 20.2$ $^3J_{\text{F}_5\text{H}_4} = 8.8$ $^3J_{\text{F}_5\text{H}_6} = 8.2$ $^4J_{\text{F}_5\text{H}_3} = 4.0$	—
<b>8</b>	−103.10; m <sup>a</sup> $^3J_{\text{F}_2\text{H}_3} = 9.0$ $^4J_{\text{F}_2\text{H}_4} = 6.9$ $^4J_{\text{F}_2\text{F}_6} = 5.0$ $^5J_{\text{F}_2\text{H}_5} = -0.4$	—	—	—	−103.1; m <sup>1</sup> $^3J_{\text{F}_6\text{H}_5} = 9.0$ $^4J_{\text{F}_6\text{H}_4} = 6.9$ $^4J_{\text{F}_2\text{F}_6} = 5.0$ $^5J_{\text{F}_6\text{H}_3} = -0.4$
<b>9</b>	—	−140.90; ddd $^3J_{\text{F}_3\text{F}_4} = 20.2$ $^3J_{\text{F}_3\text{H}_2} = 8.6$ $^4J_{\text{F}_3\text{H}_5} = 8.1$	−137.00; dddd $^3J_{\text{F}_3\text{F}_4} = 20.2$ $^3J_{\text{F}_4\text{H}_5} = 11.0$ $^4J_{\text{F}_4\text{H}_6} = 6.7$ $^4J_{\text{F}_4\text{H}_2} = 5.5$	—	—
<b>10</b>	—	−111.59; m <sup>a</sup> $^3J_{\text{F}_3\text{H}_4} = 9.3$ $^3J_{\text{F}_3\text{H}_2} = 9.0$ $^4J_{\text{F}_3\text{F}_5} = 5.4$ $^5J_{\text{F}_3\text{H}_6} = -0.5$	—	−111.59; m <sup>a</sup> $^3J_{\text{F}_5\text{H}_4} = 9.3$ $^3J_{\text{F}_5\text{H}_6} = 9.0$ $^4J_{\text{F}_3\text{F}_5} = 5.4$ $^5J_{\text{F}_5\text{H}_2} = -0.5$	—
<b>11</b>	−128.23; dddd $^3J_{\text{F}_2\text{F}_3} = 20.7$ $^4J_{\text{F}_2\text{F}_4} = 9.0$ $^4J_{\text{F}_2\text{H}_6} = 6.4$ $^5J_{\text{F}_2\text{H}_5} = 1.9$	−164.19; dddd $^3J_{\text{F}_2\text{F}_3} = 20.7$ $^3J_{\text{F}_3\text{F}_4} = 20.2$ $^4J_{\text{F}_3\text{H}_5} = 6.7$ $^5J_{\text{F}_2\text{H}_6} = 2.5$	−133.59; dddd $^3J_{\text{F}_3\text{F}_4} = 20.2$ $^3J_{\text{F}_4\text{H}_5} = 10.2$ $^4J_{\text{F}_2\text{F}_4} = 9.0$ $^4J_{\text{F}_4\text{H}_6} = 6.4$	—	—
<b>12</b>	−138.01; dddd $^2J_{\text{F}_2\text{F}_3} = 21.4$ $^5J_{\text{F}_2\text{F}_5} = 17.4$ $^4J_{\text{F}_2\text{H}_4} = 6.3$ $^4J_{\text{F}_2\text{H}_6} = 3.2$	−136.10; dddd $^2J_{\text{F}_2\text{F}_3} = 21.4$ $^3J_{\text{F}_3\text{H}_4} = 10.6$ $^4J_{\text{F}_3\text{F}_5} = 3.4$ $^5J_{\text{F}_3\text{H}_6} = 2.0$	—	−117.60; dtd $^5J_{\text{F}_2\text{F}_5} = 17.4$ $^3J_{\text{F}_5\text{H}_4} = ^3J_{\text{F}_5\text{H}_6} = 8.3$ $^4J_{\text{F}_3\text{F}_5} = 3.4$	—
<b>13</b>	−127.99; dddd	−144.95; dddd	—	—	−108.49; dddd

(Continues)



Table 2. (Continued)

Compound	Chemical shifts (ppm) and coupling constants (Hz)				
	F-2	F-3	F-4	F-5	F-6
14	$^3J_{F_2F_3} = 22.2$	$^3J_{F_2F_3} = 22.2$			$^5J_{F_3F_6} = 16.6$
	$^4J_{F_2H_4} = 9.1$	$^5J_{F_3F_6} = 16.6$			$^3J_{F_6H_5} = 7.6$
	$^4J_{F_2F_6} = 2.8$	$^3J_{F_3H_4} = 10.2$			$^4J_{F_6H_4} = 5.2$
	$^5J_{F_2H_5} = 1.9$	$^4J_{F_3H_5} = 3.2$			$^4J_{F_2F_6} = 2.8$
	−106.71; dddd	—	−131.75; dddd	−145.17; dddd	—
15	$^5J_{F_2F_5} = 15.2$		$^3J_{F_4F_5} = 21.6$	$^3J_{F_4F_5} = 21.6$	
	$^4J_{F_2H_6} = 10.1$		$^3J_{F_4H_3} = 10.9$	$^5J_{F_2F_5} = 15.2$	
	$^4J_{F_2F_4} = 7.3$		$^4J_{F_4H_6} = 5.5$	$^3J_{F_5H_6} = 10.9$	
	$^3J_{F_2H_3} = 8.8$		$^4J_{F_2F_4} = 7.3$	$^4J_{F_5H_3} = 6.3$	
	−100.13; m <sup>a</sup>	—	−107.85; m <sup>a</sup>	—	−100.13; m <sup>a</sup>
16	$^3J_{F_2H_3} = 9.3$		$^3J_{F_4H_3} = ^3J_{F_4H_5} = 8.9$		$^3J_{F_6H_5} = 9.3$
	$^4J_{F_2F_4} = 8.0$		$^4J_{F_2F_4} = ^4J_{F_4F_6} = 8.0$		$^4J_{F_6F_4} = 8.0$
	$^4J_{F_2F_6} = 6.0$				$^4J_{F_2F_6} = 6.0$
	$^5J_{F_2H_5} = -0.7$				$^5J_{F_6H_3} = -0.7$
	—	−136.99; m <sup>a</sup>	−160.05; m <sup>a</sup>	−136.99; m <sup>a</sup>	—
17		$^3J_{F_3F_4} = 19.5$	$^3J_{F_3F_4} = ^3J_{F_4F_5} = 19.5$	$^3J_{F_4F_5} = 19.5$	
		$^3J_{F_3H_2} = 8.6$	$^4J_{F_4H_2} = ^4J_{F_4H_6} = 7.7$	$^3J_{F_5H_6} = 8.6$	
		$^4J_{F_3F_5} = 6.4$		$^4J_{F_3F_5} = 6.4$	
		$^5J_{F_3H_6} = -0.7$		$^5J_{F_5H_2} = -0.7$	
	−131.99; dddd	−158.05; dddd	−154.72; dddd	−140.94; dddd	—
18	$^3J_{F_2F_3} = 21.7$	$^3J_{F_2F_3} = 21.7$	$^3J_{F_4F_5} = 20.2$	$^3J_{F_4F_5} = 20.2$	
	$^5J_{F_2F_5} = 15.0$	$^3J_{F_3F_4} = 19.0$	$^3J_{F_3F_4} = 19.0$	$^5J_{F_2F_5} = 15.0$	
	$^4J_{F_2F_4} = 5.3$	$^5J_{F_3H_6} = 2.7$	$^4J_{F_4H_6} = 8.8$	$^3J_{F_5H_6} = 10.6$	
	$^4J_{F_2H_6} = 4.7$	$^4J_{F_3F_5} = 2.1$	$^4J_{F_2F_4} = 5.3$	$^4J_{F_3F_5} = 2.1$	
	−126.04; ddd	−168.07; dddd	−132.55; dddd	—	−105.98; ddd
19	$^3J_{F_2F_3} = 21.7$	$^3J_{F_2F_3} = 21.7$	$^3J_{F_3F_4} = 20.2$		$^5J_{F_3F_6} = 11.5$
	$^4J_{F_2F_4} = 6.9$	$^3J_{F_3F_4} = 20.2$	$^3J_{F_4H_5} = 10.8$		$^3J_{F_6H_5} = 8.2$
	$^4J_{F_2F_6} = 2.4$	$^5J_{F_3F_6} = 11.5$	$^4J_{F_2F_4} = 6.9$		$^4J_{F_4F_6} = 3.8$
		$^4J_{F_3H_5} = 5.4$	$^4J_{F_4F_6} = 3.8$		
	−133.60; m <sup>a</sup>	−140.24; m <sup>a</sup>	—	−140.24; m <sup>a</sup>	−133.60; m <sup>a</sup>
20	$^3J_{F_2F_3} = -22.5$	$^3J_{F_2F_3} = -22.5$		$^3J_{F_5F_6} = -22.5$	$^3J_{F_5F_6} = -22.5$
	$^5J_{F_2F_5} = 14.8$	$^5J_{F_3F_6} = 14.8$		$^5J_{F_2F_5} = 14.8$	$^5J_{F_3F_6} = 14.8$
	$^4J_{F_2H_4} = 7.6$	$^3J_{F_3H_4} = 10.1$		$^3J_{F_5H_4} = 10.1$	$^4J_{F_6H_4} = 7.6$
	$^4J_{F_2F_6} = -1.4$	$^4J_{F_3F_5} = -2.1$		$^4J_{F_3F_5} = -2.1$	$^4J_{F_2F_6} = -1.4$
	−132.53; m <sup>a</sup>	−163.38; m <sup>a</sup>	−154.65; m <sup>a</sup>	−163.38; m <sup>a</sup>	−132.53; m <sup>a</sup>
20	$^3J_{F_2F_3} = -21.6$	$^3J_{F_2F_3} = -21.6$	$^3J_{F_3F_4} = ^3J_{F_4F_5} = -19.7$	$^3J_{F_5F_6} = -21.6$	$^3J_{F_5F_6} = -21.6$
	$^5J_{F_2F_5} = 10.0$	$^3J_{F_3F_4} = -19.7$	$^4J_{F_2F_4} = ^4J_{F_4F_6} = -2.0$	$^3J_{F_4F_5} = -19.7$	$^5J_{F_3F_6} = 10.0$
	$^4J_{F_2F_4} = -2.0$	$^5J_{F_3F_6} = 10.0$		$^5J_{F_2F_5} = 10.0$	$^4J_{F_4F_6} = -2.0$
	$^4J_{F_2F_6} = 1.4$	$^4J_{F_3F_5} = -1.2$		$^4J_{F_3F_5} = -1.2$	$^4J_{F_2F_6} = 1.4$

<sup>a</sup>AA'MM'X spin system.

is detected for compounds containing fluorine atom at *ortho* position. The values of  $\Delta(^{10}\text{B}/^{11}\text{B})$  are 2.4–2.8 Hz (Fig. 4).

The calculation using DFT method reproduces the experimental shifts quite well (Eqn (6);  $R^2 = 0.91$ ).

$$\delta_{\text{obs}}^{19\text{F}} = (1.05 \pm 0.05) \delta_{\text{calc}}^{19\text{F}} + (25.7 \pm 7.9) \quad (6)$$

## <sup>11</sup>B NMR

The <sup>11</sup>B NMR chemical shifts range for the compounds studied is rather narrow (27.40–29.46 ppm). As shown earlier, the <sup>11</sup>B NMR signal of substituted phenylboronic acids is quite insensitive to the substituent character. The reported chemical shift range for

the series of *para* substituted derivatives is only 7.0 ppm.<sup>[47]</sup> A general tendency is that the shielding of the boron nucleus increases with increasing number of fluorine substituents in aryl ring. The changes observed are 0.2–0.6 ppm for each fluorine atom. This effect decreases with increasing the number of –F groups in the molecule, i.e. it is 0.4–0.6 ppm for the first F atom (e.g., **2** vs **1** or **4** vs **1**) but only 0.2–0.4 ppm for the fourth or fifth fluorine substituent (e.g., **20** vs **17** or **18** vs **13**). The NBO analysis shows that the increasing number of fluorine atoms bonded to phenyl ring results in a growing occupancy of the  $\sigma_{\text{B-C}}$  antibond and  $p_z$  boron atom orbital, causing the deshielding of B nucleus.

The <sup>11</sup>B NMR chemical shift of the boronyl group in the compounds studied is only slightly affected by the sample

**Table 3.**  $^{13}\text{C}$  NMR chemical shifts and coupling constants for studied arylboronic acids in  $[\text{D}_6]\text{H}_2\text{O}$ -acetone (298 K)

Compound	Chemical shifts (ppm) and coupling constants (Hz)					
	C-1	C-2	C-3	C-4	C-5	C-6
1	134.5	134.85	128.22	131.02	128.22	134.85
2	~122	168.19; d $^1J_{\text{C}_2\text{F}_2} = -244.2$	115.94; d $^2J_{\text{C}_3\text{F}_2} = 24.9$	133.60; d $^3J_{\text{C}_4\text{F}_2} = 9.0$	125.04; d $^4J_{\text{C}_5\text{F}_2} = 3.1$	137.40; d $^3J_{\text{C}_6\text{F}_2} = 8.7$
3	137.1	121.18; d $^2J_{\text{C}_2\text{F}_3} = 18.9$	163.82; d $^1J_{\text{C}_3\text{F}_3} = -243.7$	118.13; d $^2J_{\text{C}_4\text{F}_3} = 21.2$	130.71; d $^3J_{\text{C}_5\text{F}_3} = 7.2$	131.10; d $^4J_{\text{C}_6\text{F}_3} = 2.8$
4	130.1	137.70; d $^3J_{\text{C}_2\text{F}_4} = 8.1$	115.47; d $^2J_{\text{C}_3\text{F}_4} = 20.1$	165.75; d $^1J_{\text{C}_4\text{F}_4} = -246.4$	115.47; d $^2J_{\text{C}_5\text{F}_4} = 20.1$	137.70; d $^3J_{\text{C}_6\text{F}_4} = 8.1$
5	~124	154.96; dd $^1J_{\text{C}_2\text{F}_2} = 246.3$ $^2J_{\text{C}_2\text{F}_3} = 11.4$	151.33; dd $^1J_{\text{C}_3\text{F}_3} = -246.2$ $^2J_{\text{C}_3\text{F}_2} = 15.2$	120.12; d $^2J_{\text{C}_4\text{F}_3} = 17.1$ $^3J_{\text{C}_4\text{F}_2} = 1.0$	125.70; dd $^3J_{\text{C}_5\text{F}_3} = 5.6$ $^4J_{\text{C}_5\text{F}_2} = 4.4$	131.80; dd $^3J_{\text{C}_6\text{F}_2} = 7.4$ $^4J_{\text{C}_6\text{F}_3} = 3.9$
6	117.3	168.68; dd $^1J_{\text{C}_2\text{F}_2} = -247.7$ $^3J_{\text{C}_2\text{F}_4} = 12.1$	104.25; dd $^2J_{\text{C}_3\text{F}_2} = 29.5$ $^2J_{\text{C}_3\text{F}_4} = 24.5$	165.98; dd $^1J_{\text{C}_4\text{F}_4} = -249.6$ $^3J_{\text{C}_4\text{F}_2} = 13.0$	112.24; dd $^2J_{\text{C}_5\text{F}_4} = 20.2$ $^4J_{\text{C}_5\text{F}_2} = 3.4$	139.02; t $^3J_{\text{C}_6\text{F}_2} = ^3J_{\text{C}_6\text{F}_4} = 10.4$
7	~123	163.92; d $^1J_{\text{C}_2\text{F}_2} = -240.6$	117.69; dd $^2J_{\text{C}_3\text{F}_2} = 28.5$ $^3J_{\text{C}_3\text{F}_5} = 8.0$	119.86; dd $^2J_{\text{C}_4\text{F}_5} = 24.5$ $^3J_{\text{C}_4\text{F}_2} = 9.6$	159.84; dd $^1J_{\text{C}_5\text{F}_5} = -239.6$ $^4J_{\text{C}_5\text{F}_2} = 1.6$	122.48; dd $^2J_{\text{C}_6\text{F}_5} = 22.4$ $^3J_{\text{C}_6\text{F}_2} = 9.6$
8	~110	166.25; m <sup>a</sup> $^1J_{\text{C}_2\text{F}_2} = -243.6$ $^3J_{\text{C}_2\text{F}_6} = 14.8$	111.90; m <sup>a</sup> $^2J_{\text{C}_3\text{F}_2} = 23.0$ $^4J_{\text{C}_3\text{F}_6} = 3.4$	132.88; m <sup>a</sup> $^3J_{\text{C}_4\text{F}_2} = ^3J_{\text{C}_4\text{F}_6} = 10.4$	111.90; m <sup>a</sup> $^2J_{\text{C}_5\text{F}_6} = 23.0$ $^4J_{\text{C}_5\text{F}_2} = 3.4$	166.25; m <sup>a</sup> $^1J_{\text{C}_6\text{F}_6} = -243.6$ $^3J_{\text{C}_6\text{F}_2} = 14.8$
9	132.5	123.63; d $^2J_{\text{C}_2\text{F}_3} = 14.5$	151.09; dd $^1J_{\text{C}_3\text{F}_3} = -245.7$ $^2J_{\text{C}_3\text{F}_4} = 11.9$	152.97; dd $^1J_{\text{C}_4\text{F}_4} = -248.3$ $^2J_{\text{C}_4\text{F}_3} = 12.8$	117.87; d $^2J_{\text{C}_5\text{F}_4} = 16.2$	132.36; dd $^3J_{\text{C}_6\text{F}_4} = 6.7$ $^4J_{\text{C}_6\text{F}_3} = 3.5$
10	139.4	117.28; m <sup>a</sup> $^2J_{\text{C}_2\text{F}_3} = 17.0$ $^4J_{\text{C}_2\text{F}_5} = 5.0$	164.01; m <sup>a</sup> $^1J_{\text{C}_3\text{F}_3} = -247.8$ $^3J_{\text{C}_3\text{F}_5} = 11.3$	106.41; m <sup>a</sup> $^2J_{\text{C}_4\text{F}_3} = ^2J_{\text{C}_4\text{F}_5} = 25.6$	164.01; m <sup>a</sup> $^1J_{\text{C}_5\text{F}_5} = -247.8$ $^3J_{\text{C}_5\text{F}_3} = 11.3$	117.28; m <sup>a</sup> $^2J_{\text{C}_6\text{F}_5} = 17.0$ $^4J_{\text{C}_6\text{F}_3} = 5.0$
11	119.2	156.06; ddd $^1J_{\text{C}_2\text{F}_2} = -248.8$ $^2J_{\text{C}_2\text{F}_3} = 8.6$ $^3J_{\text{C}_2\text{F}_4} = 3.2$	140.54; ddd $^1J_{\text{C}_3\text{F}_3} = -248.8$ $^2J_{\text{C}_3\text{F}_2} = 17.4$ $^2J_{\text{C}_3\text{F}_4} = 14.5$	153.57; ddd $^1J_{\text{C}_4\text{F}_4} = -250.3$ $^2J_{\text{C}_4\text{F}_3} = 9.7$ $^3J_{\text{C}_4\text{F}_2} = 3.5$	115.55; dd $^2J_{\text{C}_5\text{F}_4} = 16.4$ $^3J_{\text{C}_5\text{F}_3} = 3.1$	131.3; td $^3J_{\text{C}_6\text{F}_2} = ^3J_{\text{C}_6\text{F}_4} = 9.0$ $^4J_{\text{C}_6\text{F}_3} = 5.5$
12	125.7	150.77; ddd $^1J_{\text{C}_2\text{F}_2} = -242.4$ $^2J_{\text{C}_2\text{F}_3} = 17.2$ $^4J_{\text{C}_2\text{F}_5} = 3.2$	151.07; ddd $^1J_{\text{C}_3\text{F}_3} = -250.0$ $^2J_{\text{C}_3\text{F}_2} = 17.2$ $^3J_{\text{C}_3\text{F}_5} = 11.9$	107.85; dd $^2J_{\text{C}_4\text{F}_3} = 28.0$ $^2J_{\text{C}_4\text{F}_5} = 21.1$	158.44; ddd $^1J_{\text{C}_5\text{F}_5} = -244.6$ $^3J_{\text{C}_5\text{F}_3} = 8.9$ $^4J_{\text{C}_5\text{F}_2} = 2.0$	116.66; ddd $^2J_{\text{C}_6\text{F}_5} = 22.1$ $^3J_{\text{C}_6\text{F}_2} = 7.7$ $^4J_{\text{C}_6\text{F}_3} = 3.8$
13	114.5	152.63; ddd $^1J_{\text{C}_2\text{F}_2} = -244.5$ $^2J_{\text{C}_2\text{F}_3} = 14.8$ $^3J_{\text{C}_2\text{F}_6} = 13.8$	147.92; ddd $^1J_{\text{C}_3\text{F}_3} = -242.5$ $^2J_{\text{C}_3\text{F}_2} = 14.9$ $^4J_{\text{C}_3\text{F}_6} = 3.6$	119.34; dd $^2J_{\text{C}_4\text{F}_3} = 19.6$ $^3J_{\text{C}_4\text{F}_2} = 10.4$ $^3J_{\text{C}_4\text{F}_6} = 1.2$	112.26; ddd $^2J_{\text{C}_5\text{F}_6} = 27.5$ $^3J_{\text{C}_5\text{F}_3} = 6.1$ $^4J_{\text{C}_5\text{F}_2} = 4.0$	160.92; ddd $^1J_{\text{C}_6\text{F}_6} = -240.3$ $^3J_{\text{C}_6\text{F}_2} = 12.5$ $^4J_{\text{C}_6\text{F}_3} = 2.5$
14	118.7	163.39; ddd $^1J_{\text{C}_2\text{F}_2} = -244.4$ $^3J_{\text{C}_2\text{F}_4} = 9.2$ $^4J_{\text{C}_2\text{F}_5} = 2.1$	105.54; dd $^2J_{\text{C}_3\text{F}_2} = 31.5$ $^2J_{\text{C}_3\text{F}_4} = 20.4$	152.70; dt $^1J_{\text{C}_4\text{F}_4} = -251.5$ $^2J_{\text{C}_4\text{F}_5} = ^3J_{\text{C}_4\text{F}_2} = 14.2$	147.88; ddd $^1J_{\text{C}_5\text{F}_5} = -243.3$ $^2J_{\text{C}_5\text{F}_4} = 11.5$ $^4J_{\text{C}_5\text{F}_2} = 1.8$	124.24; dd $^2J_{\text{C}_6\text{F}_5} = 17.6$ $^3J_{\text{C}_6\text{F}_2} = 11.1$
15	108.5	166.72; m <sup>b</sup> $^1J_{\text{C}_2\text{F}_2} = -245.3$ $^3J_{\text{C}_2\text{F}_4} = 18.0$ $^3J_{\text{C}_2\text{F}_6} = 15.2$	100.91; m <sup>b</sup> $^2J_{\text{C}_3\text{F}_2} = 30.2$ $^2J_{\text{C}_3\text{F}_4} = 24.0$ $^4J_{\text{C}_3\text{F}_6} = 4.1$	165.10; m <sup>b</sup> $^1J_{\text{C}_4\text{F}_4} = -247.7$ $^3J_{\text{C}_4\text{F}_2} = ^3J_{\text{C}_4\text{F}_6} = 16.0$	100.91; m <sup>b</sup> $^2J_{\text{C}_5\text{F}_6} = 30.2$ $^2J_{\text{C}_5\text{F}_4} = 24.0$ $^4J_{\text{C}_5\text{F}_2} = 4.1$	166.72; m <sup>b</sup> $^1J_{\text{C}_6\text{F}_6} = -245.3$ $^3J_{\text{C}_6\text{F}_4} = 18.0$ $^3J_{\text{C}_6\text{F}_2} = 15.2$
16	131.9	118.89; m <sup>b</sup> $^2J_{\text{C}_2\text{F}_3} = 18.4$ $^3J_{\text{C}_2\text{F}_4} = 7.0$ $^4J_{\text{C}_2\text{F}_5} = 1.5$	151.93; m <sup>b</sup> $^1J_{\text{C}_3\text{F}_3} = -248.2$ $^2J_{\text{C}_3\text{F}_4} = 9.4$ $^3J_{\text{C}_3\text{F}_5} = 2.5$	142.09; m <sup>b</sup> $^1J_{\text{C}_4\text{F}_4} = -251.7$ $^2J_{\text{C}_4\text{F}_3} = ^2J_{\text{C}_4\text{F}_5} = 15.4$	151.93; m <sup>b</sup> $^1J_{\text{C}_5\text{F}_5} = -248.2$ $^2J_{\text{C}_5\text{F}_4} = 9.4$ $^3J_{\text{C}_5\text{F}_3} = 2.5$	118.89; m <sup>b</sup> $^2J_{\text{C}_6\text{F}_5} = 18.4$ $^3J_{\text{C}_6\text{F}_4} = 7.0$ $^4J_{\text{C}_6\text{F}_3} = 1.5$
17	118.0	152.00; dddd $^1J_{\text{C}_2\text{F}_2} = -246.3$ $^2J_{\text{C}_2\text{F}_3} = 9.6$ $^3J_{\text{C}_2\text{F}_4} = 3.2$ $^4J_{\text{C}_2\text{F}_5} = 1.9$	141.35; dddd $^1J_{\text{C}_3\text{F}_3} = -251.7$ $^2J_{\text{C}_3\text{F}_2} = 19.7$ $^2J_{\text{C}_3\text{F}_4} = 11.8$ $^3J_{\text{C}_3\text{F}_5} = 3.1$	142.60; dddd $^1J_{\text{C}_4\text{F}_4} = -252.9$ $^2J_{\text{C}_4\text{F}_3} = 16.6$ $^2J_{\text{C}_4\text{F}_5} = 12.4$ $^3J_{\text{C}_4\text{F}_2} = 3.7$	148.01; dddd $^1J_{\text{C}_5\text{F}_5} = -244.3$ $^2J_{\text{C}_5\text{F}_4} = 9.7$ $^3J_{\text{C}_5\text{F}_3} = 3.5$ $^4J_{\text{C}_5\text{F}_2} = 1.3$	117.21; ddd $^2J_{\text{C}_6\text{F}_5} = 17.7$ $^3J_{\text{C}_6\text{F}_2} = 9.1$ $^3J_{\text{C}_6\text{F}_4} = 4.1$
18	109.9	153.96; dddd	137.93; dddd	152.61; dddd	102.2; dddd	160.24; dddd

(Continues)



**Table 3.** (Continued)

Chemical shifts (ppm) and coupling constants (Hz)						
Compound	C-1	C-2	C-3	C-4	C-5	C-6
19	114.8	$^1J_{C2F2} = -245.7$	$^1J_{C3F3} = -246.0$	$^1J_{C4F4} = -249.4$	$^2J_{C5F4} = 31.7$	$^1J_{C6F6} = -242.4$
		$^2J_{C2F3} = 17.9$	$^2J_{C3F4} = 18.2$	$^2J_{C4F3} = 16.3$	$^2J_{C5F6} = 21.4$	$^3J_{C6F4} = 15.9$
		$^3J_{C2F6} = 10.1$	$^2J_{C3F2} = 15.1$	$^3J_{C4F6} = 11.2$	$^3J_{C5F3} = 4.1$	$^3J_{C6F2} = 13.5$
		$^3J_{C2F4} = 5.5$	$^4J_{C3F4} = 6.0$	$^3J_{C4F2} = 5.7$	$^4J_{C5F2} = 1.2$	$^4J_{C6F3} = 3.8$
		148.19; m <sup>c</sup>	146.83; m <sup>c</sup>	105.50; m <sup>c</sup>	146.83; m <sup>c</sup>	148.19; m <sup>c</sup>
		$^1J_{C2F2} = -241.2$	$^1J_{C3F3} = -247.0$	$^2J_{C4F3} = ^2J_{C4F5} = 23.2$	$^1J_{C5F5} = -247.0$	$^1J_{C6F6} = -241.2$
20	109.8	$^2J_{C2F3} = ^3J_{C2F6} = 12.8$	$^2J_{C3F2} = 16.3$	$^3J_{C4F2} = ^3J_{C4F6} = 1.7$	$^2J_{C5F6} = 16.3$	$^2J_{C6F5} = ^3J_{C6F2} = 12.8$
		$^4J_{C2F5} = 3.3$	$^3J_{C3F5} = 8.4$		$^3J_{C5F3} = 8.4$	$^4J_{C6F3} = 3.3$
			$^4J_{C3F6} = 3.0$		$^4J_{C5F2} = 3.0$	
		148.69; m <sup>d</sup>	138.22; m <sup>d</sup>	142.73; m <sup>d</sup>	138.22; m <sup>d</sup>	148.69; m <sup>d</sup>
		$^1J_{C2F2} = -242.5$	$^1J_{C3F3} = -249.1$	$^1J_{C4F4} = -251.4$	$^1J_{C5F5} = -249.1$	$^1J_{C6F6} = -242.5$
		$^2J_{C2F3} = 15.3$	$^2J_{C3F2} = 19.4$	$^2J_{C4F3} = ^2J_{C4F5} = 13.5$	$^2J_{C5F6} = 19.4$	$^2J_{C6F5} = 15.3$
	$^3J_{C2F6} = 10.3$	$^2J_{C3F4} = 12.7$	$^3J_{C4F2} = ^3J_{C4F6} = 5.6$	$^2J_{C5F4} = 12.7$	$^3J_{C6F2} = 10.3$	
	$^3J_{C2F4} = ^4J_{C2F5} = 4.2$	$^3J_{C3F5} = 5.4$		$^3J_{C5F3} = 5.4$	$^3J_{C6F4} = ^4J_{C6F3} = 4.2$	
<sup>a</sup> AXX' spin system.						
<sup>b</sup> AXX'Y spin system.						
<sup>c</sup> AXX'YY' spin system.						
<sup>d</sup> AMM'XX'Y spin system.						

**Table 4.**  $^{11}\text{B}$  and  $^{17}\text{O}$  NMR chemical shifts and line widths for studied arylboronic acids in  $[\text{D}_6]\text{acetone}$  (298 K)

Compound	Chemical shift (ppm) and line widths (Hz)			
	$^{11}\text{B}$	$^{17}\text{O}$		
<b>1</b>	29.46	95	76.3	140
<b>2</b>	28.86	120	82.0	220
<b>3</b>	28.84	130	77.3	145
<b>4</b>	29.06	100	74.6	155
<b>5</b>	28.40	110	83.2	210
<b>6</b>	28.46	120	80.9	230
<b>7</b>	28.30	115	83.2	230
<b>8</b>	28.46	105	91.9	300
<b>9</b>	28.46	100	76.1	150
<b>10</b>	28.21	110	78.4	145
<b>11</b>	28.00	110	82.2	225
<b>12</b>	27.96	100	84.3	240
<b>13</b>	28.02	120	92.7	305
<b>14</b>	27.84	120	82.1	230
<b>15</b>	27.98	110	90.8	315
<b>16</b>	27.95	100	76.7	160
<b>17</b>	27.58	120	82.7	240
<b>18</b>	27.63	120	91.4	320
<b>19</b>	27.64	115	93.5	290
<b>20</b>	27.40	105	92.1	295

concentration. The experiments were made for the derivatives of the highest solubility in acetone, that is, **2**, **6**, **16**, and **17**; however, the changes less than 0.1 ppm were observed upon changing the concentration in the range 0.01–0.5 M. The possibility of the homodimer formation is strongly limited in acetone solution, because of the hydrogen bonding between BO–H atom of the solute and O=C of the solvent. Unfortunately, very low solubility of the fluorinated phenylboronic acids in chloroform as well as in

other weakly interacting solvents does not permit studies of dimerisation of the compounds studied.

The obtained experimental results correlate well with the calculated values (Eqn (7);  $R^2 > 0.91$ ). Better accuracy is observed for the compounds with a smaller number of fluorine substituents.

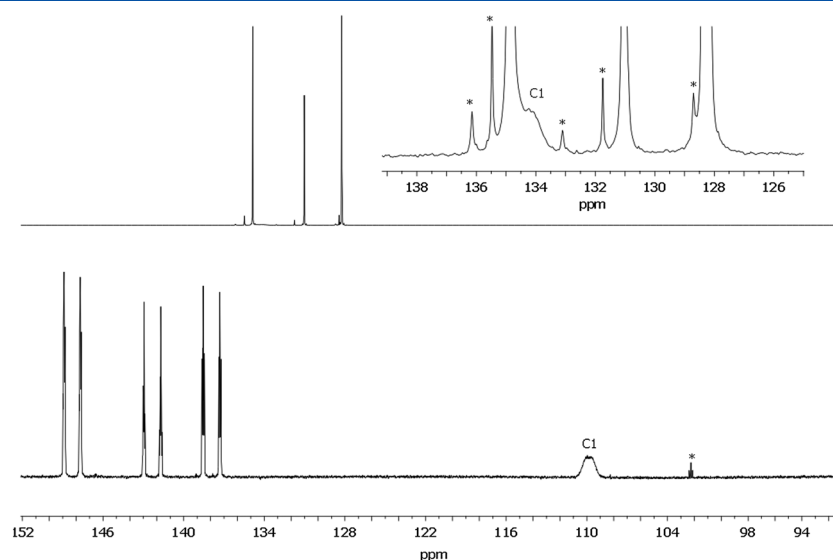
$$\delta_{\text{obs}}^{11\text{B}} = (1.02 \pm 0.07) \delta_{\text{calcd}}^{11\text{B}} + (13.2 \pm 1.1) \quad (7)$$

The  $^{11}\text{B}$  NMR chemical shifts of the compounds studied were measured against  $\text{BF}_3 \cdot (\text{C}_2\text{H}_5)_2\text{O}$ , while the calculated values were referenced to gaseous  $\text{BF}_3$ . As the boron nucleus in  $\text{BF}_3$  etherate is about 12.91 ppm more shielded than in the isolated  $\text{BF}_3$  molecules,<sup>[48]</sup> the calculated chemical shifts may be converted to the  $\text{BF}_3 \cdot (\text{C}_2\text{H}_5)_2\text{O}$  scale. This reduces the intercept in Eqn (7) to 0.3 ppm.

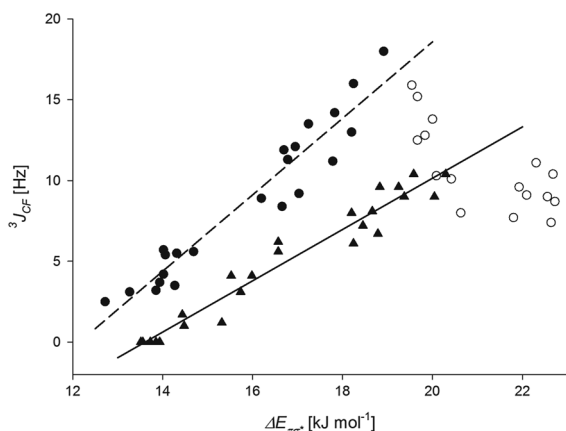
No scalar couplings were observed for  $^{11}\text{B}$  signal of studied series of boronic acids. The signal half-width ( $\Delta\nu_{1/2}$ ) of  $^{11}\text{B}$  NMR is similar (100–120 Hz) and does not decrease upon  $^1\text{H}$  or  $^{19}\text{F}$  decoupling.

### $^{17}\text{O}$ NMR

The  $^{17}\text{O}$  chemical shift values vary from 74.6 (**4**) to 93.5 ppm (**19**), while for unsubstituted phenylboronic acid, it is 76.3 ppm. Analysis of the influence of fluorine atom substituted to the phenyl ring on the chemical shift shows that the inductive effects play a minor role. The substitution in *para* position results in shielding of the oxygen atom by 1.1 (e.g., **6** vs **2** or **15** vs **8**) to 1.7 ppm (**4** vs **1** or **16** vs **10**). Also, the exchange of the *meta* hydrogen atom to fluorine causes small shifts, i.e. the deshielding by 0.5 (**17** vs **11**) to 1.5 ppm (**9** vs **4**). The effects of *ortho* substitution are much greater. One fluorine atom in this position increases the chemical shift by 5.7 (**2** vs **1**) to 6.3 ppm (**6** vs **4**) in comparison with hydrogen analog. The second F-substituent in *ortho* position results in a further deshielding by 9.2 (**18** vs **11** or **19** vs **12**) to 9.9 ppm (**8** vs **2** or **15** vs **6**). As follows from our results for monosubstituted arylboronic acids<sup>[36]</sup> and literature data for substituted aromatic compounds,<sup>[49]</sup> the chemical shift of oxygen atom is highly



**Figure 2.**  $^{13}\text{C}$  NMR spectra of **1** (top; insert  $\times 25$ ) and **20** (bottom); impurities and satellite lines marked with an asterisks.



**Figure 3.** Correlation between  $^3J_{\text{CF}}$  and the natural bond orbital second-order perturbation interaction by Fock matrix  $\pi_{\text{C}} = \text{C} \rightarrow \sigma_{\text{CF}}^* (\Delta E_{\pi\sigma^*})$ ;  $\blacktriangle$  – hydrogen-substituted carbon atoms,  $\bullet$  – fluorine-substituted carbon atoms,  $\circ$  – C2/F6 and C6/F2 pairs, (-----) – linear regression (Eqn (2)), and (—) – linear regression (Eqn (3)).

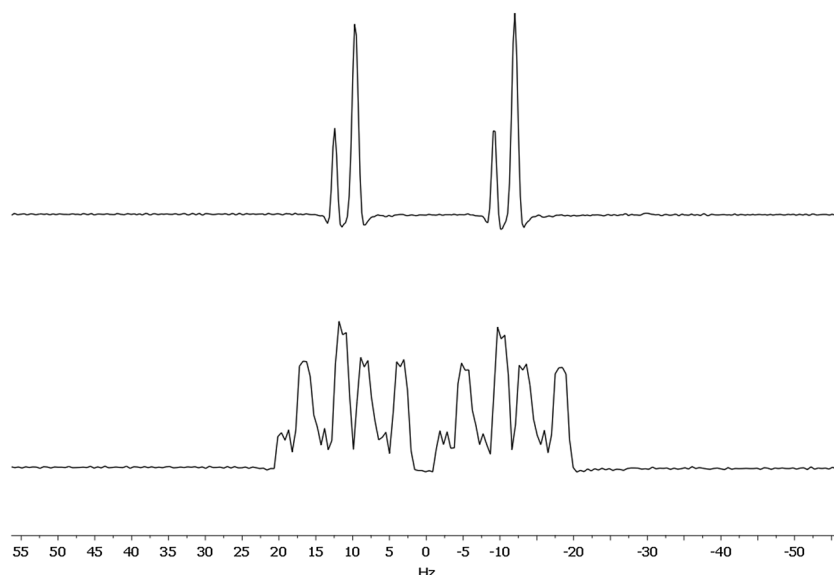
sensitive to steric interactions. The expected inductive effects in *ortho* and *para* substituted molecules are similar (*vide* substituent effects in benzenes, which are  $-0.29$  and  $-0.23$  ppm for 2-fluorobenzene and 4-fluorobenzene, respectively). In consequence, the exchange of the hydrogen *ortho* atom to fluorine should result in a small shielding of oxygen nucleus of arylboronic acid. The opposite effects observed are a result of two different mechanisms. The first is that the steric interactions between F-substituent and boronyl group result in changing in the C–C–B–O torsion angle. As the oxygen atom chemical shift is highly dependent on this parameter, the *ortho* substituent influences strongly  $\delta(^{17}\text{O})$  values. The sterically forced rotation around the C–B bond, resulting in non-planar conformation of the molecule, produces strong deshielding of the oxygen atom. The second possible mechanism is related to the formation of intramolecular hydrogen bonds between BOH hydrogen and fluorine atom. The deshielding of 3–5 ppm was reported for donor oxygen atoms of boronyl group, due to intramolecular  $\text{O–H}\cdots\text{O}$ .<sup>[36]</sup>

The  $^{17}\text{O}$  NMR signal of the compounds studied shows the  $^1J_{\text{OH}}$  coupling. The signal splitting due to this interaction is 65–67 Hz and is poorly visible due to large line widths. The signal  $\Delta\nu_{1/2}$  depends strongly on the compounds structure. For arylboronic acids without –F substituent at *ortho* position, the  $\Delta\nu_{1/2}$  values are 140–170 Hz. They reduce to *ca.* 100 Hz upon broadband  $^1\text{H}$  decoupling. The selective  $^1\text{H}$  decoupling (H-2/6 irradiation) of **4**, **10**, and **16** does not influence the  $\Delta\nu_{1/2}$  of the  $^{17}\text{O}$  signal. The signals of the compounds containing one –F group at *ortho* position are broader ( $\Delta\nu_{1/2} \sim 210$ –240 Hz), while those of the derivatives containing fluorine at both *ortho* positions  $\Delta\nu_{1/2}$  reach 290–320 Hz. These values reduce to 160–180 Hz on broadband  $^{19}\text{F}$  decoupling. This indicates a scalar coupling between  $^{19}\text{F}$  and  $^{17}\text{O}$  nuclei. For some compounds (e.g., **15** or **19**), apodisation of the  $^{17}\text{O}$  signal gives a doublet of triplets with  $^4J_{\text{OF}} \sim 25$  Hz. The  $^{19}\text{F}$  selective decoupling with resonance frequencies of *meta* or *para* fluorine substituents does not influence the oxygen-17 signal width.

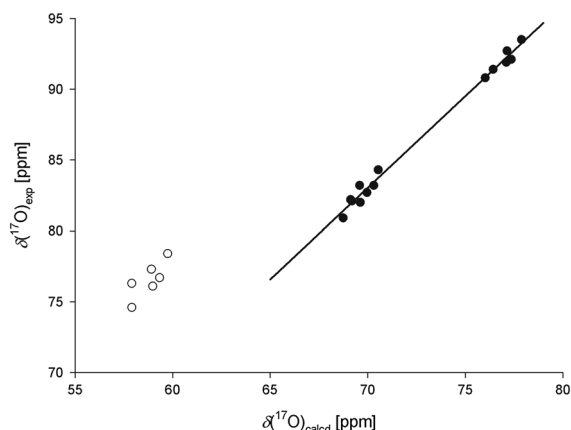
A comparison of the experimental results with calculated ones clearly shows two sets of points (Fig. 5). The first corresponds to the compounds without fluorine substituent at *ortho* position (**1**, **3**, **4**, **9**, **10**, and **16**) while the second ones to all other compounds. For the second set, an excellent correlation between measured and computed chemical shifts is found (Eqn (8);  $R^2 > 0.99$ ), while those from the first one do not show the correlation. Moreover, the latter points lie outside the regression line.

$$\delta_{\text{obs}}^{17\text{O}} = (1.29 \pm 0.03) \delta_{\text{calcd}}^{17\text{O}} - (7.5 \pm 2.2) \quad (8)$$

This may be a result of two cooperative mechanisms. According to the first, the *ortho* fluorine-substituted phenylboronic acids form an intramolecular hydrogen bond. It is in agreement with the results of X-ray measurements.<sup>[50]</sup> This interaction is taken into account in DFT calculations. This  $\text{O–H}\cdots\text{F}$  interaction limits the possibility of formation of intermolecular bonds, e.g. with solvent, water, or second solute molecule. The compounds from the first set form such intermolecular bonds that influence the experimental value of the  $\delta(^{17}\text{O})$ , but they are not taken into consideration in DFT calculations. Moreover, the presence of the –F group at *ortho* position stabilizes the conformation of the molecule. The tendency to formation of planar



**Figure 4.** Boron atom isotopic effect on  $F^2$  signal of **5**,  $^{19}\text{F}$  (bottom) and  $^{19}\text{F}\{^1\text{H}\}$  (top) spectra.



**Figure 5.** Correlation between DFT calculated and experimental values of  $^{17}\text{O}$  NMR chemical shifts for fluorinated phenylboronic acids: ● – compounds with –F substituent in *ortho* position, ○ – compounds without –F substituent in *ortho* position, and (—) – linear regression (Eqn (8)).

structure is forced by  $\pi$ - $p_z(\text{B})$  interactions and intramolecular hydrogen bonds formed but opposed by steric interactions between *ortho* substituent and boronyl group. These opposite forces stiffen the molecule. The rotation around the C–B bond in the molecules of acids belonging the first set is much easier. Dynamic phenomena were not taken into consideration during calculations.

## Conclusion

- Results of the systematic NMR studies of fluorinated phenylboronic acids have revealed a close correlation between their spectroscopic properties and their structure.
- The  $^1\text{H}$  and  $^{13}\text{C}$  NMR chemical shifts of aromatic protons and C–H/C–F carbon atoms are well reproduced by DFT calculations, contrary to the values for BOH protons and C–B atoms.
- The DFT calculations well-reproduce  $^{19}\text{F}$  NMR chemical shifts. The first examples of  $^{10}\text{B}/^{11}\text{B}$  isotopic effect on the  $^{19}\text{F}$  spectra and  $^4J_{\text{FO}}$  scalar coupling in organic compounds are reported.

- $^{17}\text{O}$  chemical shifts are mainly affected by the steric interaction with the fluorine atoms and by the formation of intramolecular hydrogen bonds, while the inductive effect plays a minor role. The effect of the hydrogen bond formation has significant influence on the correlation between experimental and calculated chemical shift values.

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