

9-2013

Structure, Theoretical Studies and Coupling Reactions of Some New Cyclic Boronic Esters

Andrew Kuttler
University of Dayton

Sravanthi Durganala
University of Dayton

Albert Fratini
University of Dayton, afratini1@udayton.edu

Alexander Morgan
University of Dayton

Vladimir Benin
University of Dayton, vbenin1@udayton.edu

Follow this and additional works at: https://ecommons.udayton.edu/chm_fac_pub

 Part of the [Analytical Chemistry Commons](#), [Biochemical Phenomena, Metabolism, and Nutrition Commons](#), [Chemical and Pharmacologic Phenomena Commons](#), [Environmental Chemistry Commons](#), [Inorganic Chemistry Commons](#), [Materials Chemistry Commons](#), [Medical Biochemistry Commons](#), [Medicinal-Pharmaceutical Chemistry Commons](#), [Organic Chemistry Commons](#), [Other Chemistry Commons](#), and the [Physical Chemistry Commons](#)

eCommons Citation

Kuttler, Andrew; Durganala, Sravanthi; Fratini, Albert; Morgan, Alexander; and Benin, Vladimir, "Structure, Theoretical Studies and Coupling Reactions of Some New Cyclic Boronic Esters" (2013). *Chemistry Faculty Publications*. 15.
https://ecommons.udayton.edu/chm_fac_pub/15

This Article is brought to you for free and open access by the Department of Chemistry at eCommons. It has been accepted for inclusion in Chemistry Faculty Publications by an authorized administrator of eCommons. For more information, please contact frice1@udayton.edu, mschlangen1@udayton.edu.

Structure, Theoretical Studies and Coupling Reactions of Some New Cyclic Boronic Esters

Andrew Kuttler^a, Sravanthi Durganala^{b,c}, Albert Fratini^a, Alexander B. Morgan^b and
Vladimir Benin^{a,*}

^a Department of Chemistry, University of Dayton, Dayton, OH 45469-2357

^b Applied Combustion and Energy Group, University of Dayton Research Institute, Dayton, OH 45469-0170

^c Currently at Chemtura/Great Lakes Solutions, West Lafayette, IN 47906

* Corresponding author: vbenin1@udayton.edu

Received

Abstract: The present report describes the X-ray structural and theoretical studies of some new pinacolboronate esters, and it also outlines the use of the target structures in Suzuki coupling reactions to produce new aromatic or heteroaromatic esters and amides. X-ray structural analysis of the studied compounds revealed that the pinacolborane ring's position with respect to the benzene ring varies, depending on the particular environment. An *ortho*-positioned carboxylic ester (methyl ester) causes a nearly perpendicular orientation of the pinacolborane unit, with respect to the benzene ring, while an *ortho*-positioned amide (N,N-dimethylamide) causes the pinacolborane unit to orient itself nearly co-planar. A plausible explanation has been provided, based on both steric and electronic factors.

Keywords: terephthalate, boronate, pinacolborane, X-ray analysis, Suzuki coupling, transition metal catalyst

Introduction

While modern polymeric materials bring many benefits by their use in society, they typically suffer from flammability/fire risk issues, and so they need to be flame retarded to provide fire protection in a variety of fire risk scenarios. When a polymeric material requires a flame retardant to be used/sold in a particular application, one can use a non-reactive flame retardant molecule/polymer, which is blended into the polymer, or one can use a reactive flame retardant molecule, which bonds directly to the polymer during polymerization or *via* side-chain/grafting reactions [1,2]. With concerns about environmental persistence of some flame retardant additives that are not bound to the polymer and may leach out over time [3-8], the use of reactive flame retardants has become more attractive. Further, there is a desire to develop condensed phase (char forming) reactive flame retardants, so more of the polymer fuel can be converted into low-flammability carbon char (graphite/glassy carbon) rather than the polymer mass being pyrolyzed as high heat release decomposition products [1,9]. To that end, we have proposed the synthesis of boron- and phosphorus-functionalized reactive structures, which could co-polymerize with thermoset-type polymers such as epoxy and polyurethane.

Boron has shown some interesting condensed phase flame retardant activity, when available as a boronic acid/boroxine structure [10,11]. We have therefore focused on the preparation of specific targets containing one or two boronic acid or ester groups, using transition metal catalyzed coupling reactions [12]. The outcome of the studies on the flame retardant properties of those structures, both in a stand-alone fashion and incorporated into polyurethane samples, is described elsewhere [12,13]. The current report is focused exclusively on the structural and theoretical analysis of the cyclic boronic ester structures, which were generated as precursors to the corresponding boronic acids. By understanding the chemical

structure of these compounds, we may gain more insight into what boron based flame retardants can be practically made for future use. Cyclic boronic esters, containing the pinacolborane unit, have been the subject of X-ray crystallographic analysis [14-17], NMR-based structural investigation [18] and some limited theoretical studies [19]. Careful analysis of our target structures and the examples available from literature provoked us, however, to conduct further investigation, in an attempt to address the following issues:

- 1) Potential influence of Lewis acid-base interactions at the boron center on the overall geometry.
- 2) Role of the steric factor on the geometry of the target boronic esters.
- 3) Comparison of the studied structures with previously published structural accounts of compounds containing a pinacolborane or similar boronic ester unit.

In order to answer these questions, we have 1) Introduced appropriate chemical modifications, in an attempt to enhance potential Lewis acid – base interactions, and 2) Conducted detailed DFT calculations, in order to determine the inherent steric preferences of the available substituents, and thus rationalize the observed structures.

Results and Discussion

A. Synthesis of boronic esters. All of the target structures were prepared using iodinated aromatic compounds as precursors. Preliminary studies using the corresponding brominated derivatives showed them to be unreactive under the reaction conditions. No attempts were made for direct introduction of the boronate ester functionality *via* C – H bond activation, as described by Hartwig *et al* [20]. The cyclic boronic ester **3** was prepared in good yield from dimethyl iodoterephthalate and pinacolborane, using (dppp)₂NiCl₂ as a catalyst (Scheme 1) [12,21]. The reaction was carried out in the presence of triethylamine or dicyclohexylmethylamine, as a base,

leading to the product in similar yields. Boronate ester **3** was used subsequently as a starting material in a number of Suzuki coupling reactions, leading to the generation of several new, multifunctional aromatic or heteroaromatic structures (*vide infra*).

Scheme 1

The cyclic boronic ester **7**, based on a terephthalamide core, was also prepared using Pd-catalyzed coupling, of the iododiamide **6** (Scheme 2). The latter was prepared in two steps from the iodoester **1**, including alkaline hydrolysis to the diacid **5** [22], followed by conversion, in a single step, to the diamide **6** [23].

Scheme 2

The diboronic ester **10** was prepared using dimethyl 2,5-diiodoterephthalate **9** as a precursor (Scheme 3) [12,24]. It involved diiodination of *p*-xylene, followed by oxidation and Fischer esterification of the resultant dicarboxylic acid. The diiodo ester **9** was converted to the target using pinacolborane, with $(\text{Ph}_3\text{P})_2\text{PdCl}_2$ as a catalyst. The generation of **10** was associated with the formation of noticeable amounts of hydrodeboration bi-products, namely compound **3** and dimethyl terephthalate.

Scheme 3

B. Suzuki coupling reactions of boronic ester 3. The cyclic boronic ester **3** was successfully used to conduct a number of Suzuki coupling reactions (Scheme 1). Those were carried out in typical conditions, employing $(\text{Ph}_3\text{P})_4\text{Pd}$ as a catalyst, in a mixture of toluene and

aqueous K_2CO_3 . It should be noted that original attempts were done using also small amounts of ethanol, as recommended by a number of literature references. However, we found out that under such conditions trans-esterification occurred, leading to a mixture of products containing methyl and/or ethyl ester functionalities. Consequently, reactions were conducted without any alcohol. Several new aromatic and heteroaromatic targets were prepared, using both bromo- and iodoarenes as starting materials.

Figure 1

C. X-ray Structural Studies. X-ray crystallographic analysis was conducted on compounds **3**, **7** and **10**. Inspection of the ORTEP drawings (Figure 1) and selected structural parameters (Table 1) reveals some significant differences, particularly between structures **3** and **10** on one hand, and structure **7** on the other. Thus, the methyl ester units in **3** and **10** are virtually co-planar with the benzene ring core, while the N,N-dimethylamide units in **7** are considerably twisted. Equally different is the relative positioning of the pinacolborane unit(s). In structures **3** and **10** the five-membered ring (or rings) is/are slightly puckered and nearly perpendicular to the benzene core, while the same substructure is nearly co-planar in **7**. The boron atom in compound **3** (or **10**) is in the center of a trigonal planar environment, with values slightly larger than 120° for the O(2)-B(1)-C(2) and O(1)-B(1)-C(2) angles, while the O(2)-B(1)-O(1) angle has a value of about 113° . Structure **10** has a center of symmetry, so the structural parameters for it listed in Table 1 use the crystallographic designation and numbering of compound **3**.

Figure 2

One of the most interesting structural features of compounds **3** and **10**, is the apparent proximity of the boron and carbonyl oxygen centers, raising the question about potential Lewis acid – base interaction. In structure **3** the two centers are at a distance of 2.59 Å, which is rather large to be qualified as a B – O dative bond. On the other hand, the dihedral angle O(1)-O(2)-C(2)-B(1) has a value of 6.1°, i.e. there is some degree of deviation from the ideal trigonal planar geometry, and a pyramidalization towards the carbonyl oxygen. We did extensive literature search, in order to provide an in-depth structural analysis and comparison of our target compounds with previously published X-ray data. Some of the literature structures are shown in Figure 2. Four of them, **11** – **14**, contain a pinacolborane unit connected to a benzene ring, and the two sub-structures are nearly coplanar.[15,17,25,26] However, compounds **3** and **10**, with a carbonyl oxygen as a potential electron donor, bear more resemblance to the remaining two structures in Figure 2, namely catechol [2-(diisopropylamino)carbonyl]phenylboronate (**15**) [27] and ethylene glycol [(1R)-1-acetamido-3-methylthio]propyl]boronate (**16**) [28], both of which contain an amide group, *ortho*-positioned to the boronate ester unit. Several structures have also been described in a recent work of Kawashima *et al.*, all having an amino or a diazo group serving as the electron donor [18]. In both structures **15** and **16**, X-ray analysis supports a true dative B – O bond, with distance values of 1.56 Å and 1.64 Å correspondingly, only slightly longer than the typical B – O covalent bond distance of 1.43 – 1.44 Å. Two different effects have been used to explain these experimental findings. On one hand, the B – O distance and degree of bonding probably depend on the electron-donating ability of the Lewis donor center, and it is expected to be greater in amides (such as **15** and **16**), as opposed to esters (such as **3** and **10**). On the other hand, the Lewis acidity of the boron center is also thought to play a crucial role. In the same work ([18]) a

clear distinction is made between a catecholborane ester and a pinacolborane ester unit. In the former, the oxygen atoms bonded to boron experience strong interactions with the fused benzene ring, leading to reduced electron-donating ability of those oxygens and a concomitant increase of the Lewis acidity of the boron center. The ability of boron in catecholborane esters to strongly coordinate to an electron-donor center, oxygen or nitrogen, is clearly demonstrated both in structure **15** and the several structures listed in Kawashima's work. In the latter work, using ^{11}B NMR studies, the pinacolborane ester unit was concluded to be incapable of coordination to a Lewis donor center, because of the inherently greater electron-donating ability of the five-membered ring oxygens, which makes the boron center less Lewis acidic. At the same time, structure **16** seems to suggest that the boron center in a cyclic ester very similar to pinacolborane, is clearly capable of strong interaction with a Lewis electron donor center.

In order to gain further insight, we undertook the preparation of the corresponding terephthalamide **7**, which would closely mimic the environment present in structure **15**. However, X-ray analysis on crystals of **7** does not lend any support to a possible B – O dative bond. In fact, as seen from Figure 1 and the data in Table 1, structure **7** has the amide units considerably twisted with respect to the benzene ring, while the pinacolborane unit is nearly coplanar.

Table 1

D. Theoretical Studies. All calculations were performed using the *Gaussian03/GaussView* software package [29], on a *Linux*-operated *QuantumCube QS16-2500C-X64Q* by Parallel Quantum Solutions [30]. Calculations, both of the actual structures and

of model compounds, were conducted using DFT at the *B3LYP* level with *6-31+G(d)* basis set [31-33]. In addition, the target structures were also calculated at the *MP2/6-31+G(d)* level [34-37], to investigate the role of method/level on the structure and geometry of the studied compounds. All stationary points were validated by subsequent frequency calculations at the same level of theory. All minimum structures had sets of only positive second derivatives, while TS structures all had one imaginary frequency. TS searches were conducted employing the Transit-Guided Quasi-Newton method (opt = qst2), or the Berny algorithm (opt = TS) [38,39]. Values of Gibbs free energy and enthalpy changes were obtained after frequency calculations and zero-point energy (ZPE) corrections, which were not scaled. Scaling factors for the ZPE values are available for related levels of theory, such as *B3LYP/6-31G(d)* and *B3LYP/6-31+G(d,p)*, and are 0.9863 and 0.9988 correspondingly, i.e. very close to unity [40]. In addition, since this work was interested in differences of Gibbs free energies (i.e. ΔG^\ddagger and ΔG values), we anticipated that such values would be largely invariant towards the introduction of the same small correction in the constituent G values. Based on this, we considered scaling ZPE values unnecessary.

Experimental data suggest that the inherent optimal positioning of a pinacolborane ester unit, attached to a benzene ring is approximately co-planar, in absence of interfering factors, such as steric bulk or electron donors. This is evident in the case of reported sulfonamide derivatives, such as **12** and the *para*-substituted analog of **11** [41]. It has been also demonstrated in some recently published X-ray structures, such as the germafluorene derivatives **13**, and modified Tröger's bases, containing the pinacolborane unit, such as **14** [14,17]. Theoretical analysis, available in published works, is in agreement. Extensive calculations conducted by Bock and coworkers, employing DFT or MP2, indicate that for (1,3,2-dioxaborolan-2-yl)benzene

the co-planar structure is a minimum, while the perpendicular arrangement corresponds to a transition state, which is roughly 5.5 kcal mol higher in energy [19].

Figure 3

As stated above, one of the main issues, arising from our X-ray structural analysis was the possibility for a Lewis acid – base interaction between the pinacolborane unit and a carbonyl oxygen center from an *ortho*-positioned ester or amide group. In order to address this issue and provide comprehensive explanation of the observed geometries of structures **3**, **7** and **10**, we undertook a series of theoretical studies. Images of the stationary points of all studied compounds are shown in Figure 3, and selected structural parameters are listed in Table 1 (italicized values). If compared with the X-ray data, it is immediately evident that the DFT calculations reproduce the experimental structures rather accurately, properly predicting the relative orientations of the pinacolborane unit and the ester (or amide, in the case of **7**) group, with values of the relevant geometry parameters very close to the experimental.

Figure 4

Based on the fact that DFT calculations reproduced much better the experimental structures, we employed them in our further, model compound studies. In order to analyze computationally the interactions of the groups attached to the benzene ring (pinacolborane ester, carboxylic ester, or amide), and rationalize the structures of **3**, **7** and **10**, we adopted an incremental approach. Each group was studied individually, using the model systems **17** – **20**, shown in Figure 4. Rotation

around the indicated bonds was investigated in an attempt to find out: 1) The ground state orientation of each moiety, and 2) The energy cost associated with deviation from the minimum orientation. The results from the analysis, in terms of enthalpies and Gibbs free energies of activation, are also shown in Figure 4. Data clearly support the conclusion that both the pinacolborane and methyl ester substructures are coplanar with the benzene ring in their ground states, while the dimethylamide group is twisted at about 45° torsion angle. In the corresponding transition states, the first two are nearly perpendicular to the benzene ring, while the dimethylamide group is coplanar. The rotational energy profiles for all three moieties are almost isoenergetic.

It seems therefore that in structures **3** and **10** the methyl ester groups are oriented in a manner corresponding to their energy minimum position (co-planar with the ring), while the pinacolborane unit is twisted in a manner resembling the transition state of its rotational profile. Assuming that twisting one of the groups minimizes steric interactions between them, then the arrangement observed in **3** and **10** is optimal, i.e. since both groups cannot be coplanar at the same time, the group that requires less energy to rotate (the pinacolborane) is twisted out of planarity. In structure **7** the situation is different: Both the amide and the pinacolborane units are oriented in a manner that is close to or coincident with their ground state orientations (coplanar pinacolborane, twisted amide). At the same time, with one of them twisted out of coplanarity to the benzene ring, it is also the arrangement with minimum steric repulsion. Structure **7** therefore presents an arrangement that is ideal from both electronic and steric standpoint.

Overall then, for all of the analyzed structures, orientations of the substituents attached to the benzene core are dictated by the relative energy costs for deviation from their respective ground state positions, while at the same time trying to achieve relative positioning that would

minimize steric interactions. The only other factor, which could additionally affect the orientation, is a stabilizing B – (carbonyl) O coordination. Experimental results and the incremental group analysis both seem to suggest that such interaction is either nonexistent or very weak and therefore incapable of compensating for the energy cost associated with rotating the individual groups out of their ground state orientations (as would be the case if a B --- O interaction were to take place in structure **7**). Thus, our studies are in line with the findings of Kawashima *et al.*, who concluded, on the basis of their ¹¹B NMR studies, that the pinacolborane unit was incapable of coordination to a Lewis donor center. Although structures **3** and **10** do display some apparent coordination, it is probably just fortuitous, as the optimal orientations of the methyl ester and pinacolborane units, from the standpoint of minimized steric interactions, place the boron and oxygen atoms in close spatial proximity.

The lack of coordination, exhibited by the pinacolborane unit, is to be related to the strong electronic interactions of the oxygen atoms in the five-membered ring with the boron center. It results in significant increase of electron density at the otherwise inherently deficient boron, reducing its affinity for additional interaction with Lewis basis. In stark contrast, a catecholborane unit behaves quite differently, due to the conjugation of the same oxygen centers with the fused benzene ring. Previous experimental studies have clearly shown the catecholborane unit to be capable of donor – acceptor interaction with an amide, as in the case of structure **15**. At the same time, our theoretical studies show that the interaction of a catecholborane unit with the benzene ring is identical to that of a pinacolborane (Structures **19** and **20**, Figure 4). Efforts to prepare and study the catecholborane analogs of structures **3** and **7** are currently under way in our laboratory.

Conclusions

New cyclic boronic esters have been successfully prepared, structurally characterized and utilized in Suzuki coupling reactions. The differences between the structures, in relative orientation of the substituents with respect to the benzene ring, have been considered and rationalized, based on 1) Minimization of steric repulsion between *ortho*-substituents, and 2) Optimal orientation of each substituent, based on theoretical results from calculations on mono-substituted model compounds. The existence of a Lewis donor – acceptor interaction between the boron center and the carbonyl oxygen from the adjacent C=O bond cannot be ruled out, but our analysis seems to suggest that, at best, it is a minor effect, in good agreement with previous studies of systems containing the pinacolborane unit.

The cyclic boronic ester **3** has been successfully utilized in a number of Suzuki coupling reactions, which has led to the preparation of several previously unknown aromatic and heteroaromatic structures.

Experimental Section

^1H and ^{13}C spectra were recorded at 300 MHz and 75 MHz respectively and referenced to the solvent (CDCl_3 : 7.27 ppm and 77.0 ppm). X-ray structures were obtained using an *Oxford Diffraction Xcalibur3* diffractometer with graphite monochromatic $\text{Cu K}\alpha$ radiation. Structure solution and refinement was performed using the SHELXTL 6.10 software package [42]. Elemental analysis was provided by Atlantic Microlab, Norcross, GA. HRMS data was provided by the Mass Spectrometry and Proteomics facility at the Ohio State University. The preparation of iodoterephthalic acid (**5**) has been reported in literature [43,44], but the method used in this study is entirely different and the experimental protocol is therefore provided. Full experimental

details on the preparation and spectroscopic characterization of compounds **1**, **3** and **10** are reported in a recent publication [12].

X-ray crystallography of dimethyl 2-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)terephthalate (3). A crystal (colorless plate) of **3** ($C_{16}H_{21}BO_6$) having approximate dimensions 0.031 x 0.161 x 0.349 mm was mounted on a glass fiber. Data acquisition was conducted at 140 K using the phi and omega scans technique. Final cell constants were determined based on the full data set, leading to a triclinic cell ($P-1$) with these dimensions: $a = 7.3513(8)$ Å, $b = 9.9505(11)$ Å, $c = 11.6181(13)$ Å, $\alpha = 76.927(10)^\circ$, $\beta = 81.665(9)^\circ$, $\gamma = 79.487(10)^\circ$, $V = 809.15(15)$ Å³. For $Z = 2$ and F.W. = 320.14, the calculated density is 1.314 g/cm³. Non-hydrogen atoms were refined anisotropically; hydrogen atoms were assigned based on geometry. The final structure has values for the unweighted agreement factor $R1 = 0.0768$ based on 1650 strong reflections ($I > 2\sigma$) and $R1 = 0.0963$ based on all 2201 reflections.

X-ray crystallography of N,N,N',N'-tetramethyl-2-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)terephthalamide (7). A crystal (colorless plate) of **7** ($C_{18}H_{27}BN_2O_4$) having approximate dimensions 0.116 x 0.236 x 0.265 mm was mounted on a glass fiber. Data acquisition was conducted at 110 K using the phi and omega scans technique. Final cell constants were determined based on the full data set, leading to a orthorhombic ($Pbca$) with these dimensions: $a = 12.9993(4)$ Å, $b = 11.9270(4)$ Å, $c = 24.2822(8)$ Å, $V = 3764.8(2)$ Å³. For $Z = 8$ and F.W. = 346.23, the calculated density is 1.222 Mg/m³. Non-hydrogen atoms were refined anisotropically; hydrogen atoms were assigned based on geometry. The final structure has values for the unweighted agreement factor $R1 = 0.0395$ based on 3278 strong reflections ($I > 2\sigma$) and $R1 = 0.0442$ based on all 3692 reflections.

X-ray crystallography of dimethyl 2,5-bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)terephthalate (10). A crystal (colorless plate) of **10** ($C_{22}H_{32}B_2O_8$) having approximate dimensions 0.110 x 0.206 x 0.268 mm was mounted on a glass fiber. Data acquisition was conducted at 110 K using the phi and omega scans technique. Final cell constants were determined based on the full data set, leading to a monoclinic cell ($P2_1/n$) with these dimensions: $a = 10.2195(5) \text{ \AA}$, $b = 11.9099(6) \text{ \AA}$, $c = 10.3627(5) \text{ \AA}$, $\beta = 108.448(6)^\circ$, $V = 1196.45(11) \text{ \AA}^3$. For $Z = 2$ and F.W. = 446.09, the calculated density is 1.234 g/cm^3 . Non-hydrogen atoms were refined anisotropically; hydrogen atoms were assigned based on geometry. The final structure has values for the unweighted agreement factor $R1 = 0.0649$ based on 1925 strong reflections ($I > 2\sigma$) and $R1 = 0.0697$ based on all 2110 reflections.

Generalized protocol for Suzuki coupling reactions of dimethyl 2-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)terephthalate (3). A mixture of compound **3** (1.0 eqv.), an aromatic halide (1.0 eqv.), aqueous K_2CO_3 (6.0 eqv. K_2CO_3 , in 0.15 mL H_2O per mmol K_2CO_3) and $(Ph_3P)_4Pd$ (0.05 eqv.), in toluene (10 mL per mmol of **3**), was stirred at reflux for 18 h, under nitrogen atmosphere. After cooling the mixture was washed with water, the organic layer separated, dried ($MgSO_4$) and the solvent removed under reduced pressure. The residue was purified by silica gel chromatography.

Dimethyl 2-phenylterephthalate (4a). Purified by silica gel chromatography (CH_2Cl_2 : hexanes = 2 : 1). Yields: 83% (with iodobenzene as the aromatic halide), 45% (with bromobenzene as the aromatic halide). Colorless oil. 1H NMR ($CDCl_3$) δ 3.66 (s, 3H), 3.95 (s, 3H), 7.32 – 7.43 (m, 5H), 7.86 (d, $J = 8.7 \text{ Hz}$, 1H), 8.07 (dd, $J_1 = 1.7 \text{ Hz}$, $J_2 = 7.1 \text{ Hz}$, 1H), 8.08 (s, 1H).

Dimethyl 2-(4-nitrophenyl)terephthalate (4b). Purified by silica gel chromatography (CH_2Cl_2 : hexanes = 1 : 1), followed by recrystallization from methanol. Yield: 71%. White solid. Mp 174 – 176 °C. ^1H NMR (CDCl_3) δ 3.72 (s, 3H), 3.97 (s, 3H), 7.49 (d, J = 8.8 Hz, 2H), 8.01 (d, J = 8.4 Hz, 1H), 8.03 (d, J = 2.0 Hz, 1H), 8.16 (dd, J_1 = 8.1 Hz, J_2 = 1.7 Hz, 1H), 8.30 (d, J = 8.8 Hz, 2H). ^{13}C NMR (CDCl_3) δ 52.5, 52.6, 123.4, 129.3, 130.6, 131.5, 133.0, 134.0, 140.7, 147.2, 165.7, 167.2; Anal. Calcd. for $\text{C}_{16}\text{H}_{13}\text{NO}_6$: C, 60.95; H, 4.16; N, 4.44. Found: C, 61.03; H, 4.15; N, 4.40.

Dimethyl 2-(2-thiophenyl)terephthalate (4c). Purified by passing through a short silica gel column (CH_2Cl_2 : hexanes = 1 : 1). Yield: 42%. Colorless oil. ^1H NMR (CDCl_3) δ 3.77 (s, 3H), 3.96 (s, 3H), 7.08 – 7.10 (m, 2H), 7.39 (dd, J_1 = 3.9 Hz, J_2 = 2.4 Hz, 1H), 7.76 (dd, J_1 = 8.0 Hz, J_2 = 0.3 Hz, 1H), 8.05 (dd, J_1 = 8.1 Hz, J_2 = 1.7 Hz, 1H), 8.17 (dd, J_1 = 1.7 Hz, J_2 = 0.3 Hz, 1H). ^{13}C NMR (CDCl_3) δ 52.5, 126.5, 126.8, 127.4, 128.5, 129.4, 132.0, 132.2, 134.2, 135.5, 140.8, 165.9, 168.6; Anal. Calcd. for $\text{C}_{14}\text{H}_{12}\text{O}_4\text{S}$: C, 60.86; H, 4.38. Found: C, 60.78; H, 4.35.

Dimethyl 2-(2-thiazolyl)terephthalate (4d). Purified by silica gel chromatography (hexanes : acetone = 7 : 1). Yield: 58%. Yellow oil. ^1H NMR (CDCl_3) δ 3.82 (s, 3H), 3.96 (s, 3H), 7.46 (d, J = 3.3 Hz, 1H), 7.78 (d, J = 8.0 Hz, 1H), 7.90 (d, J = 3.2 Hz, 1H), 8.15 (dd, J_1 = 8.0 Hz, J_2 = 1.7 Hz, 1H), 8.36 (d, J = 1.6 Hz, 2H). ^{13}C NMR (CDCl_3) δ 52.8, 52.9, 120.7, 129.6, 130.6, 131.2, 132.5, 133.1, 135.8, 143.9, 165.3, 165.8, 168.7; Anal. Calcd. for $\text{C}_{13}\text{H}_{11}\text{NO}_4\text{S}$: C, 56.31; H, 4.00; N, 5.05. Found: C, 56.29; H, 3.97; N, 4.88.

2-Iodoterephthalic acid (5). Dimethyl iodoterephthalate **1** (3.00 g, 9.37 mmol) was dissolved in 15 mL of methanol, and KOH (2.10 g, 13.75 mmol) was added to the solution. The reaction was continued for 30 min at 35 °C. Water (30 mL) was added, the aqueous layer was extracted with ether (2 x 25 mL), then acidified to pH 2 using conc. HCl. The mixture was kept

in the refrigerator for about 2 h and the white solid was vacuum-filtered and air dried to yield 2.68 g (98%) of the target. Mp 296 – 299 °C (lit. mp 299 – 300 °C [43]). ¹H NMR (DMSO-*d*₆) δ 7.74 (d, J = 8.0 Hz, 1H), 7.96 (dd, J₁ = 8.0 Hz, J₂ = 1.6 Hz, 1H), 8.39 (d, J = 1.5 Hz, 1H), 13.57 (bs, 2H).

N,N,N',N'-tetramethyl-2-iodoterephthalamide (6). Iodoterephthalic acid **5** (2.00 g, 6.85 mmol) was dissolved in DMF (20 mL), in a 50 mL round bottom flask, under nitrogen atmosphere. Thionyl chloride (2.04 g, 10.02 mmol, 1.25 mL) was added and the solution was stirred at 150 °C for 5 hours. Saturated aqueous sodium bicarbonate (2 mL) was added and the solution was stirred for 0.5 h. Solvents were removed under reduced pressure, the resultant solid was suspended in acetonitrile and vacuum filtered. Further purification *via* column chromatography on silica gel (acetone : hexane = 3 : 1), yielding the product as a white solid (1.00 g, 42% yield). Mp 179 – 183 °C. ¹H NMR (CDCl₃) δ 2.85 (s, 3H), 2.97 (bs, 3H), 3.10 (bs, 3H), 3.14 (s, 3H), 7.24 (d, J = 7.7 Hz, 1H), 7.43 (dd, J₁ = 7.7 Hz, J₂ = 1.5 Hz, 1H), 7.87 (d, J = 1.5 Hz, 1H). ¹³C NMR (DMSO-*d*₆) δ 34.0, 34.7, 37.8, 38.9, 92.9, 126.81, 126.84, 136.7, 138.0, 143.5, 167.8, 169.1; Anal. Calcd. for C₁₂H₁₅IN₂O₂: C, 41.64; H, 4.37; N, 8.09. Found: C, 41.69; H, 4.25; N, 8.11.

N,N,N',N'-tetramethyl-2-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)terephthalamide (7). Compound **6** (0.57 g, 1.73 mmol), bis(pinacolato)diboron (0.91 g, 36.00 mmol), (dppf)₂PdCl₂ (0.035 g, 0.04 mmol), potassium acetate (0.34 g, 3.47 mmol), and DMF (10 mL) were introduced into a 50 mL round bottom flask, under nitrogen atmosphere. The resultant mixture was stirred at 125 °C for 19 hours. The solvent was removed under reduced pressure and the resultant solid dissolved in benzene (40 mL). The organic layer was washed with water (2 x 50 mL), dried (MgSO₄), and the solvent evaporated under reduced

pressure. The solid material was washed with a small quantity of cold pentane to yield the product as a white solid (0.10 g, 17% yield). Further purification *via* recrystallization from methanol. Mp 183 – 185 °C. ¹H NMR (CDCl₃) δ 1.28 (s, 12H), 2.79 (bs, 3H), 2.93 (s, 3H), 3.06 (bs, 3H), 3.08 (s, 3H), 7.29 (d, J = 7.8 Hz, 1H), 7.47 (dd, J₁ = 7.8 Hz, J₂ = 1.8 Hz, 1H), 7.83 (d, J = 1.4 Hz, 1H). ¹³C NMR (DMSO-*d*₆) δ 24.9, 35.0, 35.3, 39.0, 39.5, 83.9, 125.6, 129.5, 133.7, 136.1, 144.0, 171.1, 171.8; Anal. Calcd. for C₁₈H₂₇BN₂O₄: C, 62.44; H, 7.86; N, 8.09. Found: C, 62.31; H, 7.89; N, 7.98.

Acknowledgements. Partial funding for this project was provided by the National Institute of Standards and Technology, Building and Fire Research Laboratory (NIST-BFRL), Fire Research Grant # 70NANB9H9183. Andrew Kuttler thanks the Chemistry Department at the University of Dayton for summer financial support.

Supporting Information Available. Crystallographic data (excluding structure factors) for the structures in this paper have been deposited with the Cambridge Crystallographic Data Centre as supplementary publication numbers **CCDC 795279**, **CCDC 916569**, and **CCDC 916570**. Copy of the data can be obtained, free of charge, on application to CCDC, 12 Union Road, Cambridge CB2 1EZ, UK (fax: +44-(0)1223-336033 or e-mail: deposit@ccdc.cam.ac.uk).

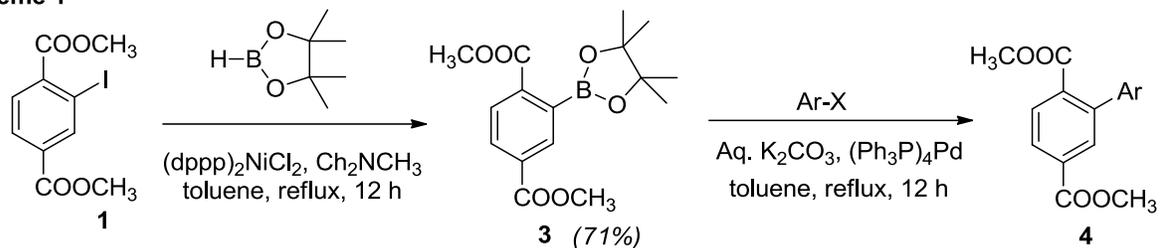
Calculated energies and thermodynamic parameters for all target boronic esters (**3**, **7**, and **10**) can be found in Table S1. Calculated energies and thermodynamic parameters for model structures **17** – **20** are listed in Table S2.

References

- [1] Fire Retardancy of Polymeric Materials; Eds. Wilkie, C. A., Morgan A. B., Taylor and Francis: Boca Raton, FL, 2010, ISBN 978-1-4200-8399-6.
- [2] Weil, E. D.; Levchik, S. V. Flame Retardants for Plastics and Textiles; Hanser Publications (ISBN 978-3-446-41652-9): Cincinnati, OH, 2009.
- [3] Simonson, M.; Blomqvist, P.; Boldizar, A.; Möller, K.; Rosell, L.; Tullin, C.; Stripple, H.; Sundqvist, J. O. In SP Report 2000:13, 2000, ISBN 91-7848-811-7.
- [4] Blomqvist, P.; Rosell, L.; Simonson, M. Fire Tech. 2004, 40, 39 - 58.
- [5] Blomqvist, P.; Rosell, L.; Simonson, M. Fire Tech. 2004, 40, 59 - 73.
- [6] Stapleton, H. M.; Dodder, N. G.; Offenbergl, J. H.; Schantz, M. M.; Wise, S. A. Environ. Sci. & Technol. 2005, 39, 925 - 931.
- [7] Tange, L.; Drohmann, D. Polym. Degrad. Stab. 2005, 88, 35 - 40.
- [8] Wadehra, I. Fire and Materials 2005, 29, 121 - 126.
- [9] Bourbigot, S.; Duquesne, S. J. Mater. Chem. 2007, 17, 2283 - 2300.
- [10] Morgan, A. B.; Tour, J. M. J. App. Polym. Sci. 2000, 76, 1257 - 1268.
- [11] Sacristan, M.; Hull, T. R.; Stec, A. A.; Ronda, J. C.; Galia, M.; Cadiz, V. Polym. Degrad. Stab. 2010, 95, 1269 - 1274.
- [12] Benin, V.; Durganala, S.; Morgan, A. B. J. Mater. Chem. 2012, 22, 1180 - 1190.
- [13] Benin, V.; Morgan, A. B. Heat Release of Flame Retardant Polyurethanes Containing Commercial and Potential Flame Retardant Chemistries 2013, in preparation.
- [14] Allard, N.; Aich, R. B.; Gendron, D.; Boudreault, P.-L.; Tessier, C.; Alem, S.; Tse, S.-C.; Tao, Y.; Leclerc, M. Macromolecules 2010, 43, 2328 - 2333.
- [15] Decken, A.; Singh, A.; Vogels, C. M.; Westcott, S. A. Acta. Cryst. 2002, E58, o1213 - o1214.
- [16] He, X.-F.; Zhang, H.; Vogels, C. M.; Decken, A.; Westcott, S. A. Heteroatom Chem. 2004, 15, 369 - 372.
- [17] Kiehne, U.; Bruhn, T.; Schnakenburg, G.; Frohlich, R.; Bringmann, G.; Lutzen, A. Chem. Eur. J. 2008, 14, 4246 - 4255.
- [18] Yoshino, J.; Kano, N.; Kawashima, T. Tetrahedron 2008, 64, 7774 - 7781.
- [19] Bhat, K. L.; Howard, N. J.; Rostami, H.; Lai, J. H.; Bock, C. W. J. Mol. Struct. (THEOCHEM) 2005, 723, 147 - 157.
- [20] Mkhaliid, I. A. I.; Barnard, J. H.; Marder, T. B.; Murphy, J. M.; Hartwig, J. F. Chem. Rev. 2010, 110, 890 - 931.
- [21] Iovine, P. M.; Kellett, M. A.; Redmore, N. P.; Therien, M. J. J. Am. Chem. Soc. 2000, 122, 8717 - 8727.
- [22] Khurana, J. M.; Chauhan, S.; Bansal, G. Monatshefte Chem 2004, 135, 83 - 87.
- [23] Kumagai, T.; Anki, T.; Ebi, T.; Konishi, A.; Matsumoto, K.; Kurata, H.; Kubo, T.; Katsumoto, K.; Kitamura, C.; Kawase, T. Tetrahedron 2010, 66, 8968 - 8973.
- [24] Perry, R. J.; Wilson, B. D.; Turner, S. R.; Blevins, R. W. Macromolecules 1995, 28, 3509 - 3515.
- [25] He, X. F.; Zhang, H.; Vogels, C. M.; Decken, A.; Westcott, S. A. Heteroatom Chem. 2004, 15, 369 - 372.
- [26] Allard, N.; Aich, R. B.; Gendron, D.; Boudreault, P. L.; Tessier, C.; Alem, S.; Tse, S. C.; Tao, Y.; Leclerc, M. Macromolecules 2010, 43, 2328 - 2333.
- [27] Liu, X.-C.; Hubbard, J. L.; Scouten, W. H. J. Organomet. Chem. 1995, 493, 91 - 94.

- [28] Matteson, D. S.; Michnick, T. J.; Willett, R. D.; Patterson, C. D. *Organometallics* 1989, 8, 726 - 729.
- [29] Gaussian 03, R. C., Frisch, M. J.; Trucks, G. W.; Schlegel, H. B.; Scuseria, G. E.; Robb, M. A.; Cheeseman, J. R.; Montgomery, Jr., J. A.; Vreven, T.; Kudin, K. N.; Burant, J. C.; Millam, J. M.; Iyengar, S. S.; Tomasi, J.; Barone, V.; Mennucci, B.; Cossi, M.; Scalmani, G.; Rega, N.; Petersson, G. A.; Nakatsuji, H.; Hada, M.; Ehara, M.; Toyota, K.; Fukuda, R.; Hasegawa, J.; Ishida, M.; Nakajima, T.; Honda, Y.; Kitao, O.; Nakai, H.; Klene, M.; Li, X.; Knox, J. E.; Hratchian, H. P.; Cross, J. B.; Bakken, V.; Adamo, C.; Jaramillo, J.; Gomperts, R.; Stratmann, R. E.; Yazyev, O.; Austin, A. J.; Cammi, R.; Pomelli, C.; Ochterski, J. W.; Ayala, P. Y.; Morokuma, K.; Voth, G. A.; Salvador, P.; Dannenberg, J. J.; Zakrzewski, V. G.; Dapprich, S.; Daniels, A. D.; Strain, M. C.; Farkas, O.; Malick, D. K.; Rabuck, A. D.; Raghavachari, K.; Foresman, J. B.; Ortiz, J. V.; Cui, Q.; Baboul, A. G.; Clifford, S.; Cioslowski, J.; Stefanov, B. B.; Liu, G.; Liashenko, A.; Piskorz, P.; Komaromi, I.; Martin, R. L.; Fox, D. J.; Keith, T.; Al-Laham, M. A.; Peng, C. Y.; Nanayakkara, A.; Challacombe, M.; Gill, P. M. W.; Johnson, B.; Chen, W.; Wong, M. W.; Gonzalez, C.; and Pople, J. A.; Gaussian, Inc., Wallingford CT, 2004.
- [30] *Parallel Quantum Solutions*, 2013 Green Acres Road, Suite A, Fayetteville, Arkansas 72703.
- [31] Becke, A. D. *Phys. Rev. A* 1988, 38, 3098 - 3100.
- [32] Frisch, M. J.; Pople, J. A.; Binkley, J. S. *J. Chem. Phys.* 1984, 80, 3265 - 3269.
- [33] Lee, C.; Yang, W.; Parr, R. G. *Phys. Rev. B* 1988, 37, 785 - 789.
- [34] Frisch, M. J.; Head-Gordon, M.; Pople, J. A. *Chem. Phys. Lett.* 1990, 166, 275 - 280.
- [35] Frisch, M. J.; Head-Gordon, M.; Pople, J. A. *Chem. Phys. Lett.* 1990, 166, 281 - 289.
- [36] Head-Gordon, M.; Pople, J. A.; Frisch, M. J. *Chem. Phys. Lett.* 1988, 153, 503 - 506.
- [37] Saebo, S.; Almlöf, J. *Chem. Phys. Lett.* 1989, 154, 83 - 89.
- [38] Peng, C.; Ayala, P. Y.; Schlegel, H. B.; Frisch, M. J. *J. Comp. Chem.* 1996, 17, 49 - 56.
- [39] Peng, C.; Schlegel, H. B. *Israel J. Chem.* 1994, 33, 449 - 454.
- [40] Johnson III, R. D.; Irikura, K. K.; Kacker, R. N.; Kessel, R. J. *Chem. Theory Comput.* 2010, 6, 2822 - 2828.
- [41] Westcott, S. A.; He, X.-F.; Vogels, C. M.; Decken, A. *Acta Cryst. E* 2004, 60, o115 - o116.
- [42] SHELXTL, version 6.10, Bruker AXS, Inc. Madison, WI, 2000.
- [43] Kommreddy, A.; Bowsher, M. S.; Gunna, M. R.; Botha, K.; Vinod, T. K. *Tet. Lett.* 2008, 49, 4378 - 4382.
- [44] Meek, S. T.; Perry IV, J. J.; Teich-Goldrick, S. L.; Greathouse, J. A.; Allendorf, M. D. *Cryst. Growth Des.* 2011, 11, 4309 - 4312.
- [45] Wang, X.; Hu, Y.; Song, L.; Xing, W.; Lu, H.; Lv, P.; Jie, G. *Polymer* 2010, 51, 2435 - 2445.

Scheme 1



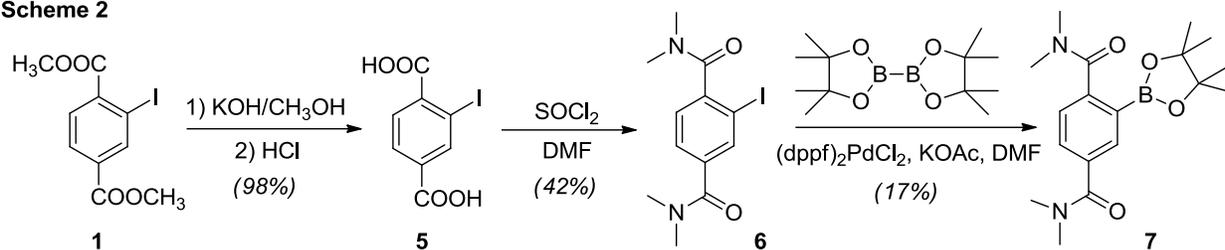
- 4a:** Ar = Ph 83% (X = I), 45% (X = Br)
4b: Ar = 4- $O_2NC_6H_4$ 71% (X = I)
4c: Ar = 2-thiophenyl 42% (X = Br)
4d: Ar = 2-thiazolyl 58% (X = Br)

Scheme 1

Kuttler, A.; Durganala, S.; Fratini, A.; Morgan, A. B.; Benin, V.

Structure, Theoretical Studies and Coupling Reactions of Some New Cyclic Boronic Esters

Scheme 2

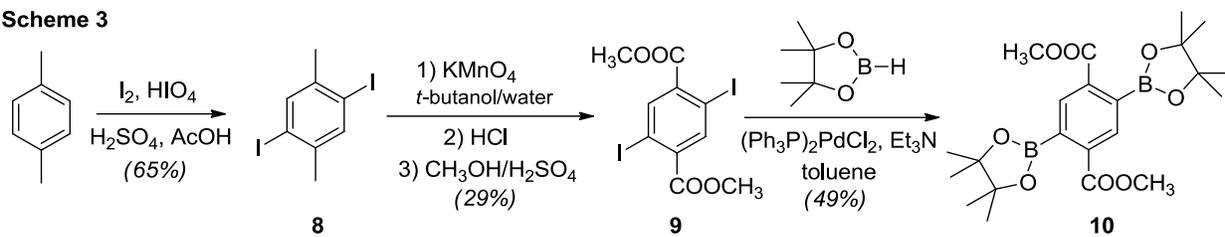


Scheme 2

Kuttler, A.; Durganala, S.; Fratini, A.; Morgan, A. B.; Benin, V.

Structure, Theoretical Studies and Coupling Reactions of Some New Cyclic Boronic Esters

Scheme 3



Scheme 3

Kuttler, A.; Durganala, S.; Fratini, A.; Morgan, A. B.; Benin, V.

Structure, Theoretical Studies and Coupling Reactions of Some New Cyclic Boronic Esters

LIST OF FIGURES WITH FIGURE CAPTIONS:

- 1) **Figure 1.** *ORTEP* drawings of dimethyl 2-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)terephthalate (**3**), N,N,N',N'-tetramethyl-2-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)terephthalamide (**7**), and dimethyl 2,5-bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)terephthalate (**10**). Thermal ellipsoids are drawn at 50% probability. Hydrogen atoms are given arbitrary radii.
- 2) **Figure 2.** Some examples of structures containing a cyclic boronic ester unit, previously studied by X-ray crystallography.
- 3) **Figure 3.** (a) Stationary points for compounds **3**, **7** and **10**, calculated using *B3LYP/6-31+G(d)*; (b) Stationary points for compounds **3** and **7**, calculated using *MP2/6-31+G(d)*.
- 4) **Figure 4.** Ground and transition state structures for model compounds **17** – **20** and their rotational barriers. Results from *B3LYP/6-31+G(d)* calculations. Dihedral angle definitions are based on the crystallographic designation and numbering from Figure 1.

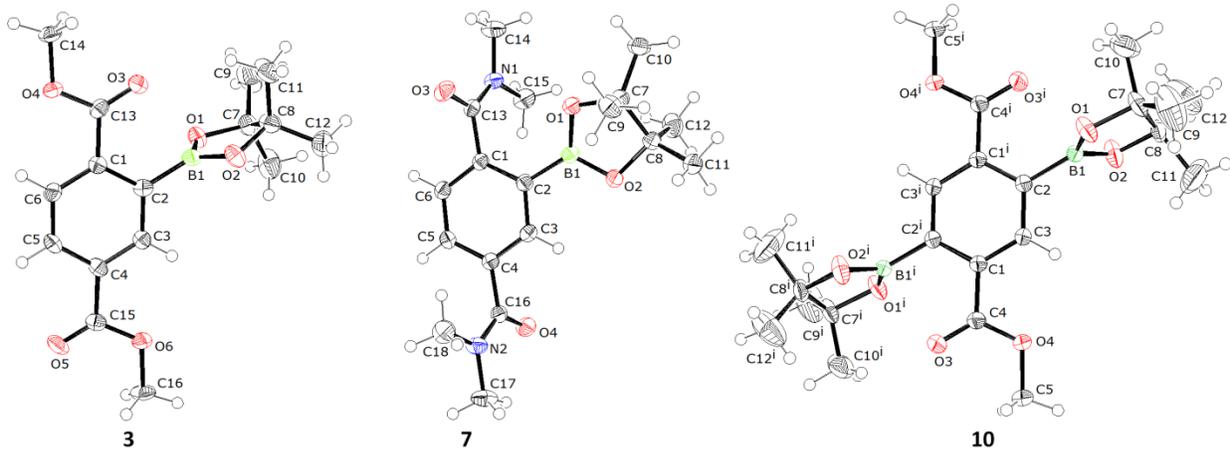


Figure 1

Kuttler, A.; Durganala, S.; Fratini, A.; Morgan, A. B.; Benin, V.

Structure, Theoretical Studies and Coupling Reactions of Some New Cyclic Boronic Esters

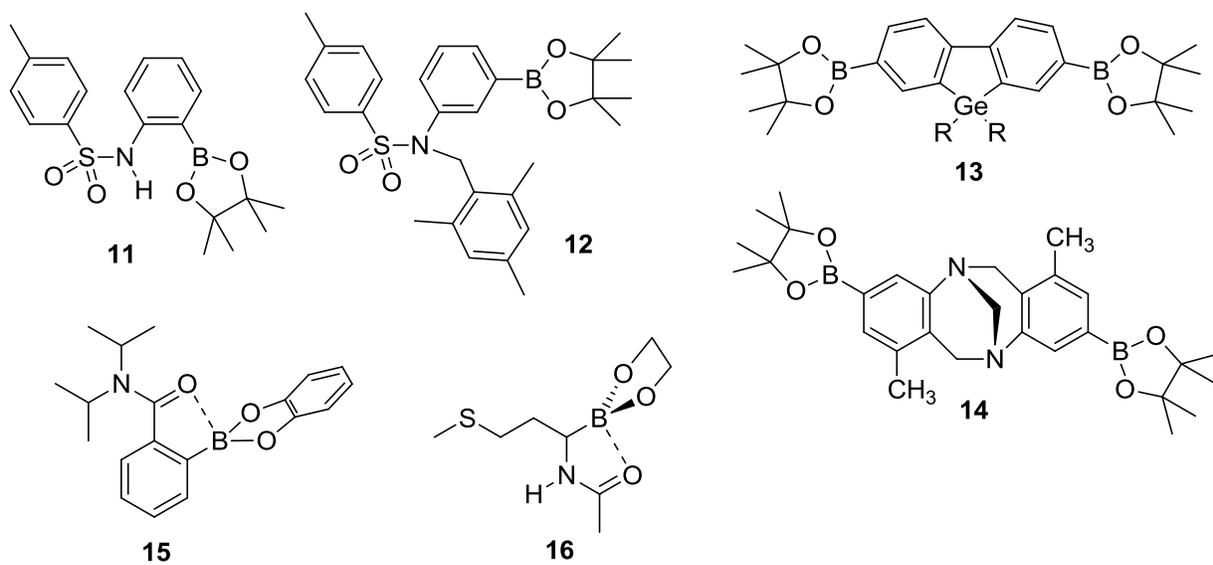


Figure 2

Kuttler, A.; Durganala, S.; Fratini, A.; Morgan, A. B.; Benin, V.

Structure, Theoretical Studies and Coupling Reactions of Some New Cyclic Boronic Esters

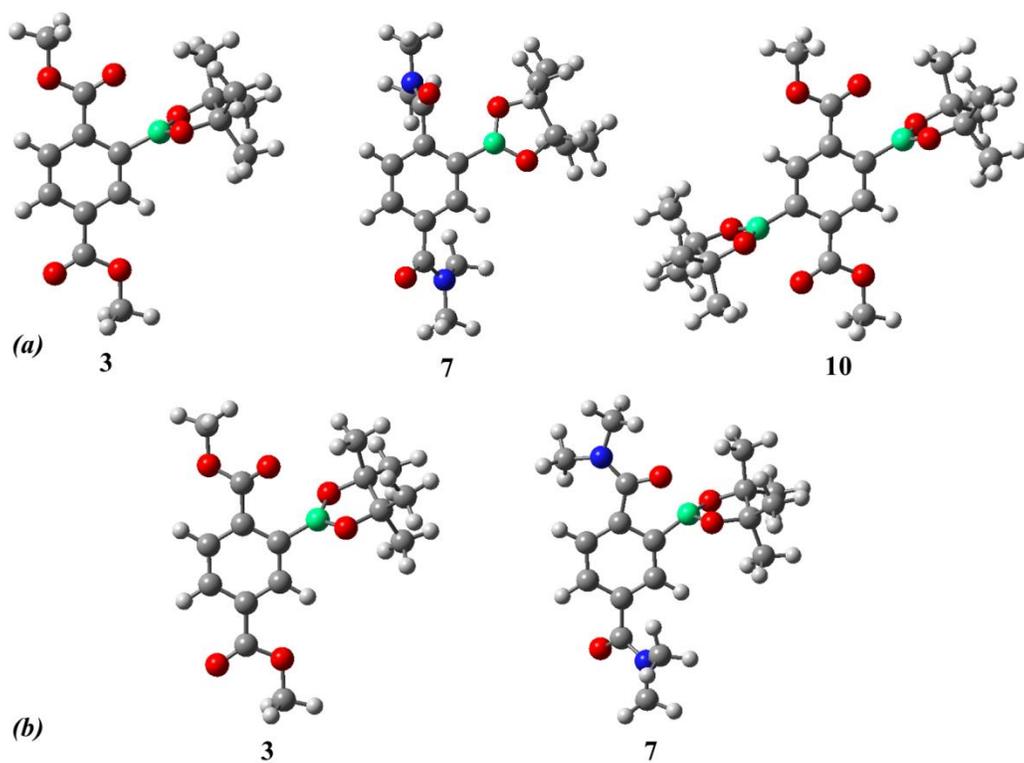


Figure 3

Kuttler, A.; Durganala, S.; Fratini, A.; Morgan, A. B.; Benin, V.

Structure, Theoretical Studies and Coupling Reactions of Some New Cyclic Boronic Esters

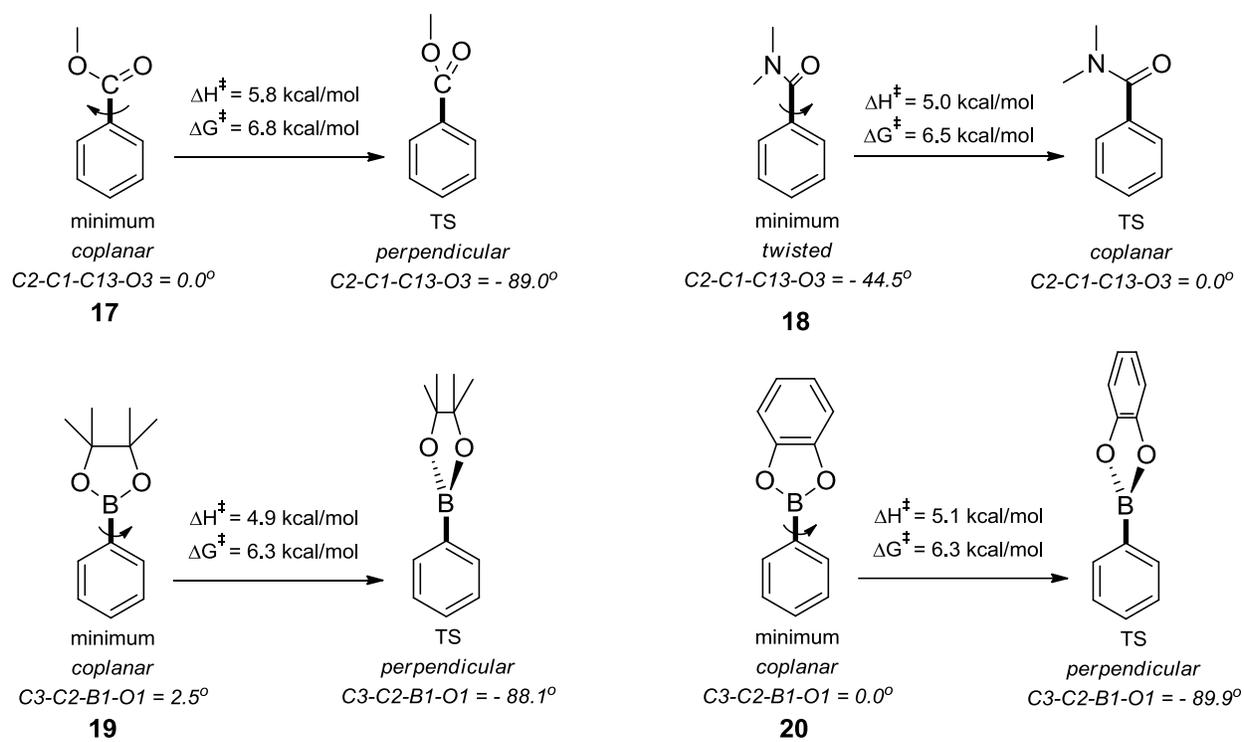


Figure 4

Kuttler, A.; Durganala, S.; Fratini, A.; Morgan, A. B.; Benin, V.

Structure, Theoretical Studies and Coupling Reactions of Some New Cyclic Boronic Esters

Table 1. Selected experimental (regular text) bond lengths (Å) and angles (deg) for dimethyl 2-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)terephthalate (**3**), N,N,N',N'-tetramethyl-2-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)terephthalamide (**7**), and dimethyl 2,5-bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)terephthalate (**10**). Theoretical values (*italicized text*) are from *B3LYP/6-31+G(d)* calculations, using Gaussian03/GaussView4[29] on a Linux-operated 16-CPU quad-core 64-bit Xeon QuantumCube™.[45]

Parameter	3	7	10^a
B(1)-O(1)	1.362(5), <i>1.37</i>	1.369(2), <i>1.37</i>	1.348(3), <i>1.37</i>
B(1)-O(2)	1.360(5), <i>1.37</i>	1.369(2), <i>1.37</i>	1.362(3), <i>1.37</i>
B(1)-C(2)	1.578(5), <i>1.58</i>	1.559(2), <i>1.56</i>	1.573(3), <i>1.58</i>
B(1)-O(3) ^b	2.59, <i>2.61</i>	3.83, <i>3.52</i>	2.60, <i>2.61</i>
O(1)-B(1)-O(2)	113.1(3), <i>113.5</i>	113.72(11), <i>113.0</i>	114.3(2), <i>113.4</i>
O(1)-B(1)-C(2)	122.3(3), <i>122.7</i>	126.13(11), <i>124.6</i>	121.7(2), <i>122.9</i>
O(2)-B(1)-C(2)	123.9(3), <i>123.0</i>	120.10(11), <i>122.4</i>	123.5(2), <i>122.8</i>
O(1)-B(1)-O(2)-C(8)	11.6(4), <i>11.5</i>	8.1(1), <i>8.1</i>	4.5(3), <i>11.6</i>
C(2)-B(1)-O(2)-C(8)	-178.5(3), <i>178.8</i>	-174.30(10), <i>-170.2</i>	-167.1(2), <i>-178.5</i>
O(1)-B(1)-C(2)-C(3)	90.9(4), <i>84.6</i>	165.49(11), <i>157.1</i>	-97.8(3), <i>87.9</i>
C(2)-C(1)-C(13)-O(3)	-2.9(5), <i>-1.1</i>	106.53(13), <i>81.4</i>	-13.6(3), <i>-1.5</i>
C(5)-C(4)-C(15)-O(5) – ester 3	10.4(5), <i>0.1</i>	-	-
C(5)-C(4)-C(16)-O(4) – amide 7	-	-108.34(13), <i>-127.3</i>	-

^a Compound **10** has a center of symmetry. For consistency, structural parameters were defined in accordance with the crystallographic designation and numbering for compound **3**, as shown in Figure 1. ^b B(1)-O(3) is a distance, not an actual bond.

Table 1

Kuttler, A.; Durganala, S.; Fratini, A.; Morgan, A. B.; Benin, V.

Structure, Theoretical Studies and Coupling Reactions of Some New Cyclic Boronic Esters