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Heats of Formation for the Boronic Acids $R-B(OH)_2$ and Boroxines $R_3B_3O_3$ ($R=H, Li, HBe, H_2B, H_3C, H_2N, HO, F,$ and Cl) Calculated at the G2, G3, and G4 Levels of Theory

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Abstract

Boronic acids ($R-B(OH)_2$) and their boroxine ($R_3B_3O_3$) dehydration products have emerged as important classes of compounds with a multitude of diverse applications. However, the available heats of formation for these compounds are not always as accurate as would be required for further use. In this study the heats of formation at 298.15 K of $R-B(OH)_2$ and $R_3B_3O_3$ ($R = H, Li, HBe, H_2B, H_3C, H_2N, HO, F,$ and Cl) have been calculated at the G2, G3[G3B3], and G4 levels of theory and used to determine the enthalpy changes for the dehydration reactions: $3 R-B(OH)_2 \rightarrow R_3B_3O_3 + 3 H_2O$; comparisons are made with other rigorous levels of theory, *e.g.* CBS-Q[CBS-QB3] and W1U, as well as with experimental values wherever possible. Enthalpy changes for the dehydration reactions have also been calculated using second-order Møller-Plesset perturbation theory (MP2) with the Dunning-Woon correlation-consistent aug-cc-pVDZ and aug-cc-pVTZ basis sets, and B3LYP density functional theory with the 6-311++G(2df,2pd) basis set. With the exception of $H_2N-B(OH)_2$, the dehydration reactions are consistently predicted to be exothermic. Our results provide a cautionary note for the use of the B3LYP functional in the calculation of structures and energies of boronic acids and boroxines. Where comparisons could be made, the G4 and W1U predictions for the heats of formation of these boron compounds differ significantly.

Keywords

Boroxines; Boronic Acids; Anhydrides; Heats of Formation; G2, G3, G4; Second-order Møller-Plesset Perturbation Theory (MP2); CBS-Q; W1U

Introduction

Boronic acids ($R-B(OH)_2$) and their condensed cyclotrimeric dehydration products boroxines (1,3,5,2,4,6-trioxatriborinanes, $R_3B_3O_3$) have emerged as important classes of compounds having diverse applications in chemistry, medicine, and material science. (1–4) Unfortunately, the thermodynamic data available for simple boronic acids and boroxines are quite limited and not always as accurate as may be required for many of these applications. For example, consider the dehydration reaction:

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Using heats of formation at 298.15 K, $\Delta H_f(298.15 \text{ K})$ (denoted $\Delta H_f(298 \text{ K})$ for brevity) from the JANAF compilation (5) for $\text{H}_3\text{B}_3\text{O}_3$, -291.0 kcal/mol , and H_2O , -57.8 kcal/mol , and taking $\Delta H_f(298 \text{ K})$ for H-B(OH)_2 from the Guest *et al.* collection (6) as -153.1 kcal/mol (since it is not listed in the JANAF tables), leads to a reaction enthalpy, $\Delta H_r(298 \text{ K})$, of -5.1 kcal/mol . However, based on the GC-MS and NMR investigations by Tokunaga *et al.* (7,8) and the DFT calculations by Kua and coworkers (9–11) on arylboroxine formation, this dehydration is not expected to be exothermic. Indeed, our recent MP2/aug-cc-pVTZ calculations suggest the reaction is significantly endothermic, with a ΔH_{298}^0 of $+12.2 \text{ kcal/mol}$. (12) Thus, there appears to be a problem with the heats of formation currently in the literature for H-B(OH)_2 and/or for $\text{H}_3\text{B}_3\text{O}_3$.

In an effort to obtain reliable thermodynamic properties for a series of fundamental boronic acids and boroxines, and the reactions that lead to their interconversion, we have undertaken a systematic study of their structural and thermochemical properties using high-level computational methods. In this article we report values of $\Delta H_f(298 \text{ K})$ for R-B(OH)_2 and $\text{R}_3\text{B}_3\text{O}_3$ ($\text{R} = \text{H, Li, HBe, H}_2\text{B, H}_3\text{C, H}_2\text{N, HO, F, and Cl}$) calculated at the G2, G3, and G4 levels of theory (13–15) and use these results to determine $\Delta H_r(298 \text{ K})$ for the dehydration reaction: $3 \text{R-B(OH)}_2 \rightarrow \text{R}_3\text{B}_3\text{O}_3 + 3 \text{H}_2\text{O}$; comparisons are also made with other extrapolation procedures, *e.g.* CBS-Q[CBS-QB3] (16) and W1U, (17,18) as well as with experimental values wherever possible. The values of $\Delta H_r(298 \text{ K})$ are compared to the corresponding values of ΔH_{298}^0 calculated for this reaction using enthalpies for geometry-optimized structures at the MP2/aug-cc-pVTZ and B3LYP/6-311++G(2df,2pd) computational levels. These particular substituents were chosen to assess various extrapolation procedures for predicting heats of formation for boronic acids and boroxines for several reasons: the availability of experimental and/or computational data for comparison, our existing computer resources (especially important for the tri-substituted boroxine calculations), and to include groups of differing electronegativity with different occupation of valence orbitals on atoms directly attached to the boron atom.

Computational Methods

Calculations at the G2, G3, and G4 levels of theory were performed on R-B(OH)_2 and $\text{R}_3\text{B}_3\text{O}_3$ ($\text{R} = \text{H, Li, HBe, H}_2\text{B, H}_3\text{C, H}_2\text{N, HO, F, and Cl}$) following procedures outlined in the literature (13–15,19,20) and implemented in the GAUSSIAN 03 (21) and GAUSSIAN 09 (22) suits of programs. It should be pointed out that the sequence of calculations used in G4 involve some significant additions, *e.g.* the Hartree-Fock energy limit is determined in G4 using a two-point extrapolation procedure, and changes, *e.g.* the QCISD(T)/6-31G(d) calculation has been replaced by CCSD(T)/6-31G(d), from those used in previous versions. Of some concern from the perspective of boron chemistry is that the geometries for the single-point calculations are determined in G4 using B3LYP density functional theory with the Pople-style 6-31G(2df,p) basis set (6-31G(2fg) for third-row nontransition metal elements); in contrast, G2 and G3 geometries for the single-point calculations are determined at the MP2(FULL)/6-31G(d) level. Unfortunately, B3LYP geometries for some boron compounds, *e.g.* boroxines, can vary significantly from the corresponding MP2 geometries. (12) Thus, for comparison with the G3 level, we also calculated heats of formation at the G3B3 level, which employs optimizations and frequency analyses at the B3LYP/6-31G(d) level. (23) In a few cases we also calculated heats of formation at the CBS-Q level (HF/6-31G(d) for frequencies and MP2(FC)/6-31G(d) geometries for single-point calculations) developed by Petersson and coworkers (16) and at the computationally-

demanding W1U level (B3LYP/cc-pVTZ+D for frequencies and single-point calculations), a variant of the W1 method developed by Martin and coworkers (17), (18) that is generally considered the most accurate benchmark for thermochemical calculations available in the Gaussian suits of programs, (21,22) again noting the potential limitations from the application of the B3LYP functional to boron based molecules.

In view of possible problems with the different geometries employed in these various methods, equilibrium geometries of all the monomers and trimers involved in this article were also obtained using second-order Møller-Plesset perturbation theory (MP2) (24) with the frozen core (FC) option, which neglects core-electron correlation; the Dunning-Woon aug-cc-pVTZ basis sets (25–28) were used in these optimizations; for a few of the boronic acids, geometry optimizations were also carried out at the MP2/aug-cc-pVQZ level. Frequency analyses were performed analytically to confirm that the optimized structures were local minima and to correct energies to 298.15 K. Density functional theory (DFT) calculations were also carried out using the hybrid B3LYP functional (29) with the 6-311++G(2df,2pd) Pople-style split-valence basis set. (30,31) Atomic charges were obtained from natural population analyses (NPA) and the bonding was analyzed with the aid of natural bond orbitals (NBOs). (32–35)

Results and Discussion

In Table 1S we list experimental/computational heats of formation from a variety of sources for the boronic acids and boroxines discussed in this paper. It is evident from the values in this Table that limited thermal data are currently available in the literature for these compounds and in some cases the spread in the reported values is considerable.

A. Boronic Acids

Obtaining accurate experimental data for monomeric boronic acids is complicated because it is difficult to obtain pure samples that actually have the formula $R-B(OH)_2$ (36) since these acids often separate from aqueous solutions as hydrates, and the latter, on standing in a desiccator over drying agents, undergo dehydration to yield boron oxides RBO, although molecular weight determinations often reveal that these oxides are actually trimers $R_3B_3O_3$. (36)

A.1 Structures—For the boronic acids three different orientations of the hydroxyl groups are possible: *endo-exo*, *anti*, and *syn*, see Figure 1.

Calculations have generally shown that the *endo-exo* form is lowest in energy in the gas-phase for a variety of small aliphatic substituents, (12), (37–42) although the energy differences among them can be rather small, *e.g.* the *anti* form of $F-B(OH)_2$ is only 0.6 kcal/mol higher in energy than the *endo-exo* form at the MP2/aug-cc-pVTZ level as a result of intramolecular $F\cdots HO$ hydrogen bonding; (12) the *syn* conformer is consistently found to be higher in energy than the other forms for the acids where computational data are available. It should be noted that the optimized structure of $H_2N-B(OH)_2$ is planar; NBO analyses using the MP2/aug-cc-pVD(T)Z densities confirms that the N–B bond is best described as a double bond composed of a σ bond and a π dative bond formed from the lone pair on the nitrogen atom and the empty *p*-orbital on the boron atom.

Since there have been relatively few studies in the literature of the corresponding conformers of $R-B(OH)_2$ for $R = Li, HBe, H_2B$, or Cl , we geometry optimized the *endo-exo* and *anti* forms for these acids at the MP2/aug-cc-pVTZ level. For the inorganic substituents Li and HBe , which provide a more ionic environment around the boron atom, the *endo-exo* conformers were ~2–3 kcal/mol lower in energy than the *anti* conformers, similar to what

we observed for H_3C and H_2N , and the calculated values of $\Delta H^\ddagger$ for the *endo-exo* $\rightarrow$ *anti* conversion were also similar, see Table 1. The PES surface of dihydroxylithioborane has been explored by Wagner *et al.* (43) Similar to their findings, the structure of our lowest-energy optimized *endo-exo* conformer is quite asymmetric with Li–B–O angles of 135.9° and 112.2° leading to a favorable Li^+O^- stabilizing interaction; the O–B–O angle, 111.9° , is the smallest we found for the boronic acids in this study. In a similar fashion, although to a lesser extent, the structure of HBe-B(OH)_2 is also asymmetric with Be–B–O angles of 128.5° and 116.7° leading to a stabilizing Be^+O^- electrostatic interaction. In contrast to the structure of $\text{H}_2\text{N-B(OH)}_2$, the BH_2 group in $\text{H}_2\text{B-B(OH)}_2$ is essentially orthogonal to the plane of the boronic acid moiety; this emphasizes the important role of the lone-pair of electrons on the nitrogen atom in boron-nitrogen bonding. The planar form of $\text{H}_2\text{B-B(OH)}_2$ is a rotational transition state (TS) with $\Delta H^\ddagger = 1.4$ kcal/mol. Surprisingly, perhaps as a result of the size of the Cl atom, the *anti* form of Cl-B(OH)_2 was 0.0₂ kcal/mol lower in energy than the *endo-exo* form at 298 K. Selected geometrical parameters for the *endo-exo* conformers of the boronic acids used in this paper are listed at the MP2(FC)/aug-cc-pVTZ level in Table 2S and at the HF/6-31G(*d*), MP2(FULL)/6-31G(*d*), and B3LYP/6-31G(2*df*,*p*) (Cl:6-31G(2*fg*)) levels in Table 3S; in a few cases MP2(FC)/aug-cc-pVQZ parameters are listed in the footnotes to Table 2S and B3LYP/6-311++G(2*df*,2*pd*) parameters in the footnotes to Table 3S for comparison. Although the MP2(FULL)/6-31G(*d*) structural parameters employed for the subsequent single-point calculations at the G2 and G3 levels are in slightly better agreement with the corresponding MP2(FC)/aug-cc-pVTZ parameters than those from the B3LYP/6-31G(2*df*,*p*) optimizations used at the G4 level, it should be noted that the B–O and B–R bond lengths can be as much as 0.005 Å shorter if the aug-cc-pVTZ basis set is replaced by the more complete aug-cc-pVQZ basis set. In any event, there are no experimental structural results available for comparison, so that the extent of the deviation from the “true” values remains unknown.

A.2 Charges—NPA charges on the boron atoms in R-B(OH)_2 ($\text{R} = \text{H, Li, HBe, H}_2\text{B, H}_3\text{C, H}_2\text{N, HO, F, and Cl}$) are listed in Table 4S and range widely, from +0.28e for Li– B(OH)_2 , where the charge on the Li atom is +0.66e, to +1.27e for F– B(OH)_2 , where the charge on the F atom is –0.48e. As would be expected, the increasing positive charges on the boron atoms in these acids reflect the increasing electronegativity of the substituent R, see Table 5S.

A.3 Heats of Formation—In Table 2A we list heats of atomization at 0 K and heats of formation at 298.15 K for the *endo-exo* conformers of R-B(OH)_2 ($\text{R} = \text{H, Li, HBe, H}_2\text{B, H}_3\text{C, H}_2\text{N, HO, F, and Cl}$) calculated at the G2, G3, and G4 levels of theory and, in selected cases, at the CBS-Q[CBS-QB3] and W1U levels of theory. Where comparisons can be made, our calculated G2 heats of formation are in good agreement with those from other authors. (41,44) Typically the calculated atomization energies at 0 K decrease in progressing from the G2 to the G4 levels of theory and the difference can amount to several kcal/mol, *e.g.* the value for F– B(OH)_2 decreases by 2.7 kcal/mol, see Table 2A. The concomitant change in the predicted heats of formation can also be significant, *e.g.* the G4 value of $\Delta H_f(298\text{ K})$ for boric acid differs from the G2 value by 2.4 kcal/mol (~1%). It can also be seen from Table 2A that the heats of formation calculated at the G3B3 level of theory are within a few tenths of a kcal/mol of the corresponding values at the G3 level, suggesting that the structural differences between the MP2(FU)/6-31G(*d*) and B3LYP/6-31G(*d*) levels noted in Table 3S are not a major source of error in calculating $\Delta H_f(298\text{ K})$ for the boronic acids in this investigation. (Consistent with this finding, the energy difference from single-point MP2(FC)/aug-cc-pV5Z calculations on H– B(OH)_2 using the G3 and G4 geometries is ca. 0.2 kcal/mol; correlating all the electrons this difference is 0.3 kcal/mol at the MP2(FULL)/aug-cc-pV5Z level and 0.2 kcal/mol at the CCSDT(FULL)/aug-cc-pVTZ level. In the case

of F-B(OH)_2 , the corresponding difference is 0.4 kcal/mol at the CCSDT(FULL)/aug-cc-pVQZ level.)

Unfortunately, the paucity of high-quality experimental thermal data for boronic acids excluded them from the various data sets that have been used to test heats of formation calculated at the G2, G3, and G4 levels of theory; indeed there are no boron-oxygen bonded species in the G3/05 data set. (45) Nevertheless, some data are available in the literature for comparison. As early as 1964, Porter and Gupta (46) determined $\Delta H_f(298\text{ K})$ for H-B(OH)_2 to be -153.8 ± 2.0 kcal/mol, see Table 1SA; although their results depended on the heats of formation of $\text{B}_2\text{H}_6(\text{g})$ and $\text{B(OH)}_3(\text{cr})$ available at that time and these values have been refined somewhat over the past 50 years, it is curious that the value for H-B(OH)_2 is not even listed in the current JANAF compilation. (5) Based on the Porter and Gupta (46) investigation of the reaction equilibrium for $(1/6)\text{B}_2\text{H}_6(\text{g}) + (2/3)\text{B(OH)}_3(\text{cr}) \leftrightarrow \text{HB(OH)}_2(\text{g})$, using rotational constants from the microwave spectra of $\text{H}^{11}\text{B(OH)}_2$ and $\text{H}^{10}\text{B(OH)}_2$, (47) an assumed geometry, and estimated spectroscopic data, Gurvich *et al.* (48) calculated a similar value of $\Delta H_f(298\text{ K})$ for this acid, -154.0 ± 2.0 kcal/mol. The remaining heats of formation for H-B(OH)_2 listed in Table 1SA involve either computer analyses of a variety of related boron compounds (6) or have a strong theoretical component. (41,49) The recent high-level computational investigation by Grant and Dixon (49) is of particular note. These authors reported a value of $\Delta H_f(298\text{ K})$ for H-B(OH)_2 of -154.6 ± 1.5 kcal/mol, which differs by less than 1 kcal/mol from either the value reported by Porter and Gupta (46) or the value estimated by Gurvich *et al.* (48) Furthermore, the predicted values of $\Delta H_f(298\text{ K})$ from the G2, G3[G3B3], and CBS-Q[CBS-QB3] levels of theory, -155.1 , $-153.9[-153.8]$, and $-154.3[-154.1]$ kcal/mol respectively, see Table 2A, all differ by less than 1 kcal/mol from the Grant and Dixon value. (49) Unfortunately, however, there remains more variability in the calculated values of $\Delta H_f(298\text{ K})$ than will be required for further applications. Specifically, the G4 heat of formation, -153.3 kcal/mol, and the W1U heat of formation, -156.2 kcal/mol, are at the opposite extremes of the uncertainty in the Grant and Dixon value, (49) even though these methods are purportedly better than the G2, G3, and CBS-Q methods.

We were unable to find any computational or experimental estimates of $\Delta H_f(298\text{ K})$ for R-B(OH)_2 ($\text{R} = \text{Li}, \text{HBe}, \text{H}_2\text{B}, \text{H}_3\text{C}, \text{or } \text{H}_2\text{N}$). Of particular interest for this collection of acids is $\text{H}_3\text{C-B(OH)}_2$ since the boronic acid moiety in the FDA approved drug Bortezomib (VelcadeTM), is directly connected to an sp^3 carbon atom making $\text{H}_3\text{C-B(OH)}_2$ a common building block of protease inhibitors. Furthermore, Bortezomib is known to exist in its anhydride form as a boroxine. (3) The calculated heats of formation for $\text{H}_3\text{C-B(OH)}_2$ are within ca. 1 kcal/mol of 170.0 kcal/mol, see Table 2A.

Experimental and computational thermal data are available for (ortho)boric acid, B(OH)_3 . The JANAF compilation (5) lists the heat of formation for boric acid as -237.2 ± 0.6 kcal/mol; Gurvich *et al.*, (48) using the enthalpy of formation and sublimation of $\text{B(OH)}_3(\text{cr})$, the observed frequencies, and estimated structural parameters calculated the heat of formation in the gas phase at 298.15 K as -240.0 ± 0.6 kcal/mol, ca. 2.8 kcal/mol lower than the JANAF (5) value. Stefani *et al.* (42) reported a G3MP2B3 heat of formation of -236.3 kcal/mol, ca. 1.1 kcal/mol greater than the JANAF (5) value. Using their high-level computational procedure, Grant and Dixon (49) predicted $\Delta H_f(298\text{ K})$ to be -239.8 ± 1.5 kcal/mol, in excellent agreement with the value reported by Gurvich *et al.* (48) The G2, G3[G3B3] and CBS-Q[CBS-QB3] values of $\Delta H_f(298\text{ K})$ are -240.1 , $-238.8[-238.9]$, and $-239.6[-239.3]$ kcal/mol respectively, see Table 2A, and are all within 1 kcal/mol of the Grant and Dixon value. (49) Unfortunately, the calculated G4 and W1U heats of formation, -237.7 and -241.7 kcal/mol respectively, differ from each other by 4 kcal/mol, and are somewhat outside the Grant and Dixon error limits at opposing ends.

Some thermochemical data are also available for F-B(OH)_2 . An early mass spectroscopic study by Porter *et al.* (50) gave 249.8 ± 2.5 kcal/mol for its heat of formation. Although $\Delta H_f(298 \text{ K})$ for F-B(OH)_2 is not listed in the JANAF compilation, (5) Gurvich *et al.* (48) used average B-F and B-OH bond energies, estimated structural parameters, and vibrational frequencies to deduce the heat of formation as -250.9 ± 5.0 kcal/mol. Duan *et al.* (41) reported a heat of formation for the *endo-exo* conformer at the G2 level of theory to be -250.6 kcal/mol, in excellent agreement with the Porter *et al.* (50) and Gurvich *et al.* (48) values. The calculated heats of formation at the G2, G3[G3B3], and CSB-Q[CSB-QB3] levels, -251.5 , $-250.5[-250.2]$, and $-251.0[-250.9]$ kcal/mol respectively, see Table 2A, are all in quite good agreement with the Gurvich *et al.* (48) value. However, similar to what we observed previously for H-B(OH)_2 and HO-B(OH)_2 , the G4 and W1U values, -248.8 and -253.0 kcal/mol respectively, differ substantially from each other and bracket the other extrapolation procedures.

The only thermodynamic data that we located for Cl-B(OH)_2 were from Gurvich *et al.* (48) Using average bond energies, estimated structural parameters, and vibrational frequencies from a variety of sources, the authors calculated the heat of formation as -192.5 ± 5.0 kcal/mol. The G2, G3[G3B3], and CBS-Q[CBS-QB3] calculations all favor a slightly more exothermic value, see Table 2A, but are within the relatively large uncertainty of the Gurvich *et al.* value. (48) Consistent with what we have noted above, the G4 and W1U level heats of formation bracket all the other calculated values.

The heats of formation calculated at the G3[G3B3] and CBS-Q[CBS-QB3] levels of theory for the boronic acids in this study consistently differ from each other by less than 1 kcal/mol for the second-row substituents in this investigation. In contrast, the heats of formation calculated using the G4 and W1U extrapolation procedures, which are expected to be the most accurate, can differ from each other by more than 4 kcal/mol and the values are on opposite sides of the corresponding G3[G3B3] and CBS-Q[CBS-QB3] results. These findings suggest we have not yet reached “chemical accuracy” for calculating heats of formation for boronic acids.

B. Boroxines

B.1 Structures— $\text{H}_3\text{B}_3\text{O}_3$ is the only boroxine compound whose gas phase experimental structure has been reported. Using electron diffraction, Chang *et al.* (51) found this molecule to be planar (D_{3h}) with $r(\text{B-H}) = 1.192 \pm 0.017 \text{ \AA}$, $r(\text{B-O}) = 1.3758 \pm 0.0021 \text{ \AA}$, $\angle \text{B-O-B} = \angle \text{O-B-O} = 120.0 \pm 0.04^\circ$, and $\angle \text{H-B-O} = 120^\circ$. (48) The structure of boroxine also has been studied computationally with mixed results, (52) specifically with respect to the values of the O-B-O and B-O-B bond angles. At the MP2/aug-cc-pVTZ level, these two angles are both predicted to be nearly 120° , see Table 2S, in excellent agreement with the experimental results, although some other computational levels report these angles to differ significantly and optimizations using MP2 and B3LYP methodologies often disagree on which of the two angles is greater. (12) As can be seen in Table 3S, this is also true for the MP2(FU)/6-31G(d) and B3LYP/6-31G(2df,p) geometries of $\text{H}_3\text{B}_3\text{O}_3$ used in the subsequent single-point calculations for the G2/G3 geometries and the G4 geometries, respectively; the calculated MP2(FU)/6-31G(d) value of the O-B-O angle, 120.2° , is in slightly better agreement with experiment and the MP2(FC)/aug-cc-pVTZ optimized value, 120.0° , than is the B3LYP/6-31G(2df,p) optimized value, 119.5° . Similar structural differences occur with several of the other boroxines, (12) *e.g.* see the values for the O-B-O angles in Tables 2S and 3S for trihydroxyboroxine: G2/G3(MP2(FU)/G-31G(d)) = 120.7° ; G4 (B3LYP/6-31G(2df,p)) = 119.9° (for comparison, at the MP2/6-31G(2df,p) and MP2/aug-cc-pVTZ levels the O-B-O angles are 120.8° and 120.6° , respectively). Nevertheless, no experimental gas-phase data for trihydroxyboroxine are available for comparison.

The O–B–O angles in the boroxine cores increase significantly as the electronegativities of the second row substituents increase - ranging from 116.7° for Li to 121.1° for F at the MP2/aug-cc-pVTZ level (the *ipso* angles for the corresponding monosubstituted benzenes at this level are 114.0° for Li and 122.5° for F; similar values have been reported by Campanelli *et al.* (53)). The O–B–O angles in the ring are typically larger than the analogous angle in the boronic acid, see Tables 2S; the F and Cl substituted compounds are the only exceptions. It may be noted that the O–B–O angle differences between the monomer and the corresponding trimer are consistently greater at the MP2 levels we employed than at the B3LYP levels, see Tables 2S and 3S. One particularly odd case involves H–B(OH)₂ and H₃B₃O₃: the O–B–O bond angles used in the G4 single-point calculations (B3LYP/6-31G(*d*)) are nearly the same for both the monomer and the trimer, whereas the O–B–O angle for the trimer is ca. 1° larger than the O–B–O angle for the monomer in the G2 and G3 calculations (MP2(FU)/6-31G(*d*)). Again, however, no experimental evidence is available to resolve this structural issue.

B.2 Charges—NPA charges on the boron atoms in the boroxine rings are consistently found to be more positive than in the corresponding monomers. For R=Li, HBe, and H₂B, the NPA charges on the adjacent Li, Be and B atoms are positive in the monomer and even more positive in the corresponding trimer, see Table 4S. For the more electronegative substituents, H₃C, H₂N, HO and F, the charge on the C, N, O, and F atoms are all negative in the monomer and become less negative in the trimer. It should be mentioned that for R = H₂N the NPA charge assigned to the N atoms in the monomer and trimer are the most negative we observed in this study. When H₂N–B(OH)₂ is optimized with an ammonia molecule dative-bonded to the B atom to fulfill its vacancy and remove the π -dative double bond character of the B–N bond, the NPA charge assigned to the nitrogen atom is even more negative, –1.123e *vs* –1.085e.

B.3 Heats of Formation—In Table 2B we list heats of atomization at 0 K and heats of formation at 298.15 K for R₃B₃O₃ (R = H, Li, HBe, H₂B, H₃C, H₂N, HO, F, and Cl) calculated at the G2, G3[G3B3], and G4 levels of theory; in selected cases, heats of formation are also given at the CBS-Q[CBS-QB3] and W1U levels of theory; we were not able to find any comparable boroxine calculations at these levels in the literature. To a large extent, the trends in atomization energies in going from G2→G4 for the boroxines mimic those for the corresponding boronic acids, *e.g.* the heat of atomization at 0 K for F₃B₃O₃ decreases by 5.6 kcal/mol and the heat of formation at 298.15 K for (OH)₃B₃O₃ is less negative by 4.8 kcal/mol (~0.9%).

As noted in the Introduction, the heat of formation of H₃B₃O₃ listed in the JANAF compilation, (5) –291.0±2.0 kcal/mol, seems to be in error. However, the ATcT (Active Thermochemical Tables) project of Ruscic and coworkers (54–56) report a similar value, –291.0±10.0, albeit with a much larger uncertainty, as do Gurvich *et al.* (48), –287.7±5.0 kcal/mol. As can be seen from Table 2B, the heats of formation calculated at the G2, G3[G3B3], G4, CBS-Q[CBS-QB3], and W1U levels of theory are all significantly less negative than the JANAF, ATcT, and Gurvich *et al.* values. (5,48,54–56) As we saw above with the boronic acids, the heats of formation calculated at the G4 and W1U levels bracket all the other calculated values. The values of $\Delta H_f(298\text{ K})$ obtained at the G2, G3[G3B3], and CBS-Q[CBS-QB3] levels differ by at most 1.1 kcal/mol from their average of –276.4 kcal/mol, ca. 15 kcal/mol less negative than the JANAF and ATcT values. Considering all of these calculations, it seems likely that the heat of formation of H₃B₃O₃ is significantly less negative than the values currently in the literature; (5,48,54–56) the precise origin of the discrepancy between the experimental and calculated values is not clear. It should be noted that heats of formation for H₃B₃O₃ predicted at the G3B3 and CBS-QB3 levels are only ~1–2 kcal/mol less negative than the corresponding values at the G3 or CBS-Q levels,

suggesting that differences in the B3LYP and MP2(FU) structural parameters noted above for $\text{H}_3\text{B}_3\text{O}_3$ are not the cause of the discrepancy. (Consistent with this finding, the energy difference from single-point CCSDT(FULL)/aug-cc-pVQZ calculations on boroxine using the G3 and G3B3 geometries is 0.2 kcal/mol; using the G3 and G4 geometries this difference is 0.3 kcal/mol.)

The authors were not able to find any estimates for the heats of formation of $\text{R}_3\text{B}_3\text{O}_3$ ($\text{R} = \text{Li}, \text{HBe}, \text{H}_2\text{B}, \text{H}_3\text{C}, \text{or } \text{H}_2\text{N}$) in the literature. This is particularly surprising in the case of $(\text{H}_3\text{C})_3\text{B}_3\text{O}_3$; the relative stability of this boroxine has led to a number of experimental and computational investigations of its properties, (11,57–60) but not its heat of formation. Based on the calculated values listed in Table 2B, $\Delta H_f(298 \text{ K})$ for $(\text{H}_3\text{C})_3\text{B}_3\text{O}_3$ is ca. –330 kcal/mol. The W1U calculation for trimethylboroxine failed with our available computer resources.

The heat of formation of trihydroxyboroxine (orthorhombic metaboric acid, MBA) is listed in the JANAF compilation as –543.0 kcal/mol, presumably for the C_{3h} conformer (MBA-I), (61) which is the lowest energy conformer in the gas-phase; (12,61) the ATcT value is the same, -543.0 ± 3.0 kcal/mol. Based on measurements of the equilibrium constants of the formation reaction of $(\text{HO})_3\text{B}_3\text{O}_3(\text{g})$, an assumed C_{3h} geometry based on semi-empirical calculations and the X-ray structural analysis of MBA-II, (62) along with estimated vibrational frequencies, Gurvich *et al.* (48) estimated the heat of formation to be -541.0 ± 5.0 kcal/mol, ca. 2 kcal/mol less negative than the JANAF or ATcT values, although the uncertainty is high. As can be seen from Table 2B, the G2, G3[G3B3], G4, and CBS-Q[CBS-Q3B] values are all less negative than the JANAF, ATcT, and Gurvich *et al.* values. (5,48,54–56) The corresponding W1U calculation failed to complete on our available computer resources; the G4 value of $\Delta H_f(298 \text{ K})$, –532.9 kcal/mol, is more than 4 kcal/mol less negative than the G3 value and ca. 8–10 kcal/mol less negative than the values recommended by JANAF, ATcT, or Gurvich *et al.* (5,48,54–56) Part of the relatively large disparity between the G3 and G4 heats of formation for $(\text{HO})_3\text{B}_2\text{O}_3$ may be the result of the structural differences noted above in the MP2(FU) and B3LYP optimized geometries. Specifically, the larger O–B–O bond angles in the ring at the MP2(FU)/6-31G(d) level lead to smaller O–B–O_{exo} angles; the B–O_{exo}–H angle is also smaller. These differences lead to shorter H···O_{ring} distances, stronger electrostatic interactions, and a more negative heat of formation at the MP2(FU) level. This is consistent with the more negative values of $\Delta H_f(298 \text{ K})$ predicted at the CBS-Q and G3 levels compared to the corresponding values at the CBS-QB3 and G3B3 level, see Table 2B.

The need for thermochemical data on F-B-O systems by workers in the fields of solid and liquid propellants around 1960 led to numerous determinations of the heat of formation of $\text{F}_3\text{B}_3\text{O}_3$, (63) see Table 1SB. From direct measurements of the equilibrium constant for the reaction

Fisher *et al.* (63) determined distances, stronger electrostatic interactions $\Delta H_f(298 \text{ K})$ for trifluoroboroxine to be –567.8 kcal/mol, in good agreement with an earlier transpiration study (64,65) of the reaction $\text{B}_2\text{O}_3(\text{gl}) + \text{BF}_3(\text{g})$, which gave -567.8 ± 0.5 kcal/mol; other estimates have been ca. –570 kcal/mol, (63) and mass spectroscopic measurements by Porter *et al.* (50) gave 569.8 ± 0.7 kcal/mol. The values listed in the JANAF (5) and ATcT (54–56) compilations, –565.3 kcal/mol and -565.8 ± 1.0 kcal/mol respectively, are several kcal/mol less negative than all the experimental values; Gurvich *et al.* (48) used updated estimates for some of the fundamental frequencies of $\text{F}_3\text{B}_3\text{O}_3$ to obtain a value for $\Delta H_f(298 \text{ K})$ of

–569.5±3.0 kcal/mol, which is more in line with the values from thermal and mass spectroscopic measurements. As can be seen from Table 2B, the heats of formation calculated at the G2, G3[G3B3], and CBS-Q[CBS-QB3] levels are more negative than the JANAF (5) and ATcT (54–56) values, but within ca. 2 kcal/mol of the value recommended in the Fisher report. (63) In contrast, the heat of formation predicted at the G4 level is nearly 5 kcal/mol less negative than the Fisher *et al.* (63) value and 2–3 less negative than the JANAF (5) and ATcT (54–56) values. The W1U calculation completed for trifluoroboroxine giving $\Delta H_f(298\text{ K}) = -571.7\text{ kcal/mol}$ and, as would be expected, is the most negative value we found.

The first reported estimate of $\Delta H_f(298\text{ K})$ for $\text{Cl}_3\text{B}_3\text{O}_3$, –378.8±3.5 kcal/mol, can be attributed to Porter and Gupta, (46,66) but it differs significantly compared to the JANAF (5) and ATcT (54–56) values of –390.0 and –390.0±2.0, respectively; Gurvich *et al.* (48) revised the JANAF value slightly to –391.0±4.0 kcal/mol. In this case the G2, G3[G3B3] heats of formation are slightly more negative than the values from these compilations, whereas the CBS-Q[CBS-QB3] heats of formation are significantly more negative, see Table 2B. Again, compared to the other calculations, the value of $\Delta H_f(298\text{ K})$ at the G4 level of theory is less negative, although in this case it is in excellent agreement with the values from the various compilations.

It is clear from the above results that there are a broad range of calculated and experimental heats of formations for the boroxines in this study. The G3B3 values of $\Delta H_f(298\text{ K})$ are consistently less negative than the corresponding G3 values, but by less than 1.5 kcal/mol for all the compounds containing second-row substituents; the relationship between the CBS-QB3 and CBS-Q heats of formation is similar, but the difference can be more 3.0 kcal/mol. Of particular concern from a computational perspective is the large difference between the predicted values of $\Delta H_f(298\text{ K})$ at the G4 and W1U levels of theory for the two boroxines where we were able to perform calculations at the W1U level. Admittedly, these two methodologies use different extrapolation procedures and basis sets, but the results seem to be diverging to some extent, and the explanation is not evident. Although the G4 method is a significant improvement over its predecessors G2 and G3 for predicting heats of formation for the compounds in the G3/05 data set, (15) there is a lack of experimental thermochemical data involving B–O bonded compounds in this set, which raises questions as to whether or not it is an improvement for molecules containing this structural feature. The computational demands of the W1U method have lead to relatively few comparisons with other extrapolation procedures.

C. Boroxine Formation from Boronic Acid Dehydration

In Table 3 we list reaction enthalpies for the dehydration

calculated from the G2, G3[G3B3], G4, CBS-Q[CBS-QB3], and W1U heats of formation given in Table 2 and compare them with values of ΔH_{298}^0 calculated at the MP2/aug-cc-pVDZ, MP2/aug-cc-pVTZ, and B3LYP/6-311++G(2df,2pd) levels. The following points may be noted: **1)** With the exception of $\text{H}_2\text{N}-\text{B}(\text{OH})_2$, all the dehydration reactions for these aliphatic boronic acids are exothermic; **2)** The calculated values of ΔH_{298}^0 for the dehydration at the MP2/aug-cc-pVDZ and MP2/aug-cc-pVTZ levels differ from each other by less than 1 kcal/mol; in a few cases, calculations at the CCSD(T)/aug-cc-pVTZ//MP2/aug-cc-pVTZ level have been shown to be in good agreement with these MP2 calculations; **(12) 3)** The calculated values of ΔH_{298}^0 at the B3LYP/6-311++G(2df,2pd) level are

consistently ~4 kcal/mol higher than the MP2 results, emphasizing again the problems with the B3LYP functional in some fundamental aspects of boron chemistry; (12,38,67–73) **4**) Despite the rather different values of $\Delta H_f(298\text{ K})$ predicted at the G2, G3[G3B3], G4, CBS-Q[CBS-QB3], and W1U levels of theory, the values of $\Delta H_f(298\text{ K})$ calculated from these heats of formation are quite consistent with each other and in good agreement with the values of ΔH_{298}^0 calculated at the MP2/aug-cc-pVD(T)Z levels; **5**) For the group of second-row substituents *in toto* ΔH_{298}^0 is not correlated with the atomic or group electronegativities, see Table 5S; **6**) For the group of substituents with lone pairs, H_2N , HO , and F , ΔH_{298}^0 increases as the σ -electron withdrawing capacity increases and the π -electron donating ability of the group decreases based on values of the Hammett constants, see Table 5S; (74) **7**) The large exothermic value of ΔH_{298}^0 for $\text{R} = \text{Li}$ is accompanied by a nearly 5° increase in the OB–O bond angle, suggesting significant strain in the resulting boroxine ring.

Concluding Remarks

Accurate heats of formation for simple boron compounds are necessary to build reliable group additivity methods and for use in balanced reactions for determining heats of formation for larger boron compounds. (75–80) Unfortunately, the available experimental thermodynamic properties for simple boronic acids and boroxines are extremely limited and their accuracy is not always as good as one might hope for. This problem is further exacerbated by the lack of reliable experimental structural and vibrational data on these compounds. Thus, the heats of formation at 298 K listed in the JANAF and Gurvich *et al.* (48) compilations have typically employed structural parameters, bond energies, and/or vibrational frequencies adopted from related molecules, making it difficult to assess the reliability of these tabulated results.

In this article we used the G2, G3[G3B3], G4, CBS-Q[CBS-QB3], and W1U levels of theory as implemented in the GAUSSIAN 03 (21) and GAUSSIAN 09 (22) suits of programs to calculate the heats of formation of R–B(OH)_2 and $\text{R}_3\text{B}_3\text{O}_3$ ($\text{R} = \text{H, Li, HBe, H}_2\text{B, H}_3\text{C, H}_2\text{N, HO, F, and Cl}$). Since the G4 and W1U heats of formation can differ by more than 4 kcal/mol for the boronic acids and nearly 10 kcal/mol for the boroxines, calculations have clearly not reached chemical accuracy for these molecules. Furthermore, some structural issues, particularly for the boroxines, need to be resolved. All this emphasizes the importance of the theoretical work of Curtiss and coworkers, (13), (14,15) Petersson and coworkers, (16) Grant and Dixon, (49) Martin and coworkers, (17,18) and Allen *et al.* (81) in developing the methodologies required to calculate improved heats of formation. It also points out the utility of the Active Thermochemical Tables (ATcT) approach developed by Ruscic and coworkers (54–56) for handling evolving thermochemical data.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Figure 1.
Endo-Exo, Anti, and Syn Conformers of the $R-B(OH)_2$ Monomers; the Bond Lengths (Å) and Bond Angles (°) shown are the MP2(FC)/aug-cc-pVTZ optimized values for $H-B(OH)_2$.

Table 1

Values of ΔH_{298}^0 and $\Delta H^\ddagger$ (kcal/mol) for the *endo-exo* $\rightarrow$ *anti* Conformer Conversion of the Boronic Acids, $R-B(OH)_2$ ($R = H, Li, HBe, H_2B, H_3C, H_2N, HO, F,$ and Cl), Calculated at the MP2(FC)/aug-cc-pVTZ//MP2(FC)/aug-cc-pVTZ Level.

R-B(OH)₂		
R	ΔH_{298}^0	$\Delta H^\ddagger$
H	+1.0	+9.3
Li	+2.8	+10.0
HBe	+2.8	+10.0
H ₂ B	+2.3	+8.9
H ₃ C	+2.0	+9.4
H ₂ N	+2.9	+7.0
HO	+4.0	+7.7
F	+0.6	+7.5
Cl	-0.0 ₂	+7.7

Table 2

Heats of Formation for Boronic Acids, Boroxines, and Water Calculated at the G2, G3[G3B3], G4, CBS-Q[CBS-QB3], and {W1U} Levels of Theory.

Molecule	G2 ^a		G3 ^a [G3B3]		G4 ^a		CBS-Q ^a [CBS-QB3] [W1U]
	ΔH _{atom} (0 K) (kcal/mol)	ΔH _f (298.15 K) (kcal/mol)	ΔH _{atom} (0 K) (kcal/mol)	ΔH _f (298.15 K) (kcal/mol)	ΔH _{atom} (0 K) (kcal/mol)	ΔH _f (298.15 K) (kcal/mol)	
A. Boronic Acids							
H-B(OH) ₂	560.8	-155.1		-153.9 [-153.8]	559.0	-153.3	-154.3 [-154.1] {-156.4}
Li-B(OH) ₂	501.5	-109.0	501.0	-108.5 [-108.8]	500.5	-108.0	-107.7 [-107.7]
HBe-B(OH) ₂	583.7	-101.1	583.2	-100.6 [-100.4]	584.7	-102.2	-100.4
H ₂ B-B(OH) ₂	714.0	-121.7	713.4	-121.1 [-120.9]	712.4	-120.1	-120.5 [-120.4]
H ₃ C-B(OH) ₂	848.8	-170.9	848.1	-170.2 [-170.0]	846.9	-169.1	-169.8 [-169.6]
H ₂ N-B(OH) ₂	753.4	-184.6	752.5	-183.7 [-183.8]	751.7	-182.9	-183.7 [-183.9]
HO-B(OH) ₂	704.4	-240.1	703.1	-238.8 [-238.9]	702.0	-237.7	-239.6 [-239.3] {-241.7}
F-B(OH) ₂	624.4	-251.5	623.4	-250.5 [-250.2]	621.7	-248.8	-251.0 [-250.9] {-253.0}
Cl-B(OH) ₂	577.8	-194.7 ^b	576.2	-193.1 [-192.7]	575.1	-192.0	-195.0 [-194.5] {-195.7}
B. Boroxines							
H ₃ B ₃ O ₃	1011.9	-277.5	1010.9	-276.5 [-275.8]	1009.1	-274.7	-276.7 [-275.7] {-280.2}
Li ₃ B ₃ O ₃	827.5	-132.2	828.7	-133.4 [-133.3]	827.0	-131.8	-131.7 [-129.0]
(HBe) ₃ B ₃ O ₃	1083.8	-118.3	1084.9	-119.4 [-118.0]	1089.4	-124.1	-117.5
(H ₂ B) ₃ B ₃ O ₃	1476.9	-182.4	1478.1	-183.6 [-182.3]	1474.7	-180.4	-181.8 [-180.0]
(H ₃ C) ₃ B ₃ O ₃	1881.4	-329.9	1882.5	-331.0 [-329.9]	1878.7	-327.5	-330.0 [-328.0]
(H ₂ N) ₃ B ₃ O ₃	1604.8	-381.2	1605.1	-381.5 [-381.3]	1602.0	-378.6	-381.0 [-380.5]
(HO) ₃ B ₃ O ₃ (MBA-I)	1448.2	-537.7	1447.5	-537.0 ^c [-536.5] ^c	1443.2	-532.9	-539.9 [-536.5]
F ₃ B ₃ O ₃	1204.7	-568.4	1205.0	-568.7 [-567.3]	1199.1	-562.9	-570.8 [-568.3] {-571.7}
Cl ₃ B ₃ O ₃	1063.3	-396.1	1060.4	-393.3 [-391.6]	1056.9	-389.8	-399.4 [-396.1]
C. H ₂ O	219.7	-58.0	219.0	-57.3 [-57.5]	218.9	-57.3	-57.8 [-58.1] {-58.4}

^aExperimental atomic heats of formation (kcal/mol) at 298K used in the calculations: H, 52.103; B, 136.3; C, 171.29; N, 112.97; O, 59.555; F, 18.97; Cl, 28.992. These values are from the JANAF compilation, except for B, which is the revised value recommended by Karton and Martin, (82)

^bUsing the *anti* conformer in place of the *endo-exo* conformer changes the G2 heat of formation by only ~ 0.07 kcal/mol.

^cThe corresponding values for MBA-II are $-536.3[-535.8]$ kcal/mol.

Table 3

Reaction Enthalpies *in vacuo* for the Dehydration Reactions

(R = H, Li, HBe, H₂B, H₃C, H₂N, HO, F, and Cl) at the MP2(FC)/aug-cc-pVDZ//MP2(FC)/aug-cc-pVDZ, MP2(FC)/aug-cc-pVTZ//MP2(FC)/aug-cc-pVTZ, B3LYP/6-311++G(2df,2dp)/B3LYP/6-311++G(2df,2dp), G2, G3[G3B3], G4, CBS-Q[CBS-QB3], and {W1U} Levels of Theory.

R	ΔH_{298}^0 (kcal/mol)		ΔH_r (298 K) (kcal/mol)				
	MP2						
	aug-cc-pVDZ	aug-cc-pVTZ	B3LYP	G2	G3 [G3B3]	G4	CBS-Q [CBS-QB3] {W1U}
H	+12.0	+12.2	6-311++G (2df,2pd) +16.2 ^c	+13.9	+13.3 [+13.1]	+13.3	+12.8 [+12.3] {+13.8}
Li	+20.0	+20.7	+24.7	+21.0	+20.1 [+20.6]	+20.4	+18.0 [+19.8]
HBe	+9.2	+9.6	+14.6	+11.2	+10.4 [+10.7]	+10.8	- [+9.4]
H ₂ B	+6.7	+7.0	+11.4	+8.8	+7.7 [+7.9]	+8.3	+6.3 [+6.9]
H ₃ C	+6.5 ^b	+6.7 ^{ab}	+10.6	+8.8	+7.0 [+7.6]	+8.0	+6.0 [+6.5]
H ₂ N	-3.3 ^b	-2.9 ^{ab}	+0.7	-1.3	-2.5 [-2.4]	-1.8	-3.3 [-3.1]
HO	+6.9 ^b	+7.3 ^b	+10.5	+8.7	+7.5 [+7.7]	+8.5	+5.5 [+5.1]
F	+11.3 ^b	+10.8 ^b	+13.9	+12.2	+10.7 [+10.8]	+11.9	+8.8 [+10.1] {+12.2}
Cl	+13.6	+13.8	+17.8	+14.2	+14.0 [+14.0]	+14.6	+12.2 [+13.1]

^a Thermal corrections are from the MP2(FC)/aug-cc-pVDZ//MP2(FC)/aug-cc-pVDZ level.

^b Values from Bhat *et al.* (12)

^c At the B3LYP/6-31G(2df,2p) level ΔH_{298}^0 is +21.6 kcal/mol.