C-Hydroxydicarba-*closo*-dodecaboranes

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An improved synthesis and a full characterization of all three 12-vertex *C*-hydroxydicarba-*closo*-dodecaboranes **1**−**3** are reported. These inorganic analogues of phenols are highly acidic, but unlike phenols, they are transparent in the near-UV region and are stable to oxidation. The structure of their oxyanions **1a**−**3a** poses an interesting issue of a closo versus a bridged nido form. Also described is an introduction of a functionalized spacer in position 2 of **1** designed to permit incorporation into more complex organic structures.

Introduction

The ortho, meta, and para isomers of dicarba-*closo*-dodecaborane[1] have been known for a long time. Early investigations showed that it is possible to prepare a variety of derivatives substituted on carbon and/or boron atoms.[2] Surprisingly, some of the simplest derivatives have remained virtually unknown. Thus, while several *B*-hydroxy derivatives have been described,[3] we have been able to find only three studies of *C*-hydroxy derivatives in the literature. The first two describe the synthesis and IR spectra of the parent *C*-hydroxy *o*- and *m*-carboranes, prepared by oxidation of the corresponding lithiocarboranes with benzoyl peroxide[4] or oxygen.[5] The para isomer remained unknown. The more recent third report deals with the synthesis and properties of 1-hydroxy-2-phenyl-*o*-carborane.[6]

12-Vertex *C*-hydroxycarboranes, which can be viewed as inorganic analogues of phenols, might have interesting properties. Because of the electron-deficient nature of the deltahedral boron cages, they are highly acidic (the pK_a values reported for the ortho and meta isomers are 5.25 and 8.24, respectively[5]), but unlike phenols, they would be expected to be transparent in the near-UV region, and presumably quite stable to oxidation.

In addition, their oxyanions pose an interesting issue of closo versus nido structure. An X-ray diffraction study showed that the 1-oxy-2-phenyl-*o*-carboranyl anion exists in the nido form with a bridging carbonyl group and the negative charge presumably mostly in the polyhedral cage,[6] while the structures of the corresponding thio and amino derivatives[7] are much closer to the closo form. It was also suggested, on the basis of molecular orbital calculations, that the structures of the corresponding meta and para oxyanions would show only very slight displacements from the closo toward the nido form.

Finally, the incorporation of the dicarba-*closo*-dodecaborane moieties into complex organic structures recently became of interest to technology and medicine.[8] It would be interesting to prepare *C*-hydroxycarboranes substituted on another vertex in a manner that permits their incorporation into such structures.

Experimental Section

Materials. Carboranes were purchased from KatChem (Prague, Czech Republic) and were used without further purification. 1,4-Diazabicyclo[2.2.2]octane, trimethylchlorosilane, *n*-butyllithium (1.6 M in hexane), chloromethyl ethyl ether, borane−tetrahydrofuran complex (1.0 M in THF) and 9-borabicyclo[3.3.1]nonane (9-BBN, 0.5 M in THF) were purchased from Aldrich. All solvents were dried prior to use. Bis(trimethylsilyl) peroxide was prepared according to the procedure of Taddei and Ricci.[9]

Physical Measurements. NMR measurements were done on a Varian XRS-300 spectrometer operating at 300, 96.23, and 75.24 MHz for ^{1}H, ^{11}B, and ^{13}C nuclei, respectively. The ^{11}B-decoupled ^{1}H NMR measurements were done on a Bruker AM-400 spectrometer operating at 400.141 MHz. Chemical shift values are relative to TMS for ^{1}H and ^{13}C and to B(OMe)$_3$ for ^{11}B and are given in δ (ppm); *J* values are given in hertz. The IR spectra were recorded on a Perkin-Elmer 1650 spectrometer in KBr pellets and in THF solutions. Elemental analyses were performed by Desert Analytics and Microanalytical Laboratory, Berkeley. GC/MS analyses were done on a Hewlett-Packard system.

Methods of Calculation. Structures were optimized using Gaussian 94[10] (HF/6-31G*) and Turbomole 95.0/3.0.0©1995, Biosym/MSI (MP2/6-31G*), programs. NMR spectra were calculated using the 6-31G* basis set and the GIAO method.[11]

1-Hydroxy-1,2-dicarba-*closo*-dodecaborane (1). *o*-Carborane (1.44 g, 10 mmol) was placed in a three-necked flask, and THF (20 mL) was added under an atmosphere of nitrogen. The solution was cooled to −78 °C, and *n*-butyllithium (6.25 mL, 1.6 M, 10 mmol) was added. The mixture was stirred for 1 h, allowed to warm to room temperature,

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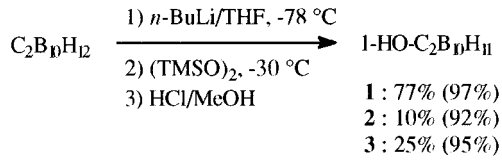
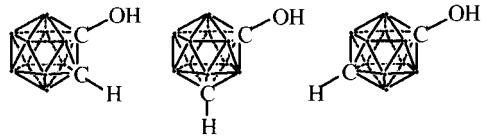
Scheme 1





1 **2** **3**

Table 1. Properties of *C*-Hydroxycarboranes **1**−**3** and of *C*-Oxycarboranyl Anions **1a**−**3a**

compd	mp (°C)	pK_a[a]	IR (cm^{-1})[b]
1	121−122	5.33 ± 0.04	3287 (O−H) 3064 (C−H) 2597 (B−H) 1232 (C−O)
1a			3087 (C−H) 2575 (B−H) 1394 (C−O)
2	124−126	8.39 ± 0.06	3356 (O−H) 3060 (C−H) 2601 (B−H) 1204 (C−O)
2a			3032 (C−H) 2614 (B−H) 1246 (C−O)
3	141−142	9.03 ± 0.07	3266 (O−H) 3065 (C−H) 2610 (B−H) 1202 (C−O)
3a			3046 (C−H) 2624 (B−H) 1253 (C−O)

[a] In 50% aqueous C_2H_5OH. [b] In KBr pellet for **1**−**3** and in THF solution for **1a**−**3a**.

and stirred for an additional 3 h. Bis(trimethylsilyl) peroxide (1.95 g, 11 mmol) was added slowly to this solution at −30 °C. The mixture was warmed to room temperature and stirred for 12 h. Pentane (25 mL) was added, and after the mixture was washed with saturated ammonium chloride solution (20 mL), the solvent was removed under reduced pressure. The mixture was eluted on a Chromatotron silica plate with CH_2Cl_2. Unreacted carborane was eluted first. The second band was identified as 1-(trimethylsiloxy)-*o*-carborane, yield 1.80 g, 77%. Yield corrected for starting material recovery is 98%. ^{1}H NMR ($CDCl_3$): δ 3.95 (s, 1 H, CH), 3.4−1.2 (m, 10 H, BH), 0.11 (s, 9 H, $SiMe_3$). ^{11}B NMR ($CDCl_3$): δ −4.91 (d, 1 B, J = 152), −13.22 (d, 7 B, J = 165), −15.57 (d, 2 B, J = 174). The 1-(trimethylsiloxy)-*o*-carborane (1.80 g, 7.76 mmol) was dissolved in a mixture of methanol and hydrochloric acid (20:1, 20 mL), and the solution was stirred at room temperature for 24 h. The mixture was diluted with water (15 mL) and extracted with ether (100 mL). The ethereal layer was treated with 10% NaOH in water (50 mL), and the alkaline layer was separated from the mixture, neutralized with dilute hydrochloric acid, and extracted with hexane (100 mL). The hexane layer was dried over anhydrous $MgSO_4$, and the solvent was removed. The resulting white solid was identified as pure **1** (yield 1.20 g, 97%; see Tables 1 and 2). ^{11}B NMR ($CDCl_3$): δ −4.18 (d, 1 B, J = 155), −12.61 (d, 7 B, J = 168), −14.90 (d, 2 B, J = 172). MS-EI (*m*/*z*): 159 (M − H, 100), 131 (M − COH, 30). Anal. Calcd: C, 15.00; H, 7.50. Found: C, 14.77; H, 7.61.

1-Hydroxy-1,7-dicarba-*closo*-dodecaborane (2) was prepared according to the procedure described for **1**. Conversion: 10%. Yield after correction for starting material recovery: 92% (see Tables 1 and 2). ^{11}B NMR ($CDCl_3$): δ −5.31 (d, 1 B, J = 166), −11.97 (d, 2 B, J = 185), −13.86 (2 B, not resolved), −16.50 (d, 5 B, J = 177). MS-EI (*m*/*z*): 159 (M-H, 100), 131 (M-COH, 27). Anal. Calcd: C, 15.00; H, 7.50. Found: C, 15.41; H, 7.42.

1-Hydroxy-1,12-dicarba-*closo*-dodecaborane (3) was prepared by following the procedure used for **1**. Conversion: 25%. Yield corrected for starting material recovery: 95% (see Tables 1 and 2). ^{11}B NMR ($CDCl_3$): δ −13.34 (5 B, d, J = 169), −17.5 (5 B, d, J = 172). MS-EI (*m*/*z*): 160 (M, 100), 131 (M − COH, 27). Anal. Calcd: C, 15.00; H, 7.50. Found: C, 15.33; H, 7.76.

Sodium 1-Oxy-1,*n*-dicarba-*closo*-dodecaboranyls (1a, 2a, 3a). The 1-hydroxycarboranes **1**−**3** (0.02 g, 0.125 mmol) were dissolved in degassed THF under an atmosphere of argon, and NaH (0.003 g, 0.125 mmol) was added. Spectra were measured after gas stopped evolving and NaH disappeared (Tables 1 and 2).

1-(Ethoxymethoxy)-2-allyl-1,2-dicarba-*closo*-dodecaborane (4). 1-Hydroxy-*o*-carborane (**1**) (0.32 g, 2 mmol) was placed in a three-necked flask, and THF (20 mL) was added under an atmosphere of nitrogen at room temperature. NaH (0.06 g, 2.5 mmol) was added under a flow of nitrogen. The mixture was stirred until the gas stopped evolving and NaH disappeared. Chloromethyl ethyl ether (0.19 g, 2 mmol) was added slowly to this solution, immediately producing a white precipitate. The mixture was stirred for 3 h and NaCl allowed to precipitate completely. The clear solution was cannulated to another three-neck flask under nitrogen and cooled to −78 °C. *n*-BuLi (1.38 mL, 2.2 mmol) was added, and the mixture was stirred for 1 h, allowed to warm to room temperature, and stirred for an additional 3 h. Allyl iodide (0.42 g, 2.5 mmol) was added, and the mixture was stirred for 12 h. The solvent was removed under reduced pressure, and the crude product was purified on a silica gel column with hexane−dichloromethane (10:1) as an eluent, providing **4** (0.49 g, 95%). ^{1}H NMR ($CDCl_3$): δ 5.74 (m, 1 H, CH═), 5.16 (dd, 1 H, ═CH_2), 5.09 (dd, 1 H, ═CH_2), 4.96 (s, 2 H, O−CH_2−O), 3.65 (q, 2 H, O−CH_2), 2.96 (d, 2 H, allylic CH_2), 1.21 (t, 3 H, CH_3). ^{11}B {^{1}H} NMR ($CDCl_3$): δ −7.63 (1 B), −12.01 (3 B), −13.22. (3 B), −14.18 (3 B). ^{13}C {^{1}H} NMR ($CDCl_3$): δ 135.67 (HC═), 114.54 (H_2C═), 112.53 (C−O), 87.74 (O−CH_2−O), 69.23 (C−CH_2), 27.24 (C−CH═). IR (cm^{-1}): 2938, 2891, 2590, 1702, 1455, 1245, 1032. MS (*m*/*z*): 258 (M, 10), 243 (M − Me, 85). Anal. Calcd: C, 37.19; H, 8.58. Found: C, 36.94; H, 8.76.

1-Hydroxy-2-(3-hydroxypropyl)-1,2-dicarba-*closo*-dodecaborane (5). 1-(Ethoxymethoxy)-2-allyl-1,2-dicarba-*closo*-dodecaborane (**4**, 0.44 g, 2 mmol) was placed in a three-necked flask, and THF (10 mL) was added, under an atmosphere of nitrogen at room temperature. 9-BBN (4.4 mL, 2.2 mmol) was added, and the mixture was refluxed for 1 h. A solution of NaOH (3 M, 0.2 mL, 0.6 mmol) was added, followed by a 30% solution of H_2O_2 (0.3 mL, 2.5 mmol). The mixture was stirred for 1 h, and the solvent was removed under reduced pressure. A mixture of methanol and HCl (20:1, 10 mL) was added. The mixture was stirred for 24 h at room temperature, diluted with water (5 mL), and extracted with ether (50 mL). The ethereal layer was treated with 10% NaOH in water (20 mL) and separated from the mixture. The alkaline layer was further treated with dilute hydrochloric acid and extracted with hexane (100 mL). The hexane layer was dried over anhydrous $MgSO_4$, and the solvent was removed to yield **5** as a white solid (0.43 g, 98%). This was further purified by crystallization from hexane. ^{1}H NMR ($CDCl_3$): δ 3.75 (t, 2 H, HO−CH_2), 2.44 (t, 2 H, 1-CH_2), 1.84 (t, 2 H, 2-CH_2). ^{11}B {^{1}H} NMR ($CDCl_3$): δ −7.75 (1 B), −11.98 (3 B), −13.34. (3 B), −14.25 (3 B). ^{13}C {^{1}H} NMR

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Table 2. Calculated and Observed NMR Chemical Shifts of *C*-Hydroxycarboranes **1**−**3** and of *C*-Oxycarboranyl Anions **1a**−**3a**

	^{1}H, δ (ppm)[a]		^{13}C, δ (ppm)[a]		^{11}B, δ (ppm)[a]	
compd	calcd	obsd	calcd	obsd	calcd	obsd
1	1.85 (1H, OH) 2.03 (4H, BH) 2.12 (2H, BH) 2.37 (2H, BH) 2.50 (1H, CH) 2.53 (2H, BH)	2.01 (4H, BH) 2.11 (4H, BH) 2.23 (2H, BH) 3.94 (s, 1H, CH) 5.15 (s, 1H, OH)	65.5 (C2) 97.7 (C1)	65.52 (CH) 102.09 (C−O)	−15.0 (B7,11) −12.0 (B3,6, B4,5, B8,10, B12) −2.4 (B9)	−14.90 (2B) −12.61 (7B) −4.18 (1B)
1a	1.04 (1H, BH) 1.16 (2H, BH) 1.45 (2H, BH) 1.66 (2H, BH) 2.02 (1H, CH) 2.27 (1H, BH) 2.48 (2H, BH)	2.18 (4H, BH) 2.45 (4H, BH) 2.98 (2H, BH) 4.54 (s, 1H, CH)	70.9 (C2) 189.1 (C1)	73.29 (CH) 204.95 (C═O)	−20.0 (B12) −18.4 (B4,5); −17.4 (B8,10) −11.8 (B7,11) −1.9 (B3,6) −1.5 (B9)	−22.91 (1B) −16.23 (4B) −13.77 (2B) −10.75 (2B) −7.65 (1B)
2	0.96 (1H, OH) 1.23 (1H, BH) 1.97 (4H, BH) 2.10 (1H, CH) 2.47 (3H, BH) 3.02 (2H, BH)	1.95 (6H, BH) 2.04 (1H, BH) 2.44 (2H, BH) 2.60 (1H, BH) 2.82 (s, 1H, CH) 4.67 (s, 1H, OH)	57.0 (C2) 102.8 (C1)	51.45 (CH) 104.51 (C−O)	−16.0 (B8,11); −15.5 (B2,3) −14.2 (B9,10) −11.9 (B12); −11.6 (B4,6) −3.8 (B5)	−16.50 (4B) −13.86 (2B) −11.97 (3B) −5.31 (1B)
2a	0.35 (2H, BH) 0.79 (1H, CH) 1.09 (2H, BH) 1.24 (2H, BH) 2.30 (2H, BH) 2.50 (1H, BH) 2.71 (1H, BH)	2.11 (6H, BH) 2.27 (1H, BH) 2.63 (2H, BH) 2.87 (1H, BH) 3.07 (s, 1H, CH)	49.4 (C2) 139.7 (C1)	61.12 (CH) 132.76 (C−O)	−26.1 (B12) −20.8 (B8,11); −18.3 (B9,10) −13.9 (B2,3) −9.7 (B4,6) −0.5 (B5)	−23.14 (1B) −17.83 (4B) −15.13 (2B) −12.95 (2B) −5.68 (1B)
3	0.75 (1H, OH) 1.15 (1H, CH) 2.02 (5H, BH) 2.25 (2H, BH) 2.59 (3H, BH)	2.04 (5H, BH) 2.44 (5H, BH) 2.89 (s, 1H, CH) 3.95 (s, 1H, OH)	62.3 (C2) 114.9 (C1)	47.94 (CH) 109.43 (C−O)	−17.7 (B7−11) −13.3 (B2−6)	−17.50 (5B) −13.34 (5B)
3a	0.23 (1H, CH) 1.23 (5H, BH) 2.30 (5H, BH)	1.89 (5H, BH) 2.53 (5H, BH) 3.46 (s, 1H, CH)	38.4 (C2) 154.3 (C1)	55.23 (CH) 144.03 (C−O)	−21.5 (B7−B11) −9.8 (B2−B6)	−21.14 (5B) −10.22 (5B)

[a] In $CDCl_3$ for **1**−**3** and in THF-d_8 for **1a**−**3a**. Chemical shifts are relative to TMS for ^{13}C and to $B(OMe)_3$ for ^{11}B.

($CDCl_3$): δ 103.15 (C−OH), 69.32 (C−C), 61.23 (H_2C−OH), 33.25 (H_2C−C), 30.74 (−CH_2−). IR (cm^{-1}): 3342, 2926, 2853, 2591, 1454, 1047. MS-EI (*m*/*z*): 217 (M − 1, 20), 200 (M − H_2O, 100). Anal. Calcd: C, 27.51; H, 8.31. Found: C, 27.98; H, 8.12.

1-Hydroxy-2-(*2*-hydroxypropyl)-1,2-dicarba-*closo*-dodecaborane (6). 1-(Ethoxymethoxy)-2-allyl-1,2-dicarba-*closo*-dodecaborane (**4**, 0.44 g, 2 mmol) was placed in a three-necked flask, and THF (10 mL) was added under an atmosphere of nitrogen at room temperature. BH_3·THF complex solution (1 mL, 1 mmol) was added, and the mixture was stirred for 1 h. A solution of NaOH (3 M, 0.2 mL, 0.6 mmol) was added, followed by a 30% solution of H_2O_2 (0.3 mL, 2.5 mmol). The mixture was stirred for 1 h, and the solvent was removed under reduced pressure. A mixture of methanol and HCl (20:1, 10 mL) was added, and the mixture was stirred for 24 h at room temperature, diluted with water (5 mL), and extracted with ether (50 mL). The ethereal layer was treated with 10% NaOH in water (20 mL) and separated from the mixture. The alkaline layer was neutralized with dilute hydrochloric acid and extracted with hexane (100 mL). The hexane layer was dried over anhydrous $MgSO_4$, and the solvent was removed. The white solid obtained (0.39 g, 90%) was identified as a 3:2 mixture of **5** and **6**, which were separated by column chromatography on silica gel, using a gradient elution with hexane−dichloromethane. Compound **6** was further purified by crystallization from hexane. ^{1}H NMR ($CDCl_3$): δ 4.25 (sxt, 1 H, CH), 2.63 (d, 2 H, CH_2), 1.31 (d, 3 H, CH_3). ^{11}B {^{1}H} NMR ($CDCl_3$): δ −7.70 (1 B), −11.95 (3 B), −13.28. (3 B), −14.31 (s, 3 B). ^{13}C NMR ($CDCl_3$): δ 104.23 (C−OH), 72.14 (C−C), 66.78 (CH−OH), 43.09 (−CH_2−), 29.57 (CH_3). MS-EI (*m*/*z*): 217 (M − 1, 30), 200 (M − H_2O, 100). IR (cm^{-1}): 3352, 2932, 2924, 2590, 1427, 1045. Anal. Calcd: C, 27.51; H, 8.31. Found: C, 27.11; H, 8.46.

pK_a Measurements. Literature procedures were followed.[12] The hydroxycarboranes were dissolved in 50% aqueous ethanol (total volume 3 mL or 6 mL) and titrated with 0.1 or 0.01 M NaOH. All solutions were freshly prepared. The pH-meter (ORION 701A) with a Ross combination pH electrode (ORION 81-02) was calibrated with aqueous buffer solutions of pH 4.0 (potassium carbonate/borate/hydroxide), 7.0 (potasium phosphate/hydroxide), and 10.0 (potassium biphthalate), purchased from Fisher Scientific. The measured pH values were plotted against volumes of NaOH consumed and pK_a values evaluated using program StatMost 2.5 for Windows, Copyright©1994 DataMost Corp.

Results and Discussion

Synthesis of *C*-Hydroxycarboranes. Two synthetic methods leading to C-substituted carboranes are commonly used: the reaction of substituted acetylenes with decaborane and substitution on carboranyllithium.[13] However, the first method does not seem to be applicable in an attempted preparation of *C*-hydroxycarboranes. It was used for the preparation of 1-ethoxy-*o*-carborane[14] in a low yield and afforded a complex mixture.

Oxidation of lithium derivatives of numerous organic compounds followed by hydrolysis is known to lead to the

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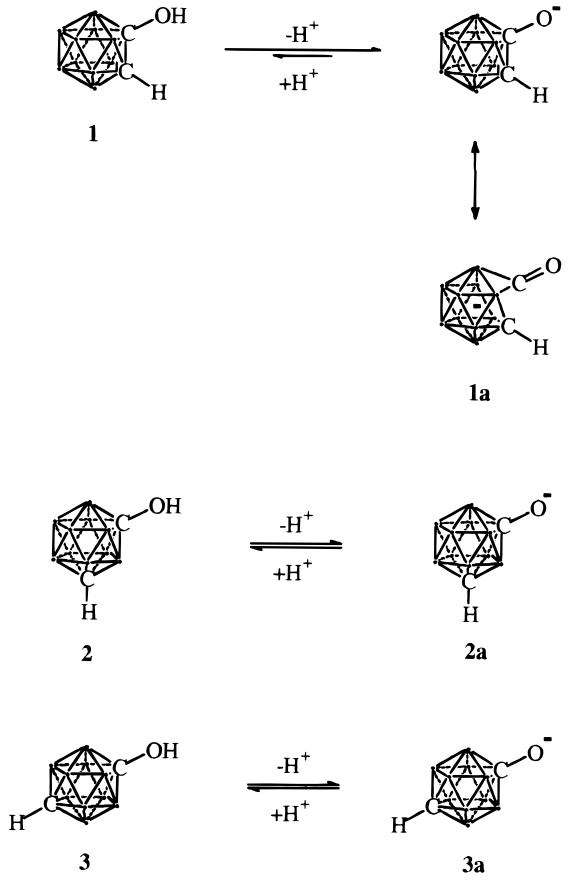
Chart 1



corresponding hydroxy compounds.[15] Although the preparation of *C*-hydroxy *o*- and *m*-carboranes by oxidation of the corresponding lithiocarboranes with benzoyl peroxide, reported earlier,[4] provided access to these compounds for the first time, it wastes half of the carborane by converting it into a 1-benzoylcarborane. Oxidation with oxygen produced *C*-hydroxycarboranes in low yields.[5]

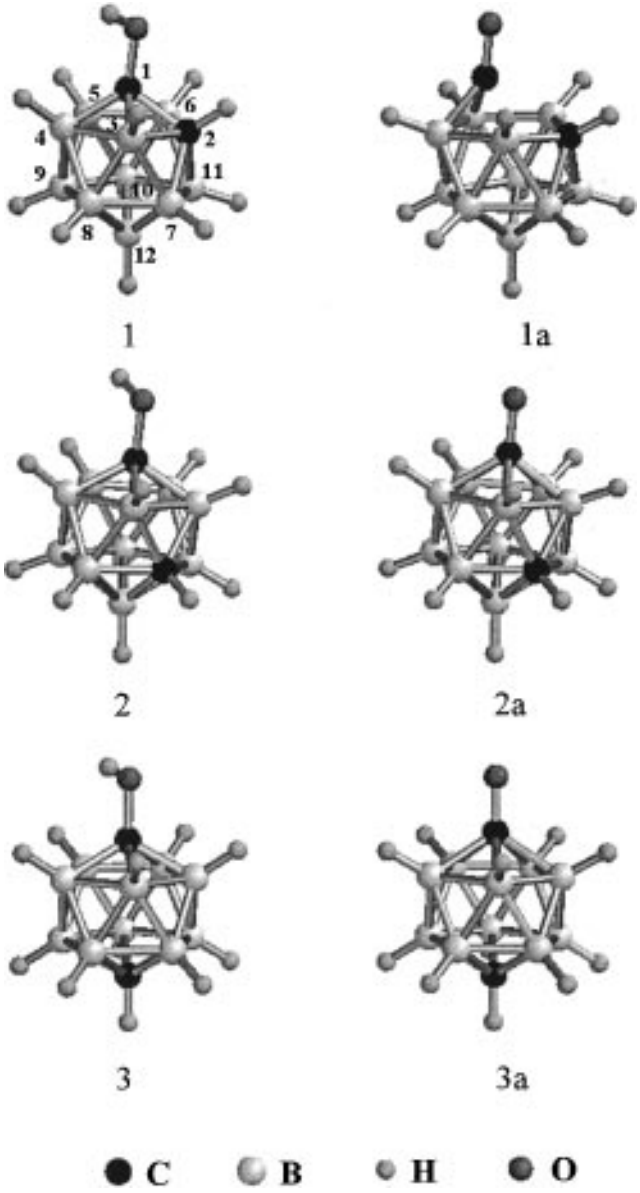
We have examined the use of other commonly used oxidants. Our attempts to prepare *C*-hydroxycarboranes from the parent 12-vertex carboranes by oxidation of the lithium salts with trimethylamine *N*-oxide, pyridine *N*-oxide, or dimethyloxirane[16] led only to traces of the desired products, together with various byproducts. However, oxidation of the lithium salts with bis(trimethylsilyl) peroxide[9] gave the target compounds in excellent yields, albeit in low conversion (Scheme 1).

Properties of *C*-Hydroxycarboranes. The *C*-hydroxycarboranes **1**−**3** are transparent in the UV region to 205 nm. Their IR spectra show C−O, B−H, C−H, and O−H stretching bands at about 1200, 2600, 3060, and 3300 cm^{-1}, respectively. The ^{11}B, ^{13}C, and ^{1}H NMR chemical shifts and characteristic IR bands are listed in Tables 1 and 2.

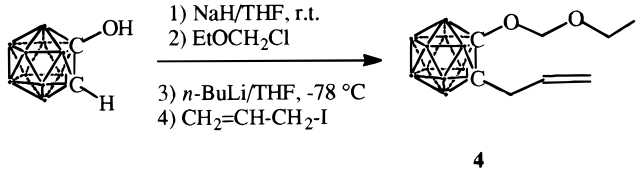
Compounds **1**−**3** are very stable toward dilute acid and base solutions. They sublime easily under reduced pressure and are soluble in most common organic solvents.

The earlier report on **1** and **2** by Zakharkin *et al.*[4] indicated their high acidity. The reported pK_a values were 5.25 and 8.24, respectively, and the high acidity was attributed mainly to "the electron-acceptor effect of the carborane ring".[4] Also, the ability

Chart 2



Scheme 2



of hydroxycarboranes to form salts upon reaction with aqueous alkalis and triethylamine was reported.[4] We prepared the corresponding sodium salts of *C*-hydroxycarboranes, **1a**−**3a**, by the reaction with NaOH in water or with NaH in THF and characterized these salts by ^{13}C, ^{11}B, and ^{1}H NMR and IR spectroscopy (Tables 1 and 2).

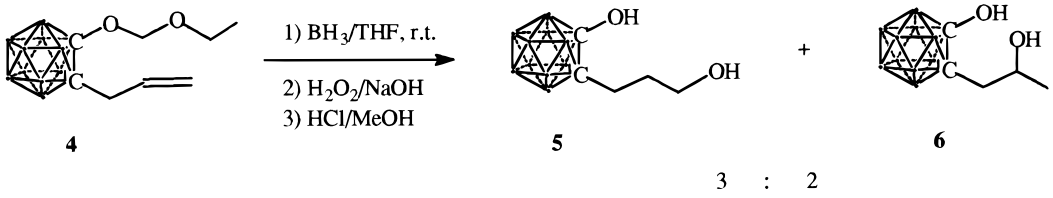
We measured the pK_a values of *C*-hydroxycarboranes **1**−**3** by titration of their solutions in 50% aqueous ethanol with NaOH (Table 1). The pK_a values for **1** and **2** are higher than those reported earlier by ca. 0.1 pK_a unit. However, we found a similar difference for benzoic acid, as our result was 5.62 ± 0.03 (Zakharkin *et al.*[4] reported a pK_a value of 5.55, while the literature value[17] is 5.65 ± 0.03), thus suggesting an instrumental

(15) Wakefield, B. J. *The Chemistry of Organolithium Compounds*; Pergamon Press: Oxford, New York, 1974.

(16) Vogel, A. I. *Vogel's Textbook of Practical Organic Chemistry*, 5th ed.; Longman Scientific & Technical, John Wiley & Sons: New York, 1989.

(17) Grunwald, E.; Berkowitz, B. J. *J. Am. Chem. Soc.* **1951**, *73*, 4939.

Scheme 3



error. The pK_a values of **1**−**3** are quite low and indicate that all three compounds are moderately strong acids. The strength of the acids decreases from the ortho to the para isomer. A similar trend was observed for 1-carboxy derivatives of *o*-, *m*-, and *p*-carboranes, with pK_a values in 50% aqueous ethanol of 2.61, 3.34,[3a] and 3.64,[18] respectively, and was attributed to a decreasing electron-withdrawing effect of the boron cage on the cage carbon atoms.[19]

The pK_a value of **1** is strikingly lower than that of **2**, by a whole 3 units, while **2** and **3** differ only by 0.6 unit. The differential effect of the *o*-carboranyl group on the acidity of a hydroxyl, compared to the effect of the isomeric *m*- and *p*-carboranyl groups, is clearly much larger than the differential effect on the acidity of a carboxyl. This is difficult to rationalize in terms of constant electron-withdrawing effects of the three intact isomeric boron cages alone. It appears that the oxyanion can provoke the *o*-carboranyl substituent into becoming a much stronger electron withdrawer. An obvious way in which this could happen is if the boron cage acquires a nido structure and accommodates the negative charge within itself.

Indeed, it was reported earlier that the oxyanion of the related 1-hydroxy-2-phenyl-*o*-carborane exists in the nido form with a bridging carbonyl group.[6] The corresponding *m*- and *p*-oxyanions were not studied experimentally. It was suggested, on the basis of frontier orbital calculations (MOBI), that *m*-oxyanions would "show only very slight displacements toward nido forms", while *p*-oxyanions would have fully closo forms.[7] The pK_a values of the three hydroxycarboranes, reported above, support this suggestion. It appears that for **1** the equilibrium is shifted much farther toward dissociation, as it produces a nido anion containing a bridging C═O bond with a strong carbonyl character (Chart 1). In contrast, **2** and **3** apparently produce closo oxyanions, with an acidity enhanced merely by the electron-withdrawing effect of the boron cage on the cage carbon atoms.

Structure of *C*-Hydroxycarboranes and *C*-Oxycarboranyl Anions. In order to confirm the above conclusions and evaluate the structures of the oxyanions **1a**−**3a** we performed *ab initio* calculations. Structures of *C*-hydroxy *o*-, *m*-, and *p*-carboranes and their oxyanions were fully optimized at the HF/6-31G* level of theory (Chart 2), and their NMR spectra were calculated (Table 2). The structure of **1** was further optimized at the MP2/6-31G* level of theory, and its NMR spectrum was calculated for the optimized geometry. Since neither significant changes in optimized geometry nor a better agreement with the observed NMR shifts was found, the MP2 calculations were not performed for the remaining structures.

Compared to the X-ray crystallographic[20] structure of the parent compound, the calculated optimized geometry of **1** (Chart 2) predicts structural changes only in the immediate vicinity of the hydroxyl group. The C1−C2 distance of 1.625 Å is somewhat shorter than that in *o*-carborane (1.630 Å).[20] Distances between C1 and B3,4,5,6 of 1.731, 1.697, 1.709, and 1.715 Å, respectively, are also somewhat shorter than those in the parent compound.[20] C−B and B−B distances of 1.65−1.85 Å within the cage fall into the range usual for carboranes.[1a] The C−O bond length of 1.360 Å is very similar to the lengths of such bonds in phenols (1.36 Å).[21]

The calculated structure for **1a** shows a drastic geometrical change upon deprotonation. This structure is very similar to the crystal structure obtained for the 1-oxy-2-phenyl-*o*-carboranyl anion.[6] Indeed, the carbon−oxygen bond is predicted to be only 1.189 Å long, typical of a carbonyl bond. This bond is somewhat shorter than the 1.245 Å long C−O bond observed[6] in the 1-oxy-2-phenyl-*o*-carboranyl anion. The C1−C2 (2.311 Å) and C1−B3,4,5,6 (2.012, 1.637, 1.638, and 2.013 Å respectively) distances show that the carbonyl unit is shifted significantly from C2 toward B4 and B5, thus producing a nido cage. This result is also in a very good agreement with the observations on the phenyl derivative.[6] Löwdin bond orders provide an additional indication of drastic changes in the structure of **1a** as compared to **1**. The C1−O bond order in **1** is 1.10, and this value increases to 1.96 in **1a**. Bond orders of C1−C2 and C1−B3,4,5,6 lie between 0.50 and 0.67 in **1**, while in **1a** the C1−B4 and C1−B5 bond orders are 0.68, the C1−C2 bond order is 0.11, and the C1−B3 and C1−B6 bond orders are 0.31, clearly indicating a shift toward the nido structure.

The optimized structures of **2** and **3** (Chart 2) are also very similar to the structure of the parent carboranes.[20] The C1−O bond lengths of 1.370 and 1.371 Å, respectively, are a little longer than those in **1**. The C−B and B−B distances lie in the range usual for carboranes. The antipodal C1−C12 distance of 3.064 Å in **3** is very similar to the value of 3.059 Å found experimentally[20] for the parent *p*-carborane.

The structural changes in structures of **2** and **3** upon deprotonation are less profound than was the case in **1** (Chart 2). The C−O bonds in **2a** and **3a** are shortend to 1.258 and 1.255 Å, respectively, and the Löwdin bond orders become 1.50 and 1.43 (compared to 1.08 and 1.02 in **2** and **3**, respectively), indicating a partial double-bond character. However, there is no indication that nido cages are formed in **2a** and **3a**. The C1−B2,3,4,5,6 distances are somewhat elongated in **2a** and **3a** (1.75−1.78 Å), compared to **2** and **3** (1.70−1.72 Å), but there is no significant shift of the C−O group toward either side of the cage. The B−B bond lengths also do not change in **2a** and **3a** compared to **2** and **3**, and a very slight observed increase of the antipodal distance is due only to the increase in C1−B distances (the C1−B12 distance increases from 3.239 Å in **2** to 3.375 Å in **2a**, and the C1−C12 distance increases from 3.064 Å in **3** to 3.210 Å in **3a**).

^{13}C and ^{11}B NMR spectra of *C*-hydroxycarboranes and their oxyanions, both measured and calculated, also demonstrate very significant differences between the three oxycarboranyl anions. Predicted NMR shifts for hydroxycarboranes and their oxyanions are in a very good agreement with measured values (Table

(18) Zakharkin, L. I.; Kalinin, V. N.; Podvisotskaia, L. S. *Izv. Akad. Nauk SSSR, Ser. Khim.* **1968**, 2661.
(19) Hawthorne, M. F.; Berry, T. E.; Wagner, P. A. *J. Am. Chem. Soc.* **1965**, *87*, 4746.
(20) Davidson, M. G.; Hibbert, T. G.; Howard, J. A. K.; Mackinnon, A.; Wade, K. *J. Chem. Soc., Chem. Commun.* **1996**, 2285.
(21) *CRC Handbook of Chemistry and Physics*, 58th ed.; CRC Press: Cleveland, OH, 1977.

2) and with peak assignments established by $^{11}B-^{11}B$ COSY for **1**.[7a] This confirms that the optimized geometries reflect correctly the structural changes due to the deprotonation of *C*-hydroxycarboranes and allows correct peak assignments for the measured NMR spectra.

As was discussed earlier for **1**,[7a] upon introduction of the anionic charge, the polyhedron resonances in **1a** shift to lower field for boron nuclei in sites 3,6 and 7,11 and to higher field for sites 4,5, 8,10, and 9 (Chart 2). The most profound effect of delocalization of the anionic charge is found for the antipodal boron atom in site 12, opposite to the site of deprotonation, whose resonance shifts upfield dramatically. Such behavior of the antipodal boron atom, the most remote from the site of deprotonation, can be understood in terms of the position of its tangential p orbitals, aligned parallel to those on the carbon atom involved in C−O multiple bonding.[22] A very similar picture is observed in the case of **2**. Upon introduction of the anionic charge into the polyhedron, resonances in **2a** shift to lower field for boron nuclei in sites 2,3 and 4,6 and to higher field for sites 8,11, 9,10, and 5 (see Chart 2). The most pronounced upfield shift is again observed for the antipodal boron atom in site 12, which can be understood similarly as in the case of **1** and **1a**. Finally, upon deprotonation of **3**, resonances of boron atoms in sites 7−11 (see Chart 2) shift to higher field, while resonances of boron atoms in sites 2−6 shift to lower field.

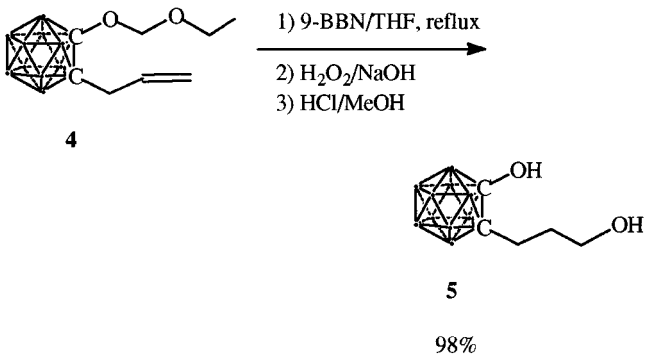
^{13}C NMR shifts provide an additional confirmation of the major difference between the structures of **1a**, on the one hand, and **2a** and **3a**, on the other. The resonance of the C1 atom shows that, in the case of **1a**, it has a significant carbonyl character (δ 204.95 ppm, compared with 102.09 ppm for **1**), a difference of over 100 ppm. For **2a** and **3a** (δ 132.76 and 144.03 ppm, respectively), the carbonyl character of C1 is much less developed.

IR spectra of **1**−**3** and **1a**−**3a** provide additional evidence for the partially doubly bonded character of the C−O bond in **1a**. The C−O stretching band of **1** is located at 1232 cm^{-1}, while for **1a** it shifts to 1394 cm^{-1}. For **2** and **3**, the C−O stretching band also lies in the 1200 cm^{-1} range, but it shifts only to about 1250 cm^{-1} for **2a** and **3a**. Clearly, resonance structures of the nido type make much smaller contributions to the description of the ground state of these anions.

Substitution on 1-Hydroxy-*o*-carborane. To incorporate *C*-hydroxycarboranes into organic structures, such as polymers, one has to introduce a suitable substituent onto another cage atom, and we have chosen the second carbon atom for this purpose. The substituent should allow some space for the bulky carboranyl moiety and offer a facile attachment to other organic fragments. It appeared to us that substituents such as 2-hydroxyethyl or 3-hydroxypropyl could be suitable for the purpose. Two possible ways to these derivatives are (i) to introduce first a spacer and then the hydroxy group and (ii) to introduce first the hydroxy group and then the spacer.

We decided to use *o*-carborane, as it is cheaper than the other two isomers and as it provides the corresponding *C*-hydroxycarborane in the highest conversion. It is known that the lithium salt of *o*-carborane readily reacts with ethylene oxide to produce 1-(2-hydroxyethyl)-1,2-dicarba-*closo*-dodecaborane.[23] However, we were unsuccessful in our attempts to prepare the hydroxy derivative of 1-(2-hydroxyethyl)-*o*-carborane, protected on the oxygen with R_3Si- or $ROCH_2$-groups, by lithiation followed by oxidation with $(TMSO)_2$, oxygen, or trimethylamine *N*-oxide. We suspect that the reason for this low reactivity may be an intramolecular chelation of lithium by the oxygen atom of the spacer.

Scheme 4



We therefore turned to the second possible synthetic sequence. We found that a trialkylsilyl protecting group on the oxygen is not suitable in the case of *C*-hydroxycarboranes, as it is too easily removed by lithiating reagents. Although the ethoxymethyl and (2-(trimethylsilyl)ethoxy)methyl protecting groups are not removed from the oxygen of **1** by lithiating agents, the lithium derivatives of these protected *C*-hydroxy-*o*-carboranes failed to react with ethylene oxide or protected iodoethanol. Fortunately, lithiated ethoxymethyl-protected **1** reacted with allyl iodide and provided 1-(ethoxymethoxy)-2-allyl-*o*-carborane (**4**, Scheme 2), which was then converted into the desired 1-hydroxy-2-(3-hydroxypropyl)-*o*-carborane by hydroboration and oxidation.

The initial hydroboration experiments were performed with the borane−tetrahydrofuran complex. After quenching with H_2O_2/NaOH, this gave a 3:2 mixture of alcohols **5** and **6** (Scheme 3) in 90% total yield.

Apparently, this reaction occurs via an intramolecular complex of BH_3 with the ether oxygens in **4**, which deliver the borane into the nonterminal position of the alkene. Thus, a bulkier borane should be used in order to achieve the desired regioselectivity. Indeed, reaction of **4** with 9-BBN in THF under reflux followed by quenching with H_2O_2/NaOH gave the desired alcohol **5** in a high yield as the only product (Scheme 4).

Conclusions

We have prepared and fully characterized all three isomers of the *C*-hydroxycarboranes. These compounds are moderately strong acids, transparent in the near-UV region, and stable toward oxidation, acids, and bases. By pK_a measurements, spectroscopic measurements, and *ab initio* calculations, we confirmed the earlier report[6] that the *C*-oxy-*o*-carboranyl anion (**1a**) exists in the nido form. We have verified the suggestion[6] that meta and para *C*-oxycarboranyl anions (**2a** and **3a**) exist in the closo form. Finally, we have developed a procedure for further functionalization of *C*-hydroxy-*o*-carborane into a derivative suitable for incorporation into more complex structures.

Acknowledgement is made to the IBM Co. and to the National Science Foundation (Grant CHE-9318469) for the support of this work.

IC970796B

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