PRNC - 76

PUERTO RICO NUCLEAR CENTER

ORGANIC BORON COMPOUNDS FOR NEUTRON ACTIVATION THERAPY OF MALIGNANT TISSUES

Progress Report

OPERATED BY UNIVERSITY OF PUERTO RICO UNDER CONTRACT
NO. AT (40-1)-1833 FOR U. S. ATOMIC ENERGY COMMISSION

PUERTO RICO NUCLEAR CENTER

Progress Report of the Project

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by

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September, 1965

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I. Introduction

In the last fifteen years the study of the organic compounds containing boron has been greatly intensified principally because of the interest in high energy fuels (1,2), and also because of the potential application of organic boron compounds in cancer therapy (3). The latter is based in the fact that two relatively harmless entities, boron-10 and thermal neutrons, produce a nuclear reaction

$$ {}_{5}B^{10} + {}_{0}n^{1} \longrightarrow ({}_{5}B^{11}) \longrightarrow {}_{3}Li^{7} + {}_{2}He^{4} + 2.4 \text{ Mev.} $$

which liberates sufficient energy to destroy the cells in which boron-10 is present. Due to the nature of the fission fragments, these travel very little in the tissue, which decreases the probability that the energy emitted in this process destroys the surrounding cells. In comparison with boron-10, the elements which abound in normal tissues have low thermal neutron cross sections, and thus there exists the possibility of sensitizing a part of an organism to thermal neutron irradiation if that part preferentially accumulates the boron-10 containing compound. Natural boron contains 80.4% of boron-11 with a thermal neutron cross section of 0.05 barns, and 19.6% of boron-10 with a cross section of 3,850 barns. It has been calculated (4) that 86% of the total radiation dose will be captured by boron-10 if its concentration can be raised to 50 mg per kilogram of tissue.

The basic techniques necessary for the application of boron-10 in the therapy of brain tumors have already been developed (5). Now, it is a challenge for the synthetic chemist to prepare the proper compounds of boron to make this therapy practicable. Some of the desired characteristics of boron compounds suitable for this purpose are: a high boron content, selective absorption by malignant cells, low toxicity, and resistance to hydrolysis and to oxidation.

This report summarizes a part of our efforts exerted in an attempt to find boron compounds suitable in cancer therapy. The work can be divided into two parts each of which reflects the synthetic paths that were explored. In the first part there is described the synthesis of some organic derivatives of boric acid, while the second part is dedicated to the study of organic boron compounds in which there exists a boron-boron bond.

II. Experimental

The melting points reported here are uncorrected, and all of the microanalyses were performed by Dr. A. Bernhardt, Max-Plank Institute, Mulheim/Ruhr, Germany. Unless stated otherwise, the reactions were run with the exclusion of humidity under an atmosphere of dry nitrogen. All of the liquid boron reagents were handled with hypodermic syringes to ensure minimum contact with air. The equipment and the azeotropic distillation technique was that described by Pratt (6).

Most of the reagents were pure commercial products used without further purification. Methyl diethanol amine and t-butyl diethanol amine were distilled under reduced pressure. Hydrazine was used in the anhydrous form (7). Benzopinacol was prepared in the usual way (8) from benzophenone.

Concerning the Nomenclature of Compounds Containing a B-B Bond

There is no general agreement on the nomenclature of the compounds containing a boron-boron bond, and this report follows essentially the system used by Chemical Abstracts (9). For example, $(RO)_2B\text{-}B(RO)_2$ is named tetraalkoxydiborane-4. The number four is used to indicate the number of substituents, or "external" valencies, of the boron atoms. By this system B_2H_6 is named diborane-6. We use a dash instead of a parenthesis as is done by Chemical Abstracts) in order not to confuse the reader because of the use of the parenthesis to denote the literature citations.

A. Attempted preparation of 2(8-quinolinoxy)-1,3,2-benzodioxaborolane (I).

To a solution of 100 ml. of dimethyl sulfoxide and 80 ml. of benzene there were added 3.13 g. (0.020 moles) of 8-hydroxyquinoline, 2.21 g. (0.020 moles) of catechol, and 1.24 g. (0.020 moles) of boric acid. The solution was refluxed until 1.16 ml. of water were removed in a Dean Stark trap. The solvent was evaporated under reduced pressure and the yellow solid obtained was extracted with benzene, while the residue was dissolved in dioxane. The dioxane solution gave a solid (0.60 g.) of m.p. 190-192° (dec.) which analyzed: C, 65.11; H, 9.50; N, 3.65; B, 4.06. From the benzene solution there was obtained a solid, which after two crystalizations from benzene yielded 0.30 g. of a yellow solid m.p. 185-190° (dec.) Analysis. Found: C, 58.92; H, 4.34; N, 3.42; B, 2.04.
Calc'd. for $C_{21}H_{16}O_5NB$ (III) : C, 67.59; H, 4.32; N, 3.75; B, 2.70.
Calc'd for $C_{15}H_{10}O_3NB$ (I) : C, 68.48; H, 3.83; N, 5.33; B, 4.11.

B. Attempted preparation of 2-(2-dimethylaminoethoxy)-4,4,5,5-tetraphenyl-1,3,2-dioxaboralane.

1. A solution of an equimolar mixture of benzopinacol, dimethylaminoethanol and boric acid in a mixture of 100 ml. of dimethyl sulfoxide and 80 ml. of benzene was dehydrated by azeotropic distillation. The mixture resisted the isolation of a pure organic derivative of boron.

2. A solution of 3.1 ml. (0.030 moles) of 2-dimethylaminoethanol in 100 ml. of toluene was dehydrated by azeotropic distillation. To this solution there were then added 11.0 g. (0.030 moles) of benzopinacol and 3.1 ml. (0.027 moles)

of trimethyl borate, and the reflux was continued over night under an inert gas atmosphere. The solvent was evaporated and the residue (14.6 g.) was crystallized from benzene and ligroin. The white solid (11.0 g., m.p. 181-189°) depressed the m.p. of benzopinacol. Fractional crystallization decreased the m.p. range of the solid to 185-190°. Thin layer chromatography on silica gel and elution with chloroform or tetrahydrofurane revealed two spots of which the faint one, of higher R_f, corresponded to that of benzopinacol. Analysis. Found: C, 78.37; H, 5.76; N, 1.02; B, 1.24. Calc'd. for $C_{164}H_{145}O_4N_2B_3$ (V): C, 82.06; H, 6.09; N, 1.17; B, 1.35. Calc'd. for: $C_{354}H_{312}O_{32}N_4B_6$ (IV): C, 81.94; H, 6.90; N, 1.11; B, 1.28.

C. Reaction of boric acid with amines

1. Boric acid (0.618 g., 0.010 moles) was added to a solution of 1.293 g. (0.010 moles) of 1,1,3,3-tetramethylbutylamine ("t-octylamine") in 100 ml. of triethylamine. The mixture was refluxed for one hour and 0.20 ml. (0.011 moles) of water was collected. A solid (0.682 g.) insoluble in the reaction mixture was isolated and was found to be soluble in water and acetic acid, and to decompose when heated above 225°. It was dried under reduced pressure over P_2O_5 at 100°. Analysis: Found: C, 22.70; H, 6.41; N, 4.40; B, 17.04. Calc'd. for $(CH_3CH_2)_3N.B_5O_{10}H_5$ (10), $C_6H_{20}O_{10}B_5N$: C, 22.65; H, 6.30; N, 4.38; B, 16.90. The infrared spectrum of this solid was similar to that of $KB_5O_{10}H_4.2H_2O$, shown in Fig. 1. The latter substance was prepared as described by Smith and Richards (11).

2. A solution of 12.37 g. (0.20 moles) of boric acid in 300 ml. of t-butylamine was refluxed for 15 hours. The reaction mixture was then cooled and filtered, and 11.80 g. of a white solid was recovered. It was washed with benzene and dried under reduced pressure at room temperature. Analysis: Found: C, 16.48; H, 5.46; N, 4.76; B, 18.36. Calc'd. for $(CH_3)_3CNH_2.B_5O_{10}H_5$ (10):

C, 16.41; H, 5.42; N, 4.79; B, 18.36. The infrared spectrum of this substance was similar to that of $KB_5O_{10}H_4 \cdot 2H_2O$ (11) (See Fig. 1).

D. Reaction of α-methyl-D-glucopyranoside with the reaction product of boric acid and an amine.

1. To a solution of 2.59 g. (0.020 moles) of 1,1,3,3-tetramethylbutylamine in 200 ml. of triethylamine there were added 2.48 g. (0.040 moles) of boric acid, and the resulting mixture was refluxed for three hours and 0.42 ml. (0.023 moles) of water was collected. The mixture obtained in this way was treated with α-methyl-D-glucopyranoside, 3.89 g. (0.020 moles), and was refluxed for 15 hours. Filtration gave 5.21 g. of a white solid, m.p. 135-140 (dec.), and distillation of the solvent gave a resinous residue that resisted purification. After washing a sample of this solid with benzene, there was obtained a solid of m.p. 130-135° which burned with a green flame. Its infrared spectrum was identical with that of the solid obtained in C-1 except for the presence of bands atributable to the spectrum of α-methyl-D-glucopyranoside.

This experiment was repeated several times and in all cases the crude solid gave, upon crystallization from a variety of solvents, fractions that were identified with the α-methyl-D-glucopyranoside or with the pentaborate.

2. A solution of 2,37 g. (0.040 moles) of boric acid in 100 ml. of t-butyl amine was refluxed for 15 hours and then concentrated by distillation. Dioxane was added and the mixture was boiled. A solid (1.56 g.) was recovered by filtration which gave a positive sodium fusion test for nitrogen and burned with a green flame. This solid was refluxed for 20 hours in dioxane with 2.43 g. (0.012 moles) of α-methyl-D-glucopyranoside. The solid which was insoluble in the reaction mixture had the same properties as the solid obtained in C-2. The solution was evaporated under reduced pressure to give a solid of m.p. 90-120° (dec.) which burned with a green flame but gave a negative nitrogen test.

Pure α-methyl-D-glucopyranoside was obtained when this solid was washed with methanol.

E. Reaction between trimethyl borate, α-methyl-D-glucopyranoside and 1,1,3,3-tetramethylbutylamine.

A solution of 170 ml. of benzene and 200 ml. of dimethyl sulfoxide was dehydrated by azeotropic distillation, mixed with 5.00 ml. (0.030 ml.) of 1,1,3,3-tetramethylbutylamine and 4.00 ml. (0.0346 moles) of trimethyl borate, and then refluxed for 18 hours. To the resulting solution there was added 5.837 g. (0.030 moles) of α=methyl-D-glucopyranoside and the mixture was refluxed for an additional 4 hours. The solvent was evaporated under reduced pressure leaving a solid (6.60 g.) that decomposed at 297°. By crystallization from acetonitrile there was obtained a solid of m.p. 93-97°. Analysis. Found: C, 36.53; H, 6.58; N, 0.86; B, 15.65. Calc'd. for $C_7H_{17}O_{12}B_3$: C, 28.96; H, 4.48; B, 11.37.

F. Preparation of 2-phenyl-4,4,5,5-tetramethyl-1,3,2-dioxaborolane (VIII - b).

A solution of 6.57 g. (0.0538 moles) of phenylboronic acid and 6.35 g. (0.0538 moles) of pinacol in 200 ml. of benzene was refluxed for 1.5 hours and 1.75 ml. (0.0972 moles) of water was collected. The solvent was evaporated under reduced pressure (15 mm) and a liquid (12.91 g.) boiling at 98° (3 mm) was collected. Analysis. Found: C, 70.59; H, 8.40; B, 5.15. Calc'd for $C_{12}H_{17}O_2B$ (VIII-b): C, 70.62; H, 8.40; B, 5.30. The infrared spectrum of this substance is shown in Fig. 2.

G. Preparation of 2-phenyl-4,4,5,5-tetraphenyl-1,3,2-dioxaborolane (VIII-a).

A solution of 2.44 g. (0.020 moles) of phenylboronic acid and 2.5 ml. (0.027 moles) of n-butanol in 150 ml. of benzene was dehydrated azeotropically, mixed with 7.33 g. (0.020 moles) of benzopinacol, and slowly concentrated by distillation until the distillate did not show an infrared absorption in the O-H region. A white solid, 4.27 g., m.p. 203-205°, crystallized from the reaction mixture. Analysis. Found: C, 85.88; H, 5.66; B, 2.13; apparent molecular weight (Rast): 400. Calc'd. for $C_{30}H_{25}O_2B$ (VIII-a): C, 87.38; H, 6.11; B, 2.62; Formula weight: 428.

An attempt to prepare the above compound directly by azeotropic dehydration of benzopinacol with phenylboronic acid failed.

H. Preparation of 2-n-butoxy-4,4,5,5-tetramethyl-1,3,2-dioxaborolane. (VIII-f).

Tri-n-butyl borate, 14.0 ml. (0.050 moles), was added to a solution of 5.91 g. (0.050 moles) of pinacol in 150 ml. of carbon tetrachloride. The solvent was slowly distilled until 3.89 g. of n-butanol was recovered.

An additional 3.24 g. was obtained in the first fraction that distilled at 30° under reduced pressure (5-8 mm), and thus a total of 0.096 moles of n-butanol was isolated. The residue distilled between 65-82° (5-8 mm) (7.63 g., 0.0375 moles). Analysis. Found: C, 60.06; H, 10.50; B, 5.23. Calc'd. for $C_{10}H_{19}O_3B$ (VIII-f): C, 60.60; H, 9.84; B, 5.46.

I. Preparation of 2-methoxy-4,4,5,5-tetraphenyl-1,3,2-dioxaborolane (VIII-c).

Trimethyl borate, 7.0 ml. (0.060 moles), was added to a previously dehydrated solution of 7.33 g. (0.020 moles) of benzopinacol in 50.0 ml. of benzene. The mixture was refluxed for two hours and the benzene was distilled while toluene was slowly being added. The toluene was evaporated at reduced pressure and the residual oil (8.23 g.) solidified on standing. Analysis. Found:

C, 80.08; H, 5.95; B, 2.21. Calc'd. for $C_{27}H_{23}O_3B$ (VIII-c): C, 79.82; H, 5.71; B, 2.66. Molecular weight: **found** (Rast): 333; calc'd: 406.

J. Preparation of 2-methoxy-4,4,5,5-tetramethyl-1,3,2-dioxaborolane. (VIII-e).

A solution of 18.05 g. (0.152 moles) of pinacol and 20.0 ml. (0.175 moles) of trimethyl borate was heated at 60° for one hour, and then distilled under reduced pressure to give a fraction (5.75 g.) of b.p. 35-40° (6 mm.). Analysis. Found: C, 53.27; H, 9.30; B, 6.04. Calc'd. for $C_7H_{15}O_3B$ (VIII-e): C, 53.60; H, 9.56; B, 6.65. The residue (9.78 g.) was crystalized **from** hexane and a solid, m.p. 185-190° was obtained.

K. Preparation of 2-hydroxy-4,4,5,5-tetramethyl-1,3,2-dioxaborolane (VIII-d).

1. Trimethyl borate, 5.00 ml. (0.043 moles), was added to a solution of 5.56 g. (0.471 moles) of pinacol in 200 ml. of benzene (previously dehydrated by azeotropic distillation). The resulting solution was refluxed for six hours and the oil obtained after evaporation of the solvent under reduced pressure was exposed to the atmosphere for three days. Crystallization of the resulting solid from heptane permitted the separation of two solids. Analysis of the first solid, (4.95 g.) of m.p. 67-69°, gave C, 50.17; H, 8.96; B, 7.56, molecular weight (Rast): 233. Calc'd for $C_6H_{13}O_3B$ (VIII-d): C, 50.05, H, 9.10; B, 7.51, formula weight: 144. The infrared spectrum of this solid is shown in Fig. 3. The second solid, (0.33 g.) m.p. 224-225°, analyzed C, 55.78; H, 9.38; B, 4.97; molecular weight (Rast) of 221. Calc'd. for $C_{12}H_{25}O_4B$: C, 59.03; H, 10.32; B, 4.43, formula weight: 244. Its infrared spectrum is also shown in Fig. 3.

2. This experiment was repeated employing a solution of 19.12 g. of trimethyl borate in 100 ml. of benzene and a reflux time of four hours. One third of the solvent was distilled at atmospheric pressure and the rest under

reduced pressure. The oil obtained in this fashion was exposed to the atmosphere for two days whereupon it solidified. Crystallization from heptane gave two products. The first solid, 14.15 g. of m.p. 62-67°, was shown by the infrared spectrum and by a mixed melting point to be identical with the product of the preceding experiment. The second, 3.57 g., m.p. 215-223°, analyzed C, 58.25; H, 9.86; B, 6.03, and gave an apparent molecular weight (Rast) of 288. Calc'd. for $C_{18}H_{36}O_6B_2$: C, 58.41; H, 9.81; B, 5.81, formula weight 370. This sample depressed the m.p. of the high melting sample of the preceding experiment.

L. Preparation of tetrakis(2-dimethylaminoethoxy)-diborane-4 (XIX).

A solution of 100 ml. (0.0416 moles) of tetrakis(dimethylamino)borane-4 and 200 g. (0.0225 moles) of dimethylaminoethanol in 150 ml. of toluene (dried by azeotropic distillation) was refluxed for 3.4 hours. The dimethylamine produced in the reaction was swept out of reaction flask with dry nitrogen. The toluene was distilled at atmospheric pressure and the residual oil was distilled under reduced pressure to give 13.0 g. of a colorless liquid, b.p. 129-131.5° (5 mm.). Analysis. Found: C, 51.41; H, 10.70; N, 15.12; B, 5.66. Calc'd. for $C_{16}H_{40}O_4N_4B_2$ (XIX): C, 51.36; H, 10.78; N, 14.98; B, 5.78.

An attempt to form the picrate from an alcoholic solution gave a solid which did not depress the m.p. of the picrate of dimethylaminoethanol.

A sample of tetrakis(dimethylaminoethoxy)-diborane-4 was treated with 10% aqueous sodium hydroxide to give the calculated amount of hydrogen. A rapid titration with standard acid gave a neutralization equivalent of 95.2 (Calc'd. neutralization equivalent is 93.6).

The infrared spectrum of XIX is shown in Fig. 4.

M. Preparation of bis(t-butylaminodiethoxy)-diborane-4 (XX).

A solution of 4.50 ml. (0.0186 moles) of tetrakis(dimethylamino)diborane-4 and 5.99 g. (0.0372 moles) of t-butylaminodiethanol, b.p. 250° (5 mm.), in 200 ml. of toluene (distilled from calcium hydride) was refluxed for 60 hours. At the end of this period the liberation of dimethylamine was very slow. The reaction mixture deposited at room temperature a yellow-brown deliquescent solid (1.7 g.). This solid resisted purification by crystallization. The filtrate of the original reaction mixture was concentrated under reduced pressure and a yellow-brown oil (4.3 g.) was obtained. Analysis. The solid analyzed: C, 39.45; H, 8.24; N, 5.93; B, 6.84, while the oil analyzed: C, 56.36; H, 9.93; N, 8.04; B, 6.15. Calc'd. for $C_{16}H_{34}O_4N_2B_2$ (XX): C, 56.50; H, 10.08; N, 8.24; B, 6.36.

Both reaction products seem to decompose when exposed to air since they liquify and produce bubbles.

N. Preparation of bis(methylaminodiethoxy)diborane-4.

1. A solution of 7.22 ml. (0.0300 moles) of tetrakis(dimethylamino)diborane-4 and 7.16 g. (0.0602 moles) of methylaminodiethanol, b.p. 76.5° (0.3 mm.), in 100 ml. of benzene (previously distilled over calcium hydrode) was heated for six days. At the end of this period 87% of the calculated dimethylamine was trapped in standard sulfuric acid. The solvent was evaporated under reduced pressure and a brown oil (8.4 g.) which was left behind was heated for one hour at 95° under 0.2 mm. pressure. Analysis. Found: C, 44.55; H, 8.51; N, 10.43; B, 5.26. Calc'd. for $C_{10}H_{22}O_4N_2B_2$: C, 46.93; H, 8.67; N, 10.95; B, 8.46. Calc'd. for: $C_{15}H_{35}N_3O_6B_2$ (XXI): C, 47.90; H, 9.38; N, 11.44; B, 5.75. The low boron content suggests the presence of the methylaminoethanol. This conclusion is supported by the presence of infrared absorption in the O-H region and the fact that alkaline hydrolysis of a sample gave only 77% of the calculated amount of hydrogen.

2. The solution of 24.11 g. (0.287 moles) of methylaminodiethanol in 150 ml. of toluene (previously distilled over calcium hydride) was distilled to ensure proper dryness until 10 ml. of toluene was removed. The resulting cool solution was mixed with 36.75 ml. (0.153 moles) of tetrakis(dimethylamino)-diborane-4 and then refluxed until no more dimethylamine was being removed by a stream of nitrogen that was bubbled through the reaction mixture (20 days). The removal of the solvent at reduced pressure gave 34.5. g. of a brown oil. Analysis. Found: C, 48.86; H, 10.12; N, 19.12; B, 7.24. Calc'd. for: $C_{10}H_{22}O_4N_2B_2$: C, 46.93; H, 8.67, N, 10.95; B, 8.46. Alkaline hydrolysis with 2.5 M sodium hydroxide produced 68.5% of the calculated amount of hydrogen. The infrared spectrum showed no absorption in the O-H region (2.5-3 μ). No significant amount of volatile amine was detected when a sample of the brown oil was dissolved in 2.5 M sodium hydroxide and flushed with nitrogen.

O. Preparation of bis(pinacolyl)diborane-4 and its hydrazinolysis.

A solution of 5.00 g. (0.0362 moles) of pinacol in 100 ml. of benzene was dried by azeotropic distillation and then mixed with 4.32 ml. (0.0180 moles) of tetrakis(dimethylamino)diborane-4.The solution was refluxed for 16 hours and the dimethylamine was removed by a stream of nitrogen. The solvent was evaporated under reduced pressure and the resulting white solid (5.08 g.) was crystallized from ligroin to give a product, m.p. 140-141. Analysis. Found: C, 56.90; H, 9.44; B, 8.41. Calc'd. for $C_{12}H_{24}O_4B_2$: C, 56.75; H, 9.53; B, 8.52. The infrared spectrum of this substance is shown in Fig. 4.

To a sample of this compound (0.309 g., 0.00122 moles) dissolved in 20 ml. of toluene (previously distilled over calcium hydride) there was added 0.20 ml. of anhydrous hydrazine (0.050 moles) and the mixture was allowed to stand for two days at 70°C. The solvent was evaporated at reduced pressure and the resulting white solid was found to decompose at 102°. Analysis. Found:

C, 57.77; H, 10.04; N, 2.11; B, 6.49. Calc'd. for $C_6H_{14}O_2BN$: C, 50.40; H, 9.86; N, 9.80; B, 7.56. The infrared spectrum of this material showed absorption at 2.73 μ and 9.0 μ which corresponds to that of O-H and B-B stretching bands. Molecular weight found (Rast): 256, calculated for $C_6H_{14}O_2BN$: 143.

P. Preparation of bis(benzopinacolyl)diborane-4 and its hydrazinolysis.

To a solution of 14.67 g. (0.040 moles) of benzopinacol in 225 ml. of toluene, dried by azeotropic distillation, there was added 4.80 ml. (0.020 moles) of tetrakis(dimethylamino)-diborane-4. The mixture was refluxed until dimethylamine ceased to be liberated (30 hours). A total of 93% of the calculated amount of amine was trapped in a standard solution of sulfuric acid. The reaction mixture was concentrated and gave, upon cooling, 10.2 g. of a white solid, m.p. 292-300°. Crystallization from toluene did not improve its m.p. very much since a solid of m.p. 295-300° was obtained. The molecular weight found for this sample by the Rast method was 786, calculated for $C_{52}H_{40}O_4B_2$: 750. The infrared spectrum of this sample (Fig. 5) was identical with that of the material previously prepared in this laboratory (28) and a mixture m.p. did not produce a depression.

A mixture of 0.657 g. (0.00088 moles) of this compound in 30 ml. of benzene (previously dried by azeotropic distillation) and 0.10 ml. (0.0025 moles) of hydrazine was refluxed for two hours. The solvent was evaporated under reduced pressure to give 0.66 g. of a solid m.p. 172-180° (dec.). The molecular weight was determined by the Rast method to be 381, calc'd. for $C_{26}H_{22}O_2NB$: 391. Analysis. Found: C, 77.24; H, 5.80; N, 3.15; B, 2.37. Calc'd. for $C_{26}H_{22}O_2NB$: C, 79.81; H, 5.67; N, 3.58; B, 2.77. The infrared spectrum of this material did not show an absorption band at 8.70 μ where one observes the B-B absorption in bis(benzopinacolyl)diborane-4.

Q. Hydrolysis of tetrakis(dimethylamino)-diborane-4 (XI) to tetrahydroxydiborane-4.

1. A solution of 5.00 ml. (0.0219 moles) of tetrakis(dimethylamino)-diborane-4 in 15 ml. of water at 0°C, was slowly acidified (3.5 hours) with 6 N hydrochloric acid. During the acidulation the reaction mixture was maintained at 0-5° by means of an ice bath. The mixture was filtered and the resulting solid was washed with 15 ml. of 2 N hydrochloric acid at 0°. The white solid (1.22 g., 63% yield) analyzed: B, 23.98; H, 4.25; Calc'd. for $B_2(OH)_4$: B, 24.13; H, 4.49. Its infrared spectrum is shown in Fig. 5.

A repetition of this experiment in acetone at 0-10°C gave a 59% yield of tetrahydroxydiborane-4 (subboric acid). The solution of this solid in distilled water reduces silver ion but the reducing power is lost upon standing.

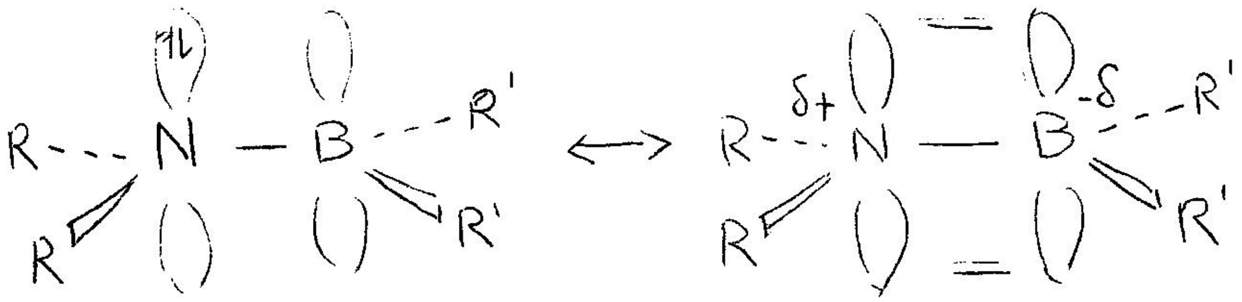
2. The mixture of 10.0 ml. (0.0438 moles) of tetrakis(dimethylamino)-diborane-4 in 300 ml. of acetone was refluxed for two hours. Filtration of the reaction mixture gave 5.07 g. of a white solid which did not melt up to 350°. Analysis. Found: C, 13.93; H, 5.90; N, 8.16; B, 19.22. Calc'd. for $B_3O_6H_3 \cdot NC_2H_7$: C, 13.63; H, 5.67; N, 7.94; B, 18.38.

3. To a refluxing solution of 26.95 g. (0.136 moles) of tetrakis(dimethylamino)diborane-4 in 300 ml. of toluene there was slowly added 17.0 ml. (0.94 moles) of water. Filtration of the reaction mixture gave a white solid (11.5 g.) which did not liberate any gas when dissolved in 2 M sodium hydroxide solution. Analysis. Found: C, 10.96; H, 5.07; N, 6.26; B, 19.57. Calc'd. for $B_5O_{10}H_5 \cdot NC_2H_7$: C, 9.10; H, 4.58, N, 5.31; B, 20.45. The infrared spectrum of this material was similar to that of $K \cdot H_4B_5O_{10} \cdot 2H_2O$ shown in Fig. 1.

III. Discussion

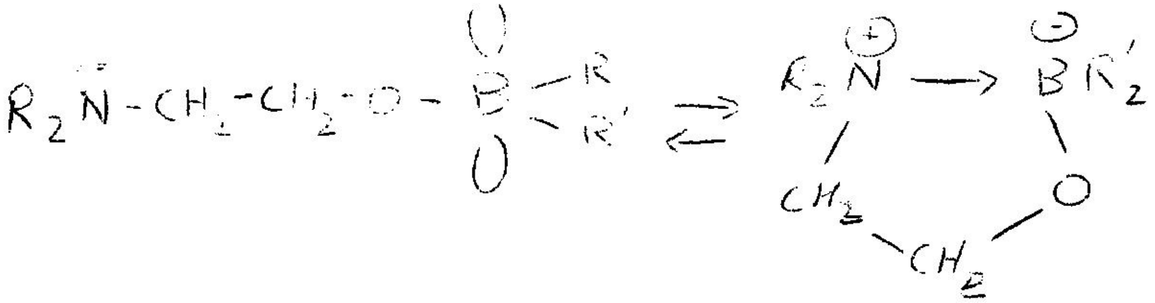
Part I. Organic Derivatives of Boric Acid

Generally speaking, the organic derivatives of boric acid are readily hydrolyzed to the latter, and this is especially true in the case of the simple orthoborates. The ease of hydrolysis of tricovalent boron compounds is believed (12) to be due to the vacant p orbital of the boron atom when the latter is in a state of sp^2 hybridization. The vacant p orbital is subject to a ready attack by a nucleophile such as water or a hydroxide ion, and is thus responsible for the ease of the hydrolysis of the boron compound. With this in mind, the hydrolysis of an organic derivate of boric acid can be restrained by the variation of two factors. Firstly, the vacancy of the empty orbital can be decreased through "back-bonding" by the atom attached to the boron. In other words, an atom capable of delocalizing its non-bonding electrons into the vacant p orbital will, *ipso facto*, reduces the capacity of the boron to coordinate water or other nucleophilic reagents. The "back-bonding" is believed to vary in accord with the basicity of the atom: $-\ddot{\underset{|}{N}}- > -\ddot{\underset{..}{O}}- > -\ddot{\underset{..}{F}}\,:$, and in the case of a nitrogen group it can be represented as follows:



The partial double bond character between boron and nitrogen is supported by recent spectroscopic work (13, 14, 15) which shows the existence of cis and trans isomers in some aminoboranes due to restricted rotation around the boron-nitrogen bond.

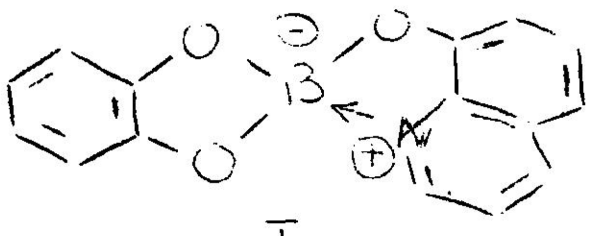
A more direct manner to eliminate the vacancy of the p orbital of boron is by way of a reaction with a nucleophilic portion of the side chain, i.e., through chelation (16, 17, 18). A typical situation which increases the resistance of the boron atom toward hydrolysis is shown as follows:



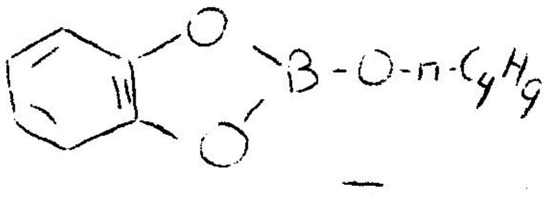
The second method of reducing the hydrolytic ability of a boron compound is based on steric inhibition of the approach of a nucleophile toward the vacant orbital of the boron center (19).

The application of both principles to the build-up of boron structures resistant to hydrolysis is found in the literature (16, 17, 19).

In our attempt to arrive at orthoborates resistant to hydrolysis we considered advisable to employ bi- or polyfunctional hydroxy compounds so that two of the groups attached to the boron would produce a cyclic structure. One of these, catechol, was treated with boric acid and 8-hydroxyquinoline under dehydrating conditions and there was isolated the expected spiroborate (I) in nearly pure

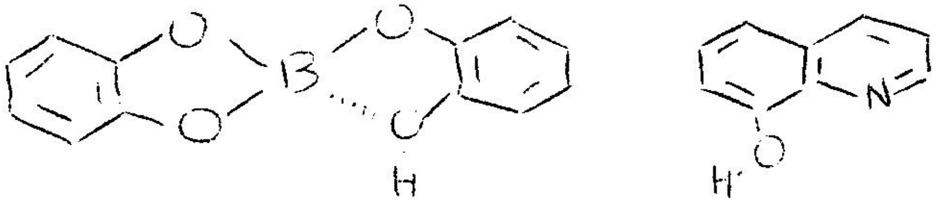


I



II

state. It was impossible to purify this compound by crystallization, and it is apparent that heating of the reaction mixture during the azeotropic distillation of water leads to the formation of byproducts that are extremely difficult to remove from the desired compound. The analytical data of one fraction, m.p. 185-190°, isolated from a crude reaction product, suggests the structure of a complex of hydroxyquinoline with a spiroborate formed from two catechols (III). The formation of this compound, m.p. 203°, was reported by Schafer in 1949 (20).

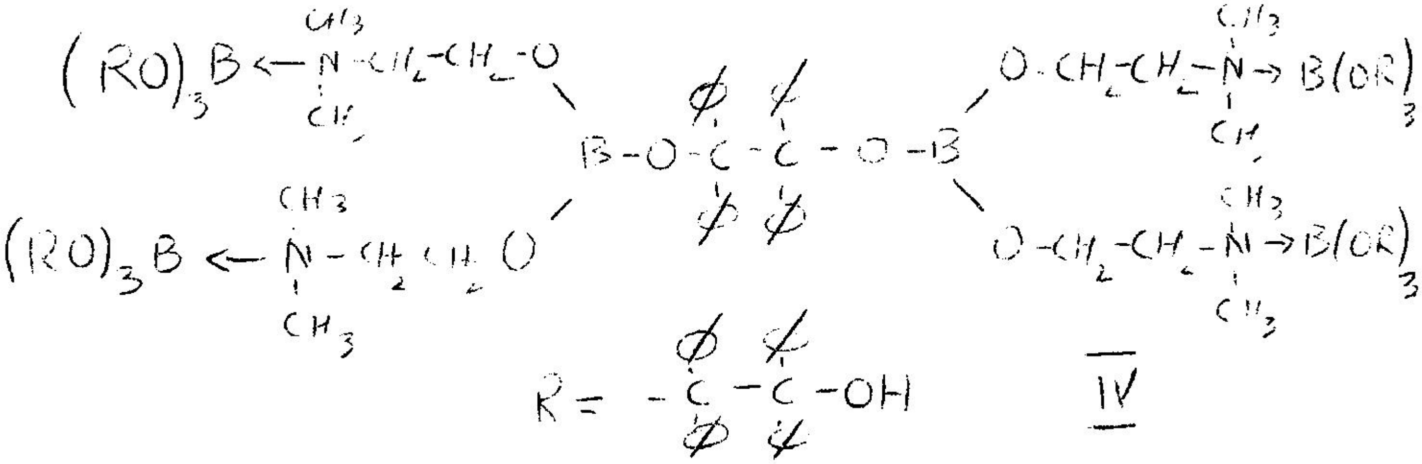


III

Previous investigators seem to have encountered similar difficulties since Schafer and Braun described compound I in 1952 simply as a yellow crystalline substance (21). Recently Balaban and co-workers (22) did prepare compound I in an analytically pure form by the displacement of the n-butoxy group of 2-n-butoxy-1,3,2-dioxaborolane (II) with 8-hydroxyquinoline and by avoiding the crystallization of the high melting and rather insoluble I. Due to the high insolubility of this structure in most organic solvents, and especially water, the preparation of I in pure form was not pursued any further.

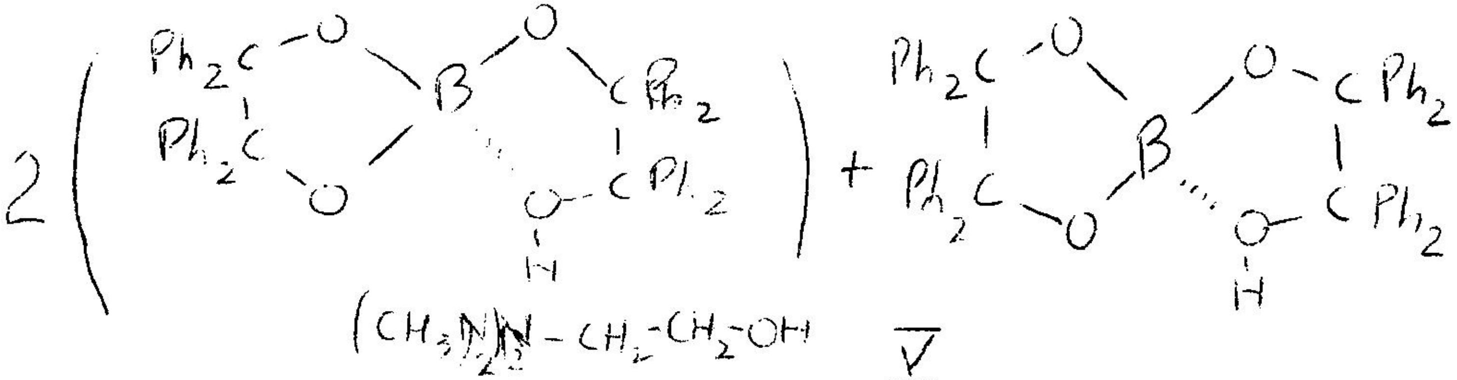
Little if any work appears in the literature on the utilization of benzopinacol for the preparation of orthoborates. The accumulation of the phenyl groups should produce a steric barrier near the boron center, although, by the same token, the solubility in water is markedly decreased. An attempt to synthesize a mixed chelated orthoborate derived from benzopinacol and dimethylaminoethanol gave a solid the melting range of which did not very with repeated crystallizations from benzene and ligroin. The analytical results indicate a ratio of three boron to two nitrogen atoms and the elementary analysis suggests a complex structure such as shown in IV, or a mixture of two spiroborates as shown in V. The infrared spectrum (KBr pellet) shows the expected hydroxyl, aliphatic and romantic C-H stretching bands, and the CH_2 bending bands, but does not allow the assigment of the structure. It is of interest to note that strong absorption is absent in the range of 7.20-7.90 microns where one normaly encounters the absorption of aliphatic B-O bonds when the boron atom is tricovalent. This fact can be taken as evidence of a tetrahedral boron-oxygen system (23), and on this basis structure V is preferred over IV.

<u>Analysis</u>. Found: C, 78.37; H, 5.76; N, 1.02; B, 1.24.



IV

Calc'd. for $C_{354}H_{312}O_{32}N_4B_6$: C, 81.94; H, 6.90; N, 1.11; B, 1.28.



V

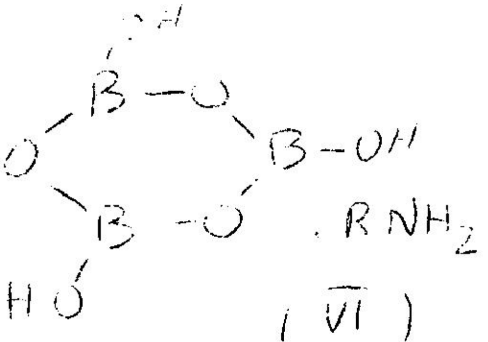
Calc'd. for $C_{164}H_{145}O_4N_4B_3$: C, 82.06; H, 5.76; N, 1.17; B, 1.35.

In the hope of preparing a substituted aminoboronic acid, $R\text{-}NH\text{-}B(OH)_2$, from a sterically hindered amine (R = t-butyl or "t-octyl") and boric acid,

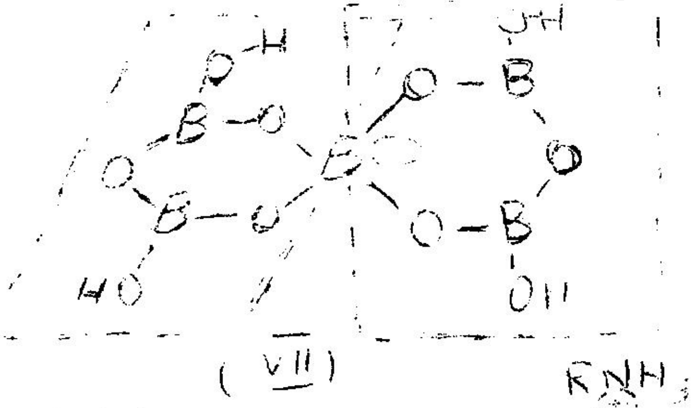
$$R\text{-}NH_2 + B(OH)_3 \longrightarrow R\text{-}NH\text{-}B(OH)_2 + H_2O$$

there were heated mixtures of the boric acid with an excess of t-butylamine or in a solution of "t-octylamine in triethylamine. The resultant products were shown by elementary and infrared analysis to be the pentaborates of t-butylamine and triethylamine, respectively. Previous investigators have attempted and even claimed the preparation of aminoboronic acids, but an examination of the results raises serious doubts whether true aminoboronic acids were indeed obtained. Chaudhuri described in 1920 (24) the preparation of a boroanilide (C_6H_5NHBO) and of a series of derivatives of the latter, but the physical and chemical properties of these materials do not coincide with those of the expected trimer, i.e. the anilide derivatives of metaboric acid. In 1939 Ferrari (25) described the preparation of a series of "alkylammonium borates" from boric acid and various amines or quarternary ammonium hydroxides which most likely are alkylammonium pentaborates (vide infra). The patent literature also records (26) the reaction of boric acid and di- or polyamines but the structure of the resinous products is not identified.

While this work was in progress, other investigators began to publish information on the formation of the tri- and pentaborates of many different amines. Thus, in 1964 Vinegard and Godt (10) showed that, depending on the ratio of boric acid and the amine and on the steric requirement of the latter, there can be obtained either N-substituted ammonium tri- or pentaborates. The triborates are obtained from sterically non-hindered amines, and when the boric acid: amine ratio is five, or greater, there are obtained the pentaborates. X-ray data of these solids lead to structures VI and VII for the tri- and pentaborates, respectively. It is of interest to note that substituted aminoboronic



(VI)



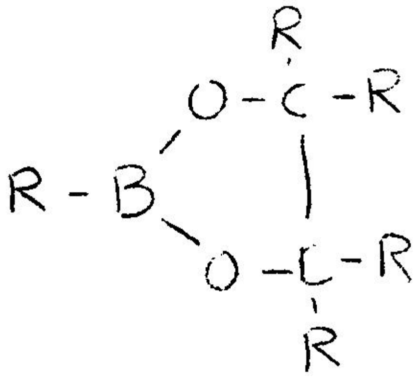
(VII)

acids apparently have been prepared in 1963 (27) by Russian investigators using a reaction of amines with boric acid at 130-170° in the presence of zinc chloride. The success of the reaction seems to depend on the presence of the acid catalyst.

The reaction between boric acid and the t-butyl and "t-octyl" amines was also attempted in the presence of methyl α-D-glucopyranoside in the hope that the carbohydrate would participate in the formation of an orthoborate and thus impede the polymerization of boric acid. Tedious fractionations of the reaction mixtures from a variety of solvents yielded fractions which were identified either as pentaborates or the recovered carbohydrate.

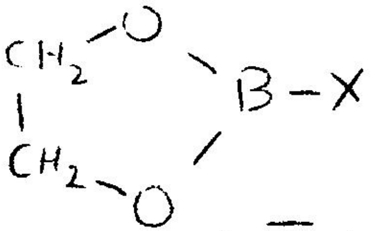
In order to circumvent the formation of pentaborate, another experiment was performed using an ester of boric acid, namely trimethyl borate, with "t-octyl-amine" and methyl-α-D-glucopyranoside. There was produced a high melting hygroscopic solid. Extraction of this solid with acetonitrile gave a solid of m.p. 93-97° . The infrared spectrum of this material shows bands characteristic of methyl-α-D-glucopyranoside and of the pentaborate ion, while elementary analysis suggests a complex mixture of these species.

In connection with the study of the derivatives of diborane-4 (see Part II), it was of interest to prepare a series of 2-substituted-1,3,2-dioxaborolanes. The new compounds reported here are VIII-a, VIII-b, and VIII-c. For comparison

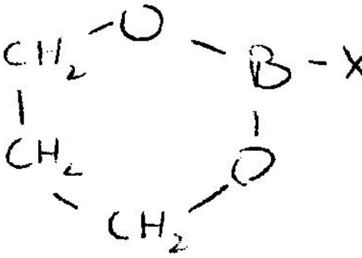


VIII -a	R' = C_6H_5 ,	R = C_6H_5
b	C_6H_5 ,	CH_3
c	CH_3O ,	C_6H_5
d	HO ,	CH_3
e	CH_3O ,	CH_3
f	n-C_4H_9O ,	CH_3

there were prepared also VIII-d, VIII-e, and VIII-f. The question under consideration is the difference between the gem-effect of methyl and phenyl substituents, and the resulting effect on the behavior of the boron center, and for this purpose one could compare the physical and chemical properties of the pairs VIII-a and VIII-b, and VIII-c and VIII-e. In a series of studies of 1,3,2-dioxaborolanes (IX) and 1,3,2-dioxaborinanes (X) Finch and Garner (28)



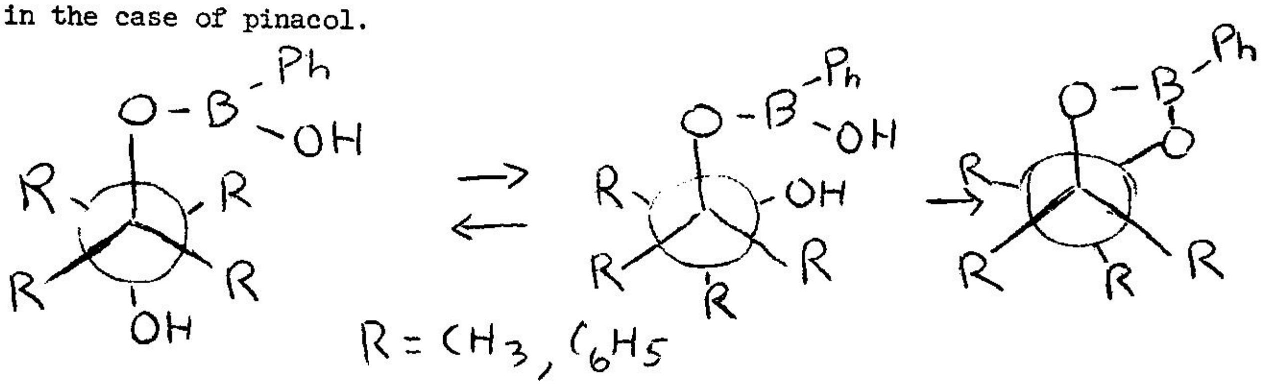
(IX)



(X)

have compared the effect of ring size and the nature of the substituent X on the association of these compounds. The association is believed to involve bonding between the oxygen of one molecule and the boron of another, and thus it provides a measure of the relatively electron vacancy around the boron center. In our case, we are interested in the relative mutual repulsion of the four congested methyl and phenyl substituents in the 1,3,2-dioxaborolanes of the series VIII. It is expected that the mutual repulsion of the R grups will bring about a decrease in the O-C-C bond angles and consequently also a decrease in the O-B-O bond angle. As the latter bond angle is decreased, the tendency of the boron to acquire a sp^3 hybridization should increase, and thus its tendency to associate with an electron donor should also increase. Cryoscopic measurements of the molecular weights of compounds VIII in benzene solution are currently being completed in this Laboratory in order to obtain qualitative data with respect to the self-association as a function of the R substituents.

An interesting difference in the behavior of pinacol and benzopinacol was noted when an attempt was made to prepare compounds VIII-a and VIII-b from phenylboronic acid and the respective glycols. While pinacol and phenylboronic acid could readily be dehydrated to VIII-b by means of azeotropic removal of water with benzene, benzopinacol refused to react under these conditions and could be recovered from the reaction mixture. This difference in behavior most probably can be attributed to differences in the steric effects involved when the phenylboronic acid, or its anhydride, combines with the first hydroxide group of the glycols. Also, the subsequent cyclization requires that the glycol derivative acquires the gauche conformation, and the energy barrier for the anti-gauche conversion must be considerably higher in the case of benzopinacol than in the case of pinacol.



$R = CH_3, C_6H_5$

Part II. Organic Derivatives of Diborane-4.

The chemistry of compounds containing a boron-boron bond is relatively new. The first representative of this family was synthesized in 1925 (30) in poor yield by passing an electric discharge through boron trichloride,

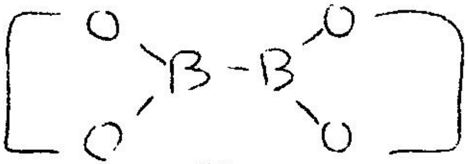
$$2\ BCl_3 \xrightarrow{\text{electric discharge}} Cl_2B\text{-}BCl_2 + Cl_2$$

but more recently there was developed (31) a convenient synthesis of tetrakis(dimethylamino)diborane-4 ,

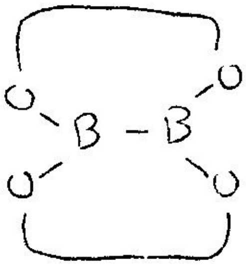
$$2(Me_2N)_2B\text{-}Cl \xrightarrow{Na} (Me_2N)_2B\text{-}B(NMe)_2 \quad (XI)$$

The latter substance is now used as the starting material for the preparation of most derivatives of diborane-4 (32).

The alcoholysis of XI was reported by Brotherton and co-workers (33) to be incomplete unless the dimethylamine is precipitated by the addition of four equivalents of hydrogen chloride in anhydrous ethyl ether. However previous work in this Laboratory (34) showed that cyclic derivatives of diborane-4 could be prepared in excellent yields by the reaction of glycols and XI in an aprotic medium at approximately 100°. Solid derivatives of diborane-4 prepared in this fashion are those derived from pinacol, benzopinacol, and 2,2-dimethyl-1,3-propanediol. In order to decide whether the cyclic derivatives have the structure XII or XIII there was utilized a controlled cleavage of the compounds

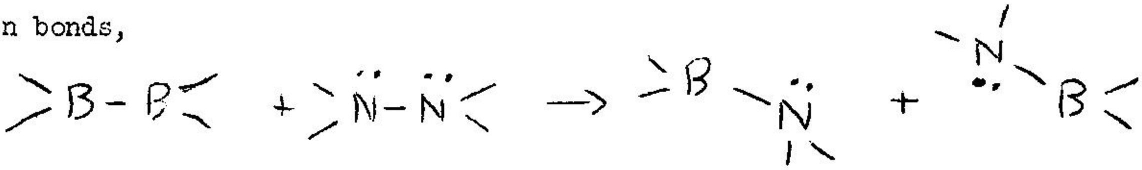


XII



XIII

by means of anhydrous hydrazine. The cleavage of the boron-boron and nitrogen-nitrogen bonds,



was expected to differentiate XII from XIII provided that the alkoxy-boron bonds remained intact. The hydrazinolysis of the diborane-4 derivative of

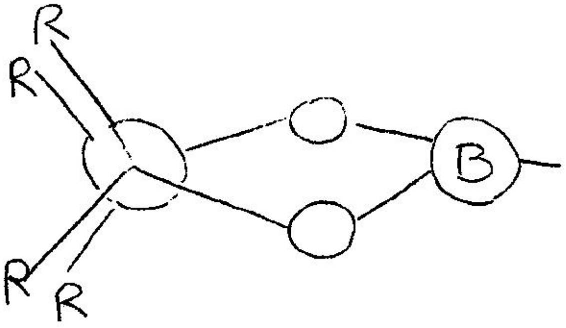
2,2-dimethyl-1,3-propanediol gave the amino derivative expected of XII. The result with the benzopinacol derivative was less clear-cut since the carbon analysis was distinctly lower than that calculated for the simple amino derivative of either the diborane-4 compound XII or XIII, while the molecular weight indicated a cleavage product expected for XII. Finally, the hydrazinolysis of the pinacol derivative gave an essentially nitrogen-free product the elemental and infrared analysis of which corresponded to that of 2-hydroxy-4,4,5,5-tetramethyl-1,3,2-dioxaborolane (VIII-d). The molecular weight determination (by the Rast method) gave a value nearly double of the expected one, but this was also found to be the case for the authentic XIV prepared by exposure of the corresponding 2-methoxy derivative to atmospheric moisture. This indicates that the hydroxy compound either exists as a dimer or that it suffers dehydration to the anhydride during the fusion in camphor.

The purpose of the work reported here was to confirm and elucidate the above mentioned results obtained with the diborane-4 derivatives of pinacol and benzopinacol since the change from methyl to phenyl substituents obviously was causing a marked difference in their behavior.

The hydrazinolysis of the diborane-4 derivative of pinacol was carried out under conditions designed to avoid an exposure of the initial reaction product to atmospheric moisture. In spite of these precautions, the product contained only 30% of the theoretical nitrogen. The molecular weight of this material was again found to be nearly double of the expected value. The infrared spectra of this product suggests that the material still contains the diborane-4 derivative of pinacol.

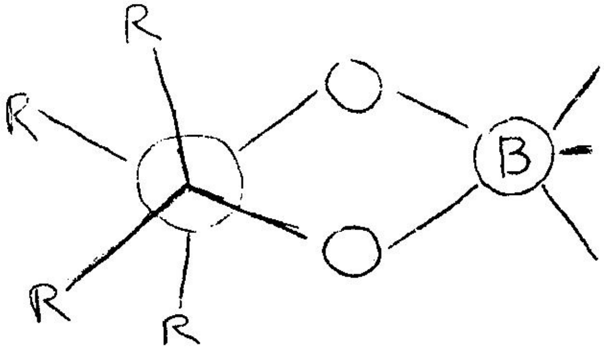
The hydrazinolysis of the diborane-4 derivative of benzopinacol was carried out under similar conditions designed to avoid hydrolysis, and it gave a product of nearly correct nitrogen and boron content. Moreover, unlike the pinacol derivative, the reaction product of the hydrazinolysis of the benzopinacol derivative turned out to be, most of the times, a gummy solid which required repeated crystallizations to give a solid suitable for analysis. Also, of interest is the fact that the analysis consistently gave a low carbon content. In order to obtain an authentic sample of 2-hydroxy-4,4,5,5-tetraphenyl-1,3,2-dioxaborolane (XIV) there were performed several experiments in which the corresponding 2-methoxy- and 2-ethoxy compounds were exposed to mild hydrolysis. In spite of the expected high crystallinity of XIV, all attempts to obtain this substance failed, and instead, benzopinacol and boric acid were recovered from the reaction mixtures.

All these observations with regard to the hydrazinolysis of the cyclic derivatives of diborane-4 are consistent with the following interpretation. It stands to reason that during the hydrazinolysis there is a change in hybridization from sp^2 to sp^3 at the boron atom which relieves the ring strain exhibited by the 1,3,2-dioxaborolanes (28). This electronic reorganization is accompanied by a decrease in the OBO bond angle which favors a decrease in the OCC bond angles and consequently a relief from the mutual repulsions between the chain substituents. This change in hybridization is also accompanied by an increase in the B-O bond distance (35). Thus, in going from $B(OH)_3$ to $B(OH)_4^-$ the B-O bond distance increases 0.13 Å which is probably due to the supression of "back-bonding" between the oxygen and boron atoms. Also, the O-O distance increases by 0.10 Å. This increase in the O-O distance contributes to the more stable conformation in which the R groups are staggered instead of being eclipsed.



Eclipsed conformation

B - sp^2

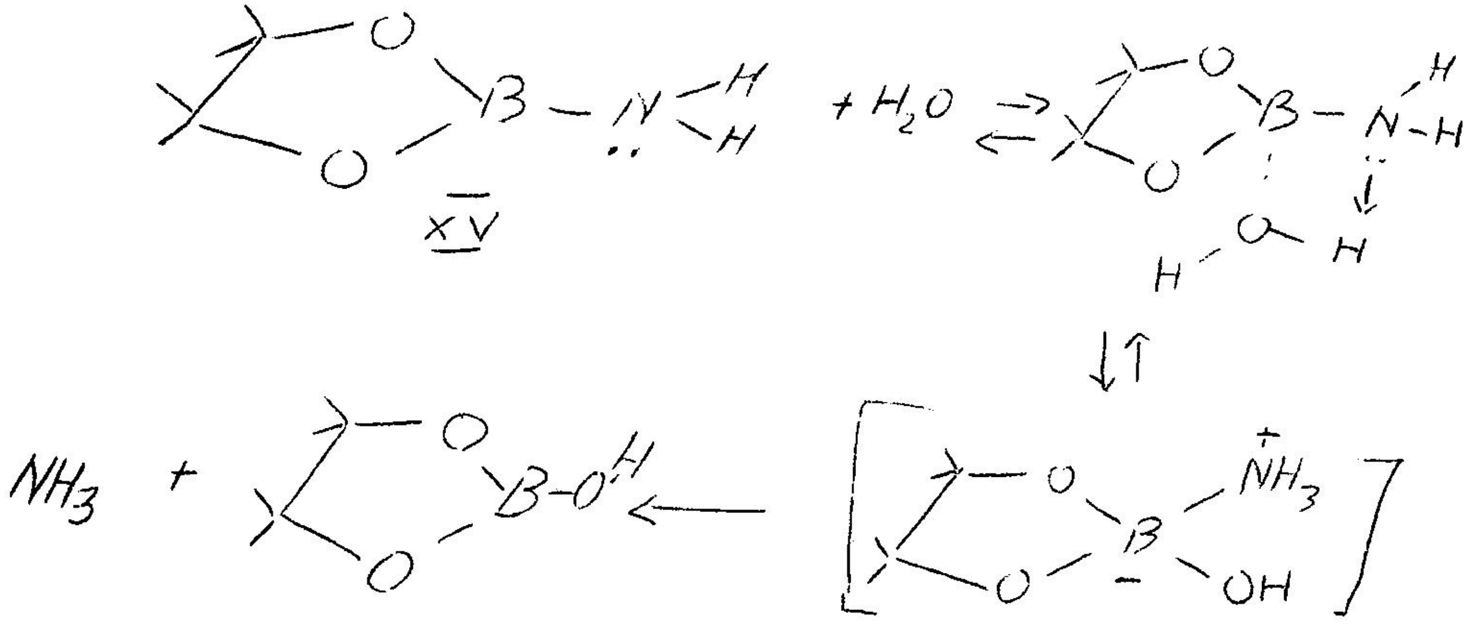


Staggered conformation

B - sp^3

This reasoning leads us to conclude that as the nucleophilic reagent, hydrazine, approaches the boron atom of the diborane-4 derivative of benzopinacol, rather than forming a sp^3 hybridized boron system, the repulsions between the phenyl groups induces a great strain so that there occurs a cleavage of the boron-boron and boron-oxygen bonds. This conclusion is supported by two facts: (a) the simple hydrolysis of the cyclic orthoborate VIII-c always causes a break-down of the ring system (vide infra), and (b) the boron-boron bond of the diborane-4 derivative of benzopinacol is cleaved completly in two hours while the cleavage of the pinacol derivative is still incomplete after a reaction period of two days.

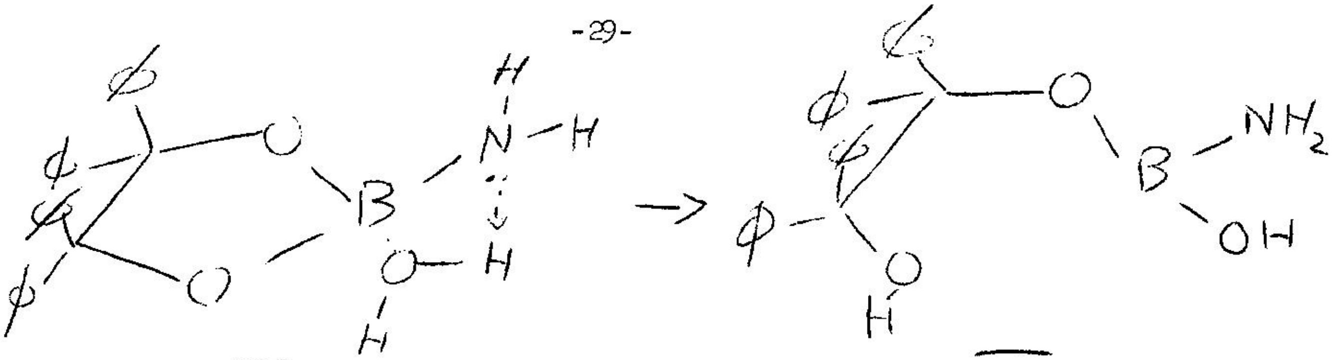
The product of the hydrazinolysis XV of the pinacol derivative, as well as the corresponding hydroxy compound VIII-d, have the three B-X bonds nearly coplanar, and thus the boron interacts with the non-bonding electrons of all three neighboring atoms. Consequently, the amino group is relatively basic and capable of coordinating a water molecule through hydrogen bonding. This then could explain the facil hydrolysis of the amino compound (XV) as shown in the equation that follows.



XV

Once formed, the hydroxy compound VIII-d is capable of association in accord with the observations of Finch and Gardner (28) on the tendency of the borolanes to undergo self-association, and under dehydrating conditions, it gives the anhydride bis(1,3,2-dioxaborolo)oxide as described by Mehrotra and Srivastava (36).

The initial product of the hydrazinolytic cleavage of the boron-boron bond of the benzopinacol derivative may well be similar in structure to that obtained from the pinacol derivative, and the amino group may also easily coordinate a water molecule. However, the fate of the intermediate species XVI turns out to be different because of the very high strain in the borolane ring produced by the mutual repulsions of the four phenyl groups, and instead of the replacement of the amino group, there occurs preferentialy a rupture of the ring.

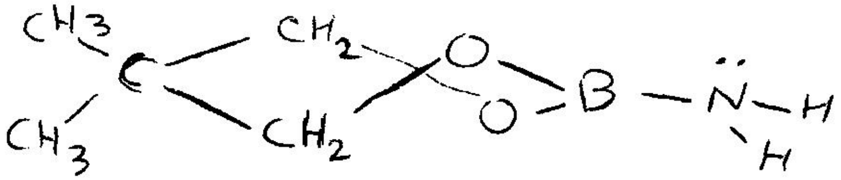


XVI

XVII

The instability of systems such as XVII produces an immediate decomposition to gummy materials which stubbornly resist the isolation of crystalline products. As stated above, while the borolanes derived from benzopinacol were obtained by way of a transesterification reaction, the hydroxy compound XIV analogous to VIII-d, could not be obtained in spite of repeated efforts on our part. Also, it is noteworthy that the literature fails to mention cyclic boron compounds derived from benzopinacol. In view of this situation, our failure to isolate a cyclic hydroxy- or aminoborolane derived from benzopinacol can be traced to the apparently facil ring cleavage which in turn is attributed to the strain induced by the four phenyl substituents.

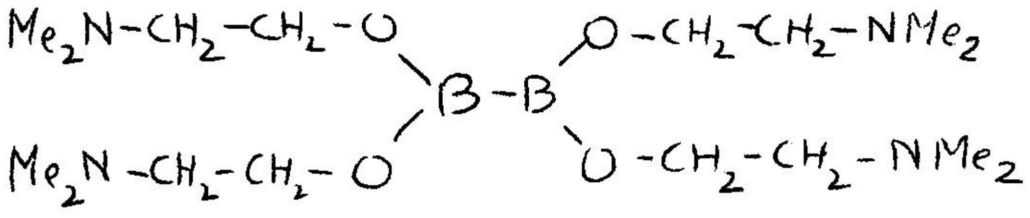
The isolation (34) of the 2-amino-1,3,2-dioxaborinane (XVIII) by direct crystallization from the reaction mixture is an indication of its relatively high stability, and by the same token, the stability of XVIII is probably the driving force which facilitates the ready cleavage of the boron-boron bond during the nucleophilic attack by hydrazine. The relative stability and the failure to associate of compound XVIII can be attributed to the fact that the six membered ring (28) probably exists in a skew-boat conformation (XVIII) to avoid axial orientation of the methyl groups and to minimize any strain.



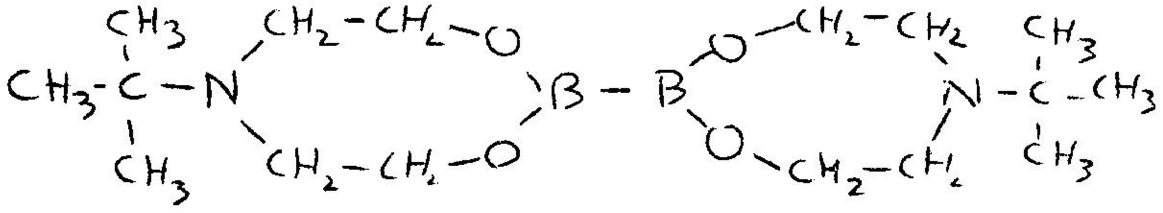
XVIII

An expected consequence of conformation XVIII is a very strong interaction between the vacant orbital of boron and the non-bonding electrons of nitrogen. This strong "back-bonding" between boron and nitrogen in XVIII brings about a relative resistance of the boron toward an attack by water, and also decreases its self-association.

Another phase of our work with the derivatives diborane-4 consisted in the preparation of tetraalkoxyl derivatives containing a basic substituent. The reaction between tetrakis(dimethylamino)diborane-4 and N,N-dimethylaminoethanol, N-t-butyl-N,N-di(2-hydroxyethyl) amine, or N-methyl-N,N-di(2-hydroxyethyl) amine gave in the first two cases the expected products XIX and XX, respectively.

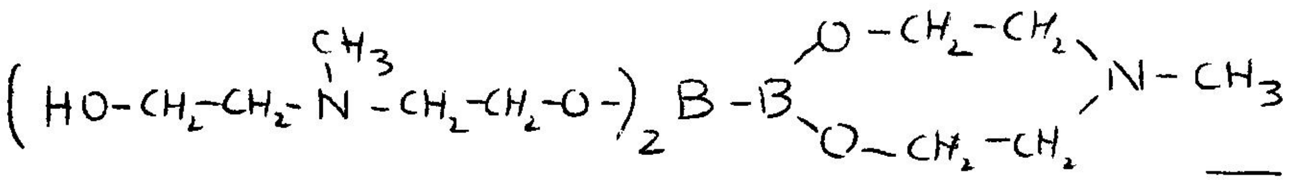


XIX



XX

The last mentioned aminoethanol gave an oily product the elementary analysis of which indicates the presence of a product of structure XXI.



XXI

This conclusion is supported by the infrared spectrum which shows the presence of hydroxyl groups.

The amino substituted tetraalkoxy derivatives of diborane-4 do not aid to inhibit the hydrolysis of the boron-boron bond. Thus, an attempt to prepare a picrate of XIX gave the derivative of N,N-dimethylaminoethanol, and treatment with dilute alkali at 70° C gave a stoichiometric evolution of hydrogen. Exposure of XX to atmospheric moisture produces bubbles in the oily material, most probably also due to hydrogen evolution, and a similar evolution of hydrogen is obtained upon treatment of XXI with dilute alkali.

The third phase of our work with compounds containing a boron-boron bond consisted in the preparation of an analytically pure sample of tetrahydroxydiborane-4 (XXII). The method employed for this purpose (37) involved the hydrolysis of tetrakis(dimethylamino)diborane-4 and the main problem consisted of avoiding the simultaneous cleavage of the boron-boron bond. The latter reaction can be followed by the evolution of hydrogen. In our hands the best preparation of XXII was obtained by the addition of 6 N hydrochloric acid to a cold solution of tetrakis(dimethylamino)diborane-4 in acetone or in water. The purity of the product was determined by elementary analysis and the examination of its infrared spectrum. The latter showed the presence of the boron-boron absorption at 2.70 microns (37), and what is more significant, the absence of the bands at 7.10, 8.90, and 10.90 microns which are characteristic of boric acid. Attempts to hydrolyse tetrakis(dimethylamino)diborane-4 in refluxing toluene were made in the hope of obtaining condensation polymers of XXII, but instead, the products turned out to be the dimethylamine salts of the tri- or pentaborates.

In connection with the preparation of XXII there were investigated the conditions for the cleavage of the boron-boron bond. The results are summarized in Table I and it can be seen that hydrogen is evolved in acidic and alkaline solutions, but not under neutral conditions. However, the solution of XXII in distilled water, loses its reducing power for the silver cation upon standing for a few hours. This indicates that $B_2(OH)_4$ is very sensible to hydrolysis (38) even under neutral conditions.

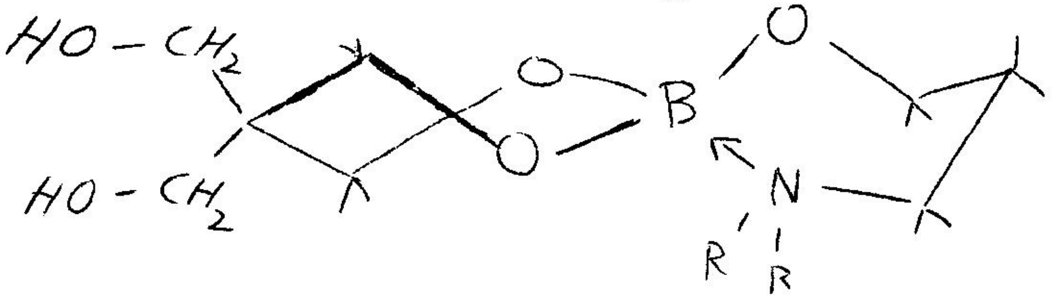
Table I

Hydrolysis of $B_2(OH)_4$

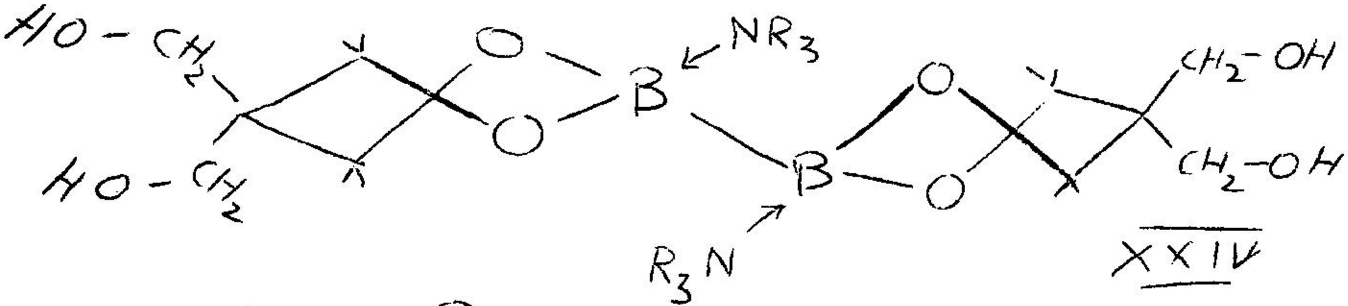
Moles of Sample X 10^4	Medium	Temperature (°C)	Moles of Hydrogen X 10^4	Reaction time (days)
8.42	water	0	0	1
6.82	water	24-25	0	1
2.91	water	66-68	0	1
5.07	water	70-71	0	1
9.34	10% NaOH	reflux	6.5	1
4.87	10% NaOH	74-77	4.5	1
9.32	10% NaOH	75-77	11.0	1
8.62	10% NaOH	24-25	4.0	4
9.77	0.6 N HCl	75-77	5.0	4

IV. Conclusions

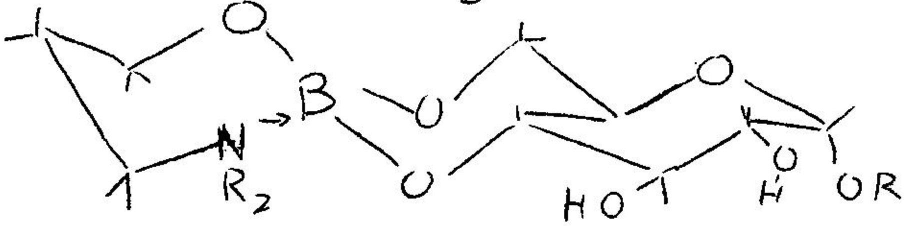
On the basis of the experiences acquired in the course of this work, and considering the set of properties desired in a boron compound suitable for utilization in the neutron activation therapy of malignant tissues, it is thought advisable to explore the synthesis of six-membered ring systems exemplified by structures XXIII - XXVI.



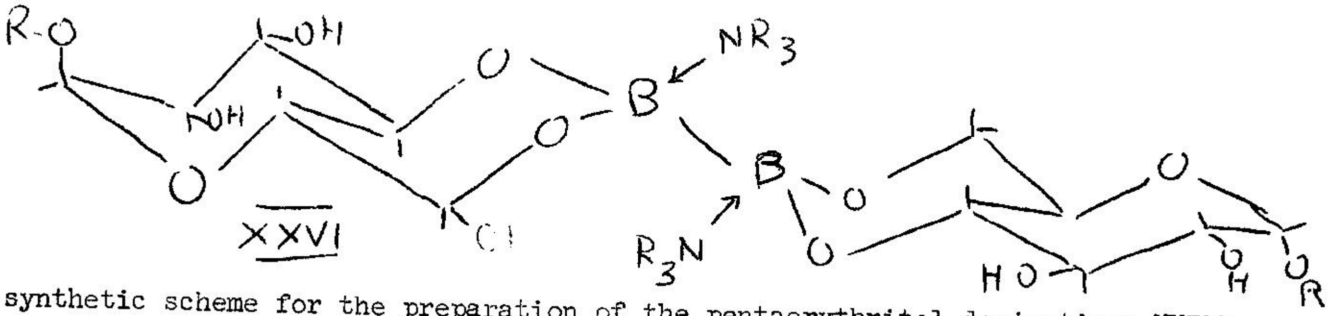
XXIII



XXIV



XV



XXVI

The synthetic scheme for the preparation of the pentaerythritol derivatives XXIII and XXIV should utilize the monobenzylidene or the monoacetonide of this alcohol in transesterification reactions employing methyl orthoborates or tetrakis-(dimethylamino)diboron, respectively. In the case of XXIII, the first step should be followed by an alcoholysis using the desired 3-hydroxypropyl amine. In the synthesis of XXV and XXVI it is proposed to take advantages of the reactions of carbohydrates known (39) to give six-membered rings containing a boron atom.

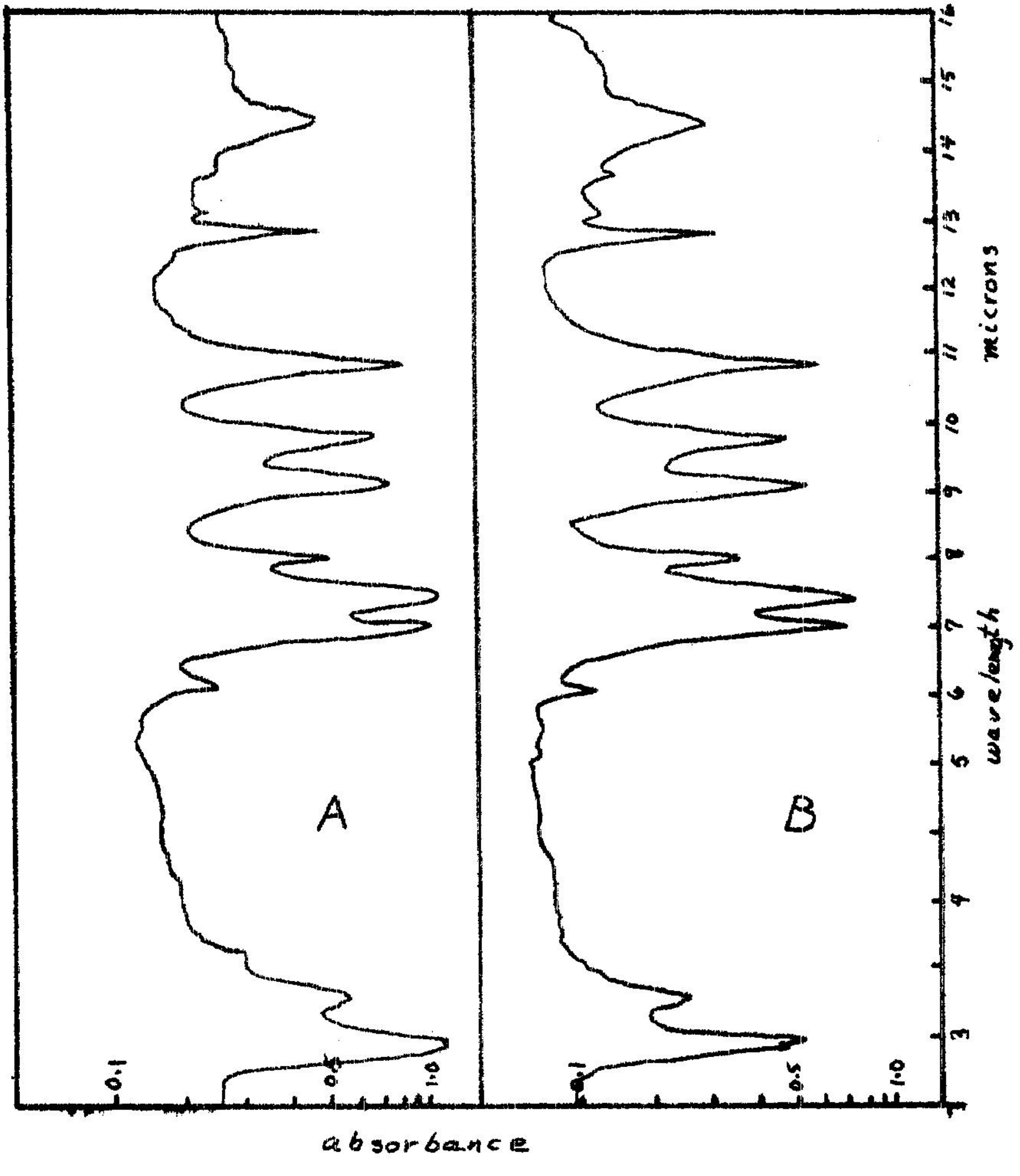


Figure 1. Infrared spectrum of (A) dimethylammonium pentaborate and (B) potassium pentaborate dihydrate in KBr mull.

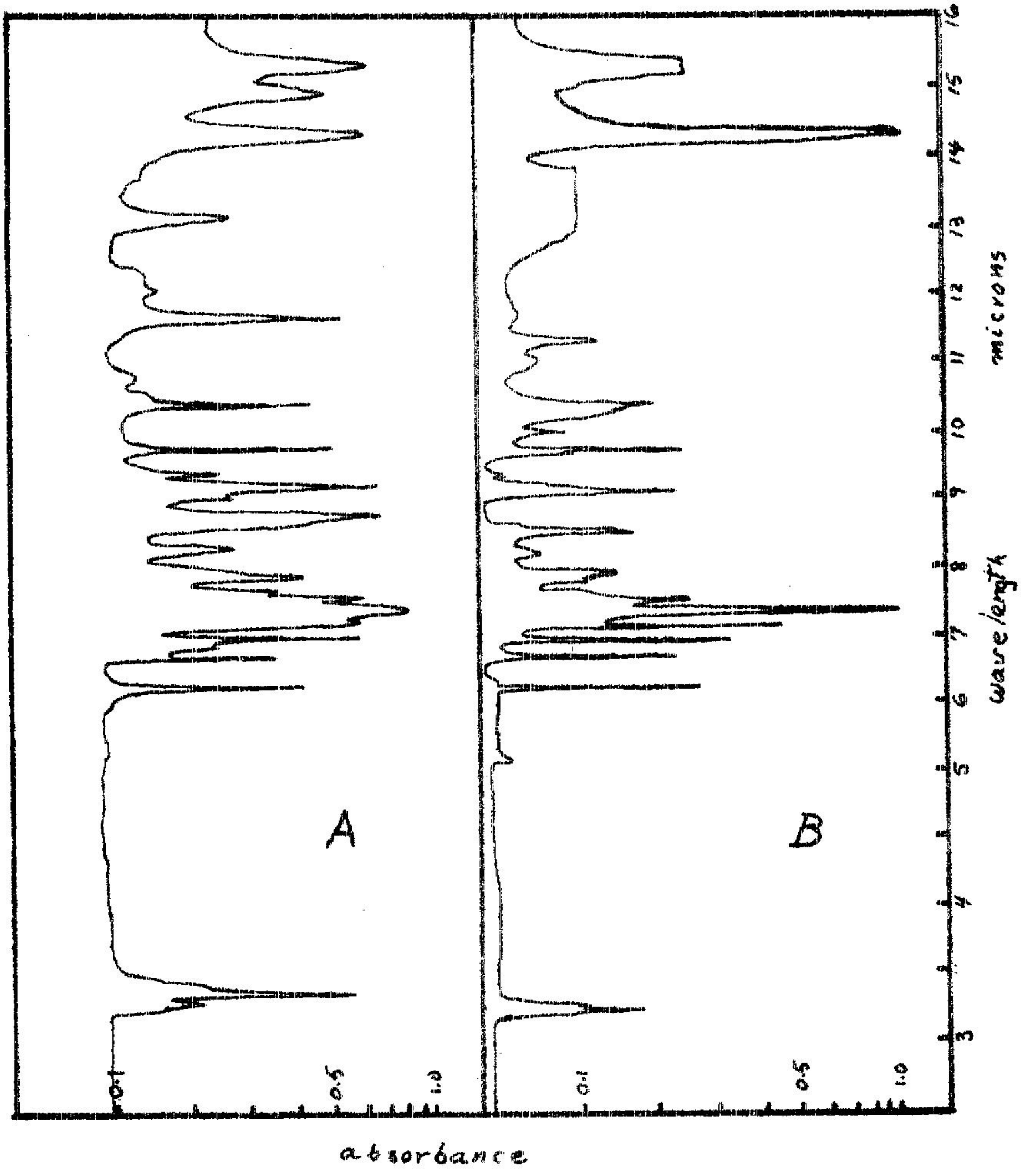


Figure 2. Infrared spectrum of (A) 2-phenyl-4,4,5,5-tetramethyl-1,3,2-dioxaborolane and (B) 2-phenyl-4,4,5,5-tetraphenyl-1,3,2-dioxaborolane in CCl_4 solution.

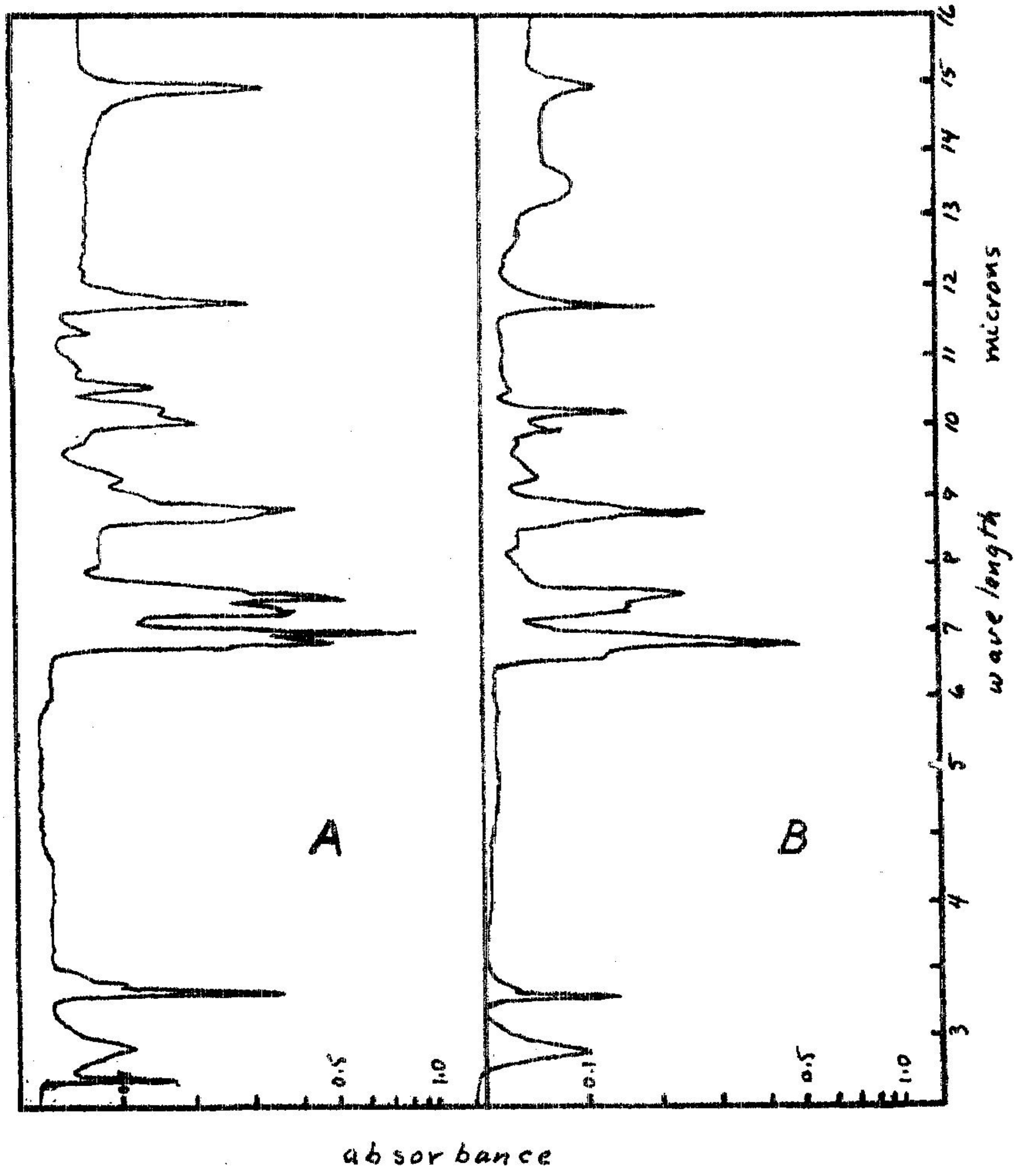


Figure 3. Infrared spectrum of (A) 2-(2-hydroxy-1,1,2,2-tetramethylethoxy)-4,4,5,5-tetramethyl-1,3,2-dioxaborolane and (B) 2-hydroxy-4,4,5,5-tetramethyl-1,3,2-dioxaborolane in CCl_4 solution.

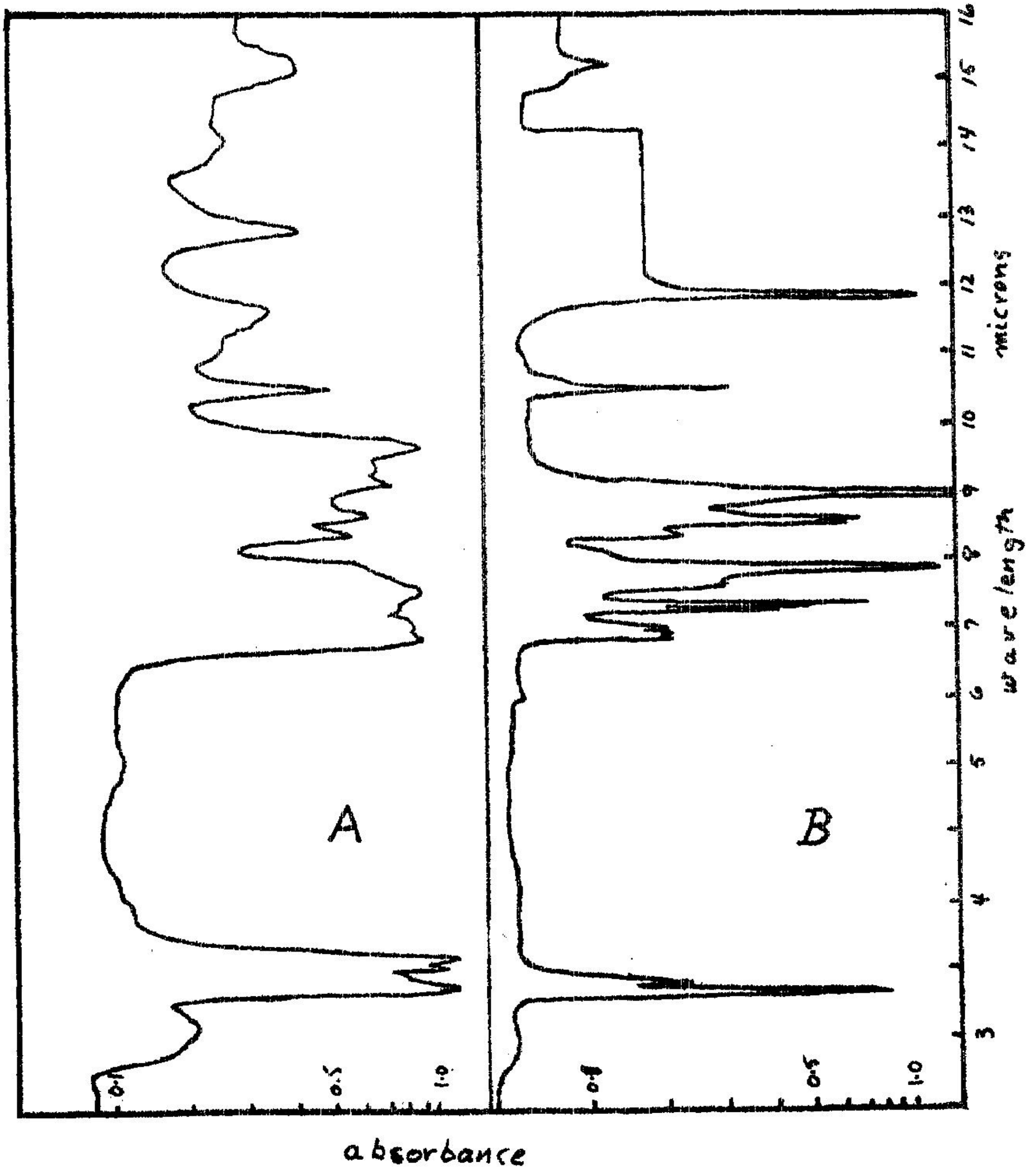


Figure 4. Infrared spectrum of (A) tetrakis(2-dimethylaminoethoxy)diborane-4 and (B) bis(pinacolyl)diborane-4 in CCl_4 solution.

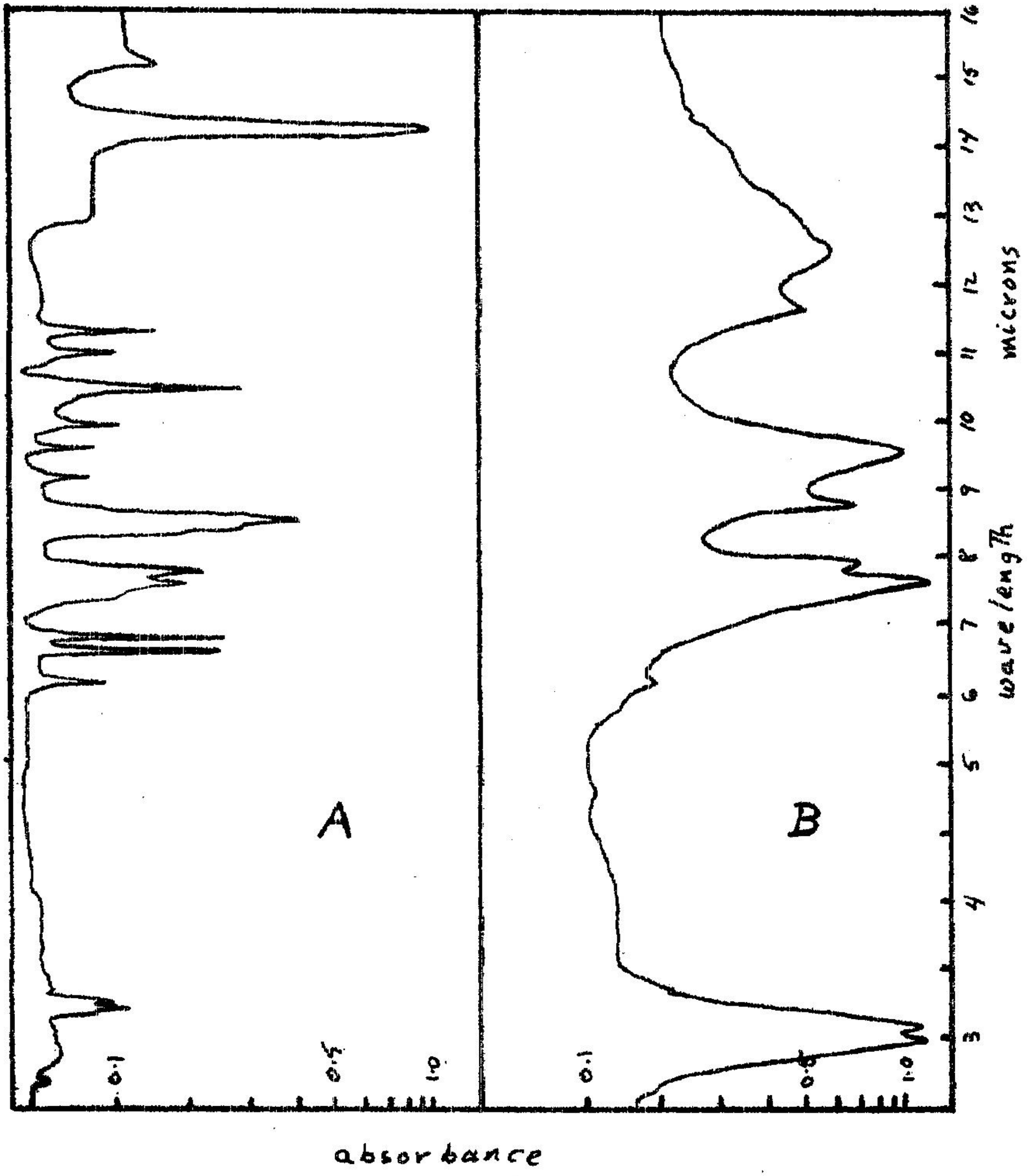


Figure 5. Infrared spectrum of (A) bis(benzopinacolyl)-diborane-4 in CCl_4 solution and (B) tetrahydroxydiborane-4 in KBr mull.

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