HETEROCYCLIC ORGANIC BORON COMPOUNDS

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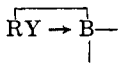
I. INTRODUCTION

This review covers the chemistry of cyclic organic molecules with an annular boron, including those with one or two other heteroatoms in the ring as well. This field is one which was virtually unexplored ten years ago; since then a large amount of work has been

published. Purely inorganic cyclic boron compounds such as some boron hydrides, the borazines, boroxins, borthiins, and cyclic boron–phosphorus compounds are not included since they have all been reviewed recently (12, 64, 82, 93, 99, 108, 109). A large number of compounds also are known in which a cyclic molecule is formed by chelation between the boron and a donor group, each at one end of an acyclic molecule



(where R represents the carbon chain and Y is usually $-NR_2$, $-OR'$, $=O$, etc.). In view of the lack of quantitative information about them, their enormous variety, and the great differences in the strengths of the donor bonds, they really cannot be classed as true heterocyclic molecules and will not, for the most part, be included. Only rings in which all the annular atoms are σ-bonded to each other will be discussed.

The special properties and high reactivities of boron-containing molecules stem from the fact that normal trigonal boron is electron-deficient. Great interest has therefore centered recently on the preparation of more stable and less reactive boron compounds, most of these being cyclic systems. In particular the borazarenes (six-membered unsaturated rings containing boron and one other heteroatom, section III) and the related boroles (section IV) have been extensively investigated and it is now possible to give a comprehensive account of their properties. The review has been arranged to start with these unsaturated rings; section V deals with the boracycloalkanes and section VI with cyclic borate esters and amides. Some of the latter compounds have been reviewed by Lappert (64) and only the more recent developments will be emphasized.

Cyclic boron compounds have been proposed for use as antiseptics, fungicides and insecticides (18, 40), and there has also been much interest in their possible use in cancer therapy (86). Two lines of approach are being followed here: (i) the preparation of compounds which are selectively taken up by cancer tumors and which can then be treated by neutron capture therapy (62) and (ii) synthesis of boron-containing purines and similar compounds which might act directly as antimetabolites in neoplastic tumor cells (13, 15, 86).

The nomenclature of boron compounds is very confused and a unified system has yet to be adopted. The standard Ring Index names and numbering will be applied to most of the cyclic systems here, using the normal prefixes for heteroatoms, *e.g.*, bora-, aza-, oxa-, and suffixes for ring size and degree of unsaturation (Table 1). The main exceptions are the borazarenes (section III) and a few compounds where trivial names have been widely adopted and where their use leads to a considerable shortening of the name.

TABLE 1

NOMENCLATURE OF RINGS (SUFFIXES) CONTAINING BORON AND OTHER HETEROATOMS

Ring size	Rings containing nitrogen: Unsaturated	Rings containing nitrogen: Saturated	Rings containing no nitrogen: Unsaturated	Rings containing no nitrogen: Saturated
5	-borole	-borolidine	-borole	-borolane
6	-borine	-boracyclohexane	-borin	-borinane
7	-borepine	-boracycloheptane	-borepin	-borepane

BH_3 and its derivatives are named as boranes rather than borines (as used by *Chemical Abstracts*), so as not to confuse with the suffix for unsaturated six-membered rings. However, because of common usage, compounds of the type $RB(OH)_2$ and $RB(OR')_2$ will be referred to as boronic acids and esters, rather than dihydroxyboranes and dialkoxyboranes.

The literature has been covered through May, 1961; the appendix contains some further material published up till May, 1962.

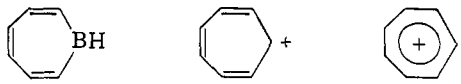
II. HETEROAROMATIC BORON COMPOUNDS (BOREPINS)

A. THEORETICAL

Trigonal boron in the ground state has two 2s and one 2p electrons available for bond formation. The trivalent compounds do not therefore have a complete shell of valence electrons and are electron-deficient. Boron in this state is very reactive toward nucleophiles, that is, toward any reagents or groups which can donate electrons to, and thereby stabilize, the boron. In some cases, as in the borate esters $(RO)_3B$ or $R'B(OR)_2$ (R, R' = alkyl or aryl), it is effected internally, the oxygens stabilizing the molecule *via* their lone-pair electrons by back-coördination. Structures such as $^-B{=}{}^+O-$ are then important. Compounds in which this is not possible such as the simple trialkylboranes (BR'_3) readily add on nucleophiles such as amines (NR_3) to form complexes of the type $^+NR_3{-}{}^-BR'_3$ or organometallic compounds (R'–Y) to form salts $(BR'_4)^-Y^+$. In both of these classes of compound the boron is now tetrahedral and no longer electron deficient. In the absence of such stabilization trialkylboranes and similar compounds are unstable toward air and react readily with molecular oxygen to form peroxides which rearrange to borate esters (alkoxyboranes). Cleavage of the B–R' bonds is also effected by many other nucleophilic reagents and in each case goes *via* an initial adduct which then rearranges. Compounds containing a boron which is either stabilized by back-coördination or by adduct formation with a nucleophile are much less sensitive to autoxidation but undergo solvolysis reactions more readily than the unstabilized molecule due to the increased ionic character of the compound.

An alternative method of stabilizing boron which

has only recently begun to be investigated is by incorporation of the boron in a cyclic unsaturated molecule. As trigonal boron has a vacant 2p orbital, it can, like the isoelectronic $-\overset{|}{\underset{|}{C^{\oplus}}}-$, allow conjugation to proceed through it; thus, for example, if a boron were inserted into a cyclic system where groups already present could provide six π-electrons, the resultant molecule should then have aromatic properties. By analogy with tropylium (IIa), which exists in the form IIb, the aromaticity of which was predicted by Hückel (55) and which has been prepared and found to have a stability considerably greater than that of normal carbonium ions (37), the isoconjugate borepin (I) should also have aromatic properties. Only one derivative of borepin, dibenzo[b,f]borepin, has as yet been prepared; the simpler derivatives are unknown.

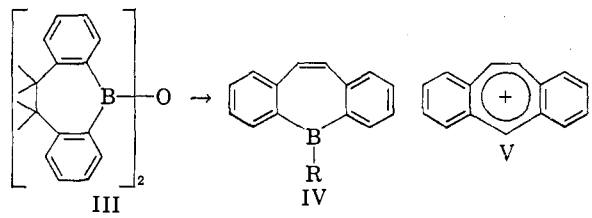


I IIa IIb

B. DIBENZO[b,f]BOREPIN

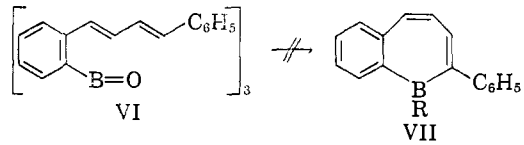
Action of N-bromosuccinimide on the anhydride of 5-hydroxy-10,11-dihydro-5H-dibenzo[b,f]borepin (III) (section VC) gave, presumably, the 10-bromo derivative, which was not isolated but treated directly with sodium methoxide in methanol to give 5-hydroxy-5H-dibenzo[b,f]borepin IV (R = OH), isolated as the ethanolamine complex IV (R = $-OCH_2CH_2NH_2$), m.p. 222–226° (101). This compound was deboronated readily by ammoniacal silver nitrate to *cis*-stilbene. Reduction with lithium aluminum hydride gave the parent compound, 5H-dibenzo[b,f]borepin IV (R = H), isolated as the unstable pyridine complex, which easily underwent acid-catalyzed hydrolytic oxidation to give back the 5-hydroxy compound. The ultraviolet spectrum of the ethanolamine derivative showed no resemblance to that of the isoconjugate dibenzo[b,f]-tropylium (V) and in fact is quite close to that of *cis*-stilbene (2). Coupled with the low stability of the derivatives, this suggests that the hetero-ring here has no aromatic character. This does not, of course, rule out the possibility that borepin and the benzoborepins may show more aromatic character, since it has been shown that the stability of the tropyliums decreases in the order tropylium > benzotropylium > dibenzo[b,f]-tropylium (1). The borepins would also be expected to be less stable than the tropylium since there is more charge localization in the former; in resonance language the latter is expected to be the more stable since seven canonical forms can be written for II as against only one for I.

An attempt to prepare the benzoborepin (VII) by Friedel–Crafts cyclization of the dichloroborane de-



III IV V

rived from the boronic anhydride (VI) failed (80). This may also be due to the lack of aromatic stabilization of the seven-membered ring.



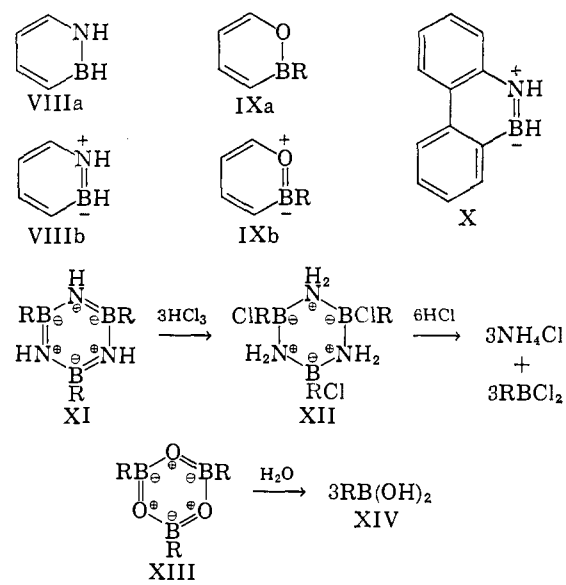
VI VII

III. HETEROAROMATIC COMPOUNDS CONTAINING BORON AND ONE OTHER HETEROATOM IN A SIX-MEMBERED RING (BORAZARENES)

A. INTRODUCTION

The most important heteroaromatic boron compounds which have been prepared to date are the derivatives of 2,1-borazarene (VIIIa) and 2,1-boroxarene (IXa). These compounds are derived from benzene by replacement of a pair of carbon atoms by boron and another heteroatom such as nitrogen or oxygen which can stabilize the electron-deficient boron by use of its lone-pair electrons. For this reason the structure is written as in VIIIb and IXb, the charges on the nitrogen or oxygen and the boron emphasizing the aromatic nature of the ring and the relationship to the isoconjugate benzene.

The first compounds of this series, derivatives of 10,9-borazarophenanthrene (X), were prepared by Dewar, Kubba, and Pettit in 1958 (30). It was soon obvious that by comparison with the long-known



VIIIa IXa X VIIIb IXb XI XII XIII XIV

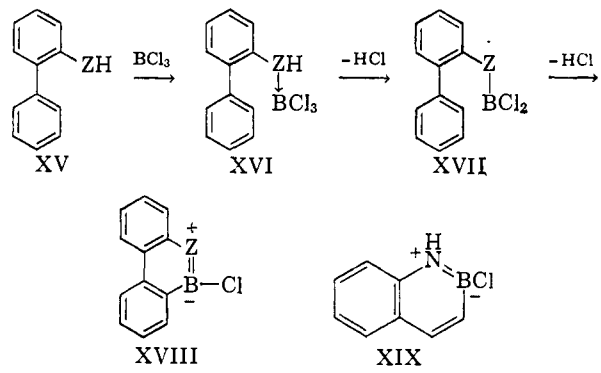
borazine (borazole) XI (R = H) these compounds were vastly more stable toward all types of reagents and could really be classed as aromatic compounds, whereas borazine and its derivatives are at best only borderline. Borazines and their analogs, the boroxins XIII, can again be considered as derived from benzene by replacement of all the carbon atoms by pairs of $-^{+}NH=$ $^{-}BH-$ or $-^{+}O=^{-}BR-$ groups. Due, however, to the considerable charge localization in these compounds, they show very few aromatic properties. Thus they readily undergo addition reactions under mild conditions, with loss of conjugation in the ring to give analogs of cyclohexane which in turn are cleaved by excess of the reagent. Borazines, for example, add on three moles of hydrogen chloride to give the borazane XII which, with excess hydrogen chloride, yields a dichloroborane and ammonium chloride (108). The boroxins (XIII) are even less stable and are simply anhydrides of the boronic acids (XIV) which they generate on treatment with water. Incorporation of only one $-^{+}NH=^{-}BR-$ or $-^{+}O=^{-}BR-$ group in the ring leads to molecules which exhibit aromatic character. To date the parent borazarenes and boroxarenes are still unknown, but a large number of benzo and dibenzo derivatives have been prepared and studied.

The nomenclature of these compounds presents considerable difficulties since standard chemical nomenclature does not allow for charges which are so important here. They should, according to the Ring Index, be named as derivatives of 1,2-dihydrobenzene; for example, VIII should be 1,2-dihydro-1,2-azaborine and X, 9,10-dihydro-9-aza-10-boraphenanthrene. This, however, omits the essential fact that these compounds are isoelectronic with the aromatic hydrocarbons and not with their dihydro derivatives. The convention adopted here is that developed by Dewar and Dietz (22) in which they are named as derivatives of the isoelectronic hydrocarbon with insertion of the prefix "aro-" to denote the aromaticity of the system. Thus VIIIb is 2,1-borazarene, IXb is 2,1-boroxarene and X, 10,9-borazarophenanthrene.

Two main groups of borazarenes have been prepared to date: (i) the 2,1-borazarenes with the two heteroatoms adjacent, and (ii) the 4,1-borazarenes with the two heteroatoms separated by a vinyl group. These will be considered separately.

B. PREPARATION OF 2,1-BORAZARENES

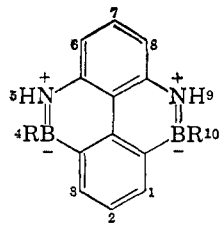
Only one main route to the basic ring systems is available. In an inert solvent phenols and primary aromatic amines XV (Z = O or NH) form complexes (XVI) with boron trichloride which, on heating, lose one mole of hydrogen chloride and give the phenoxy- or anilino-dichloroborane (XVII). These compounds undergo Friedel–Crafts type cyclizations, if the geometry of the system permits, to form a six-membered



ring (XVIII). The ease with which these reactions proceed depends on the ease of formation of the cation $-ZB^{\oplus}Cl$ and on the reactivity of the position being attacked. In the case of the borazarophenanthrenes XV–XVIII (Z = NH) the reaction proceeds in three distinct stages; formation of the complex XVI occurs in the cold, in benzene solution. On refluxing the solution of the complex for some hours, (2-biphenylylamino)-dichloroborane XVII (Z = NH) is formed. Cyclization here only occurs on heating the dichloroborane in the absence of solvent to 180° with aluminum chloride as a catalyst (30). The cyclization stage proceeds much more easily in the 10,9-boroxarophenanthrenes XV–XVIII (Z = O) (23), while the 2-chloro-2,1-borazaronaphthalene (XIX) is formed directly on refluxing the complex of *o*-aminostyrene and boron trichloride in benzene. No catalyst is required here (22), and the anilinodichloroborane is not isolated.

Two cases in which double cyclizations occurred also have been reported (14). 4,10-Dibora-5,9-diazaropyrenes XX (R = C_6H_5, m.p. 200–202°) and 3,6-diphenyl-2,7-dibora-1,8-diazaroanthracenes XXI (R = C_6H_5, m.p. 270°, and R = H, m.p. 211°) have been prepared from the appropriate diamines. However, neither 2,2′-diaminobiphenyl (14) nor *trans*-2,2′-diaminostilbene underwent double cyclizations. The former gave no boron-containing product, while the latter, even in the presence of a large excess of reagent, only gave derivatives of 3-(*o*-aminophenyl)-2,1-borazaronaphthalene XXII (R = C_6H_5, m.p. 142°) (16). Presumably the positions at which cyclization should occur in the former and double cyclization in the latter are very strongly deactivated to electrophilic attack.

The cyclic chloro compounds of type XVIII or XIX are easily converted to other derivatives since the chlorine is very reactive and easily replaced. Hydrolysis yields the free acid XXIII (R = OH), lithium aluminum hydride reduction gives the boron hydride XXIII (R = H) and Grignard reagents give the appropriate B-alkyl or B-aryl derivatives (30). These latter compounds can also be obtained more conveniently from the acids, the anhydrides or the alkyl esters by nucleo-



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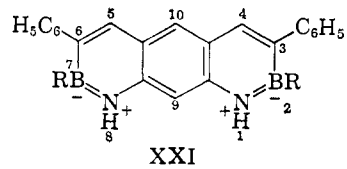
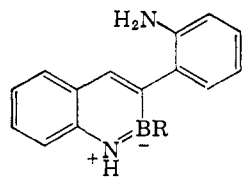
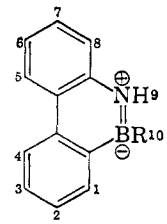


XXI



XXII



XXIII

philic replacement at the boron (26). The B-phenyl compounds have also been prepared directly from phenylboron dichloride and the amine or phenol. Yields in either case are about 50–60% over-all (30). The compounds and their melting points have been summarized in Table 2.

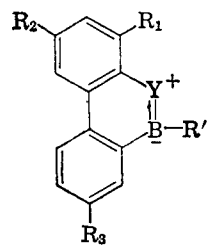
C. PROPERTIES OF THE 10,9-BORAZAROPHENANTHRENES

1. Physical Properties

The 10,9-borazarophenanthrenes (and most of the other borazarenes) are, with a few exceptions (see below), mostly extremely stable colorless crystalline compounds with sharp melting points. They are easily soluble in all the common organic solvents and usually

TABLE 2

10,9-BORAZAROPHENANTHRENES AND 10,9-BOROXAROPHENANTHRENES



R_1	R_2	R_3	Y	R′	M.p., or b.p., °C.	Mm.	References
H	H	H	NH	H	69–70		30, 26
H	H	H	NH	CH_3	103–104		30
H	H	H	NH	C_2H_5	77–78		30
H	H	H	NH	C_6H_5	110–111.5		30
H	H	H	NH	Cl	93–94		30
H	H	H	NH	OH	169–170[a]		30
H	H	H	NCH_3	CH_3	117–118		34
H	H	H	NCH_3	C_6H_5	122.5–123.5		34
H	H	H	$NCOOC_2H_5$	CH_3	160	0.3	35
H	H	H	$NCOOC_2H_5$	C_6H_5	113–115		35
Cl	H	H	NH	CH_3	170–175	0.5–0.6	27
H	Cl	H	NH	CH_3	86–87		27
H	H	Cl	NH	CH_3	98–99		27
NO_2	H	H	NH	CH_3	165–166		27
H	NO_2	H	NH	CH_3	209–210		27
NH_2	H	H	NH	CH_3	137–138		27
H	NH_2	H	NH	CH_3	125–126		27
H	CH_3CO	H	NH	CH_3	164–165		29
CH_3CO	CH_3CO	H	NH	CH_3	205–207		29
NO_2	H	H	NH	OH	266–267		27
H	NO_2	H	NH	OH	360 dec.		27
NH_2	H	H	NH	OH	195–196		27
H	NH_2	H	NH	OH	218–220		27
H	CH_3CO	H	NH	OH	233–235		29
CH_3CO	CH_3CO	H	NH	OH	>350		29
Cl	Cl	H	NH	OH	263–264		28
NH_2	H	H	NH	O/2	240–242		29
Br	Br	H	NH	O/2	295–296		28
Cl	Cl	Cl	NH	O/2	285–286		28
NO_2	H	H	NH	OCH_3	155–156		27
H	NO_2	H	NH	OCH_3	237–238		27
H	H	H	NH	OC_2H_5	54–55		26
NO_2	H	H	NH	OC_2H_5	125–126		27
H	CH_3CO	H	NH	OC_2H_5	210–211		29
H	H	H	O	OH	205–206		23
H	H	H	O	O/2	205–206		23
H	H	H	O	Cl	115–120 dec.		23
H	H	H	O	OCH_3	63.5–64.5		23
H	H	H	O	C_6H_5	82–83		23
Br	Br	H	O	OH	279–280.5		23
Br	Br	Br	O	OH	>310		23
Br	Br	Br	O	OC_2H_5	141–142		23

[a] In practice the melting point of this compound varies considerably, depending on the degree of dehydration.

TABLE 3

ELECTROPHILIC SUBSTITUTION OF THE 10,9-BORAZAROPHENANTHRENES (XXIII)

Reagent, moles	Conditions/t, °C.	R in XXIII	Orientation of substn.; isomers formed, % 6-	8-	6,8-	2,6,8-	Reference
Cl_2 (1)	CH_3COOH/25	CH_3	—	58	—	—	27
CH_3COCl (1)	$CS_2/AlCl_3$/0	CH_3	42.4	—	17.4	—	29
HNO_3 (1)	$(CH_3CO)_2O$/0	CH_3	33	63	—	—	27
Cl_2 (2)	CH_3COOH/25	OH	—	—	75	—	28
Cl_2 (3)	CH_3COOH/90–100	OH	—	—	—	80	28
Br_2 (2)	CH_3COOH/50–80	OH	—	—	80	—	28
CH_3COCl (1)	$CS_2/AlCl_3$/25	OH	46.7	—	17.8	—	29
HNO_3 (1)	CH_3COOH/0	OH	29	57	—	—	27

crystallize best from ether or light petroleum. They can be chromatographed on alumina without decomposition and this property is useful for separation or purification purposes.

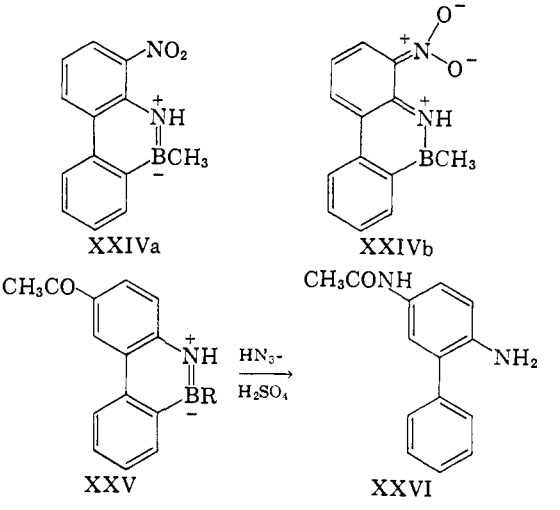
A characteristic feature of the borazarenes is the similarity of the ultraviolet spectra to those of the isoconjugate aromatic hydrocarbons and the dissimilarity to the spectra of the uncyclized starting materials. For example, the spectrum of 10,9-borazarophenanthrene XXIII (R = H) resembles that of phenanthrene very closely in the positions of the main bands, though the intensity of the α-band at 275 mμ is very much stronger in the heterocycle than in phenanthrene (30). This relationship is usual between aromatic heterocycles and the isoconjugate hydrocarbons and has been given a theoretical explanation (32, 84). The similarity between the borazarophenanthrene and phenanthridine is even more pronounced, and provides good confirmatory evidence for the aromaticity of these boron compounds.

10-Hydroxy-10,9-borazarophenanthrene (XXIII, R = OH) dissolves in alkali and is a weak acid. The acidity is not increased on the addition of mannitol (25).

2. *Chemical Properties*

(*a*) *Electrophilic Substitution.*—The borazarophenanthrenes readily undergo electrophilic substitution reactions typical of aromatic compounds such as nitration, chlorination, bromination, and Friedel–Crafts acetylation. The most reactive positions are the 6- and 8-positions; under more vigorous conditions 2,6,8-trisubstituted products are obtained. The results are summarized in Table 3.

In the nitration of 10-methyl-10,9-borazarophenanthrene XXIII (R = CH_3) varying amounts of 10-hydroxy-8-nitro-10,9-borazarophenanthrene were formed as a by-product, shown to arise by oxidation of the B-methyl group of 10-methyl-8-nitro-10,9-borazarophenanthrene (XXIVa) by the reaction mixture (27). This effect is not unexpected since the presence of a nitro group *ortho-* to the –NH– will reduce the electron-donating power of the latter and thus destabilize the boron, making it more easily oxidizable.



This can be expressed as due to the importance of structure XXIVb in the molecule.

The orientation of the substitution products has been shown to be in agreement with the predictions of molecular orbital calculations (27). The absence of the 8-isomer in the monoacetylation of both the 10-methyl- and 10-hydroxyborazarophenanthrenes has been explained as due to the formation of an adduct between the boron compound and aluminum chloride which interferes with 8-substitution. Adduct formation is not favored in the 6-acetyl compounds and hence does not interfere with further substitution (29).

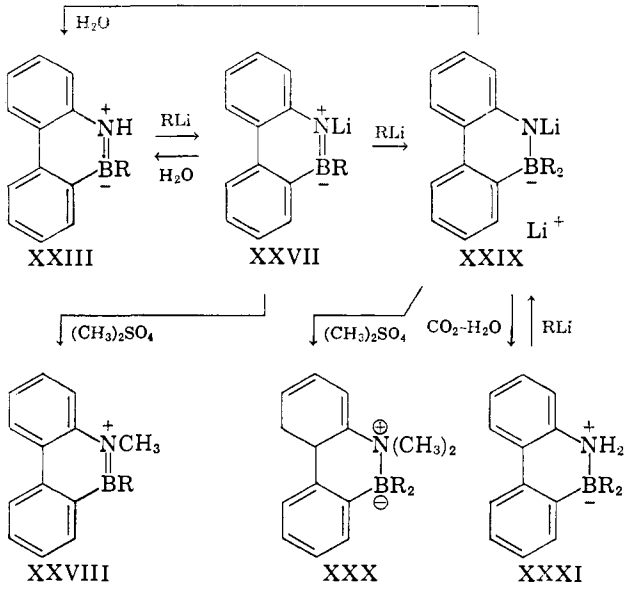
The orientations of the various substitution products have been determined by two methods: (i) Direct synthesis: This was only applicable to the bromo- and chloro-borazarophenanthrenes which were synthesized from the appropriate chloro- and bromo-2-aminobiphenyls. (ii) Degradation: Concentrated sulfuric acid converts the borazarophenanthrenes smoothly into 2-aminobiphenyls. This reaction usually goes in the cold in good yield and is a convenient way to establish the position of substitution. An extension of this method was used to identify the 6-acetyl-borazarophenanthrenes (XXV) in which a Schmidt reaction was carried out on the compound. This caused simultaneous removal of the boron and conversion of the acetyl group into an acetamido group, giving 5-5-acetamido-2-aminobiphenyl (XXVI) in 80% yield

(29). It was found that the monoacetyl and diacetyl compounds underwent deboronation with difficulty in sulfuric acid and are among the most acid-resistant boron compounds yet prepared.

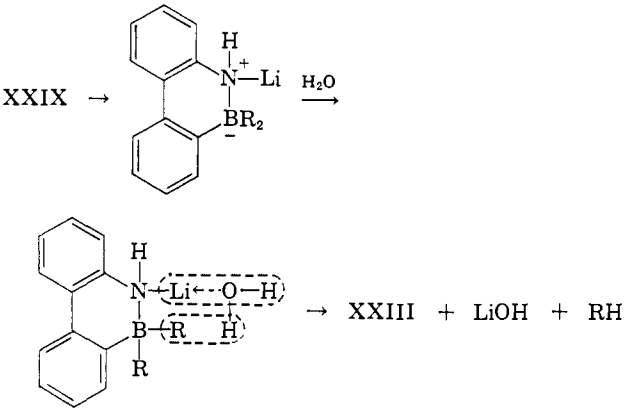
The nitroborazarophenanthrenes were reduced to the aminoborazarophenanthrenes by hydrazine hydrate and palladium-on-charcoal; the amines did not undergo Sandmeyer reactions (27).

(*b*) *Reactions with Nucleophilic Reagents.*—Since the nitrogen in B-methyl and B-phenyl-10,9-borazarophenanthrene bears a partial positive charge, these compounds should undergo nucleophilic substitution reactions at the nitrogen similar to those undergone by carbazole (98). The rapid exchange of hydrogen by deuterium which 10-methylborazarophenanthrene underwent in deuterium oxide in the presence of sodium deuteroxide showed that the imino hydrogen must be appreciably acidic. Reaction with one mole of an organolithium compound gave the N-lithio derivative XXVII which was converted into 9,10-dimethyl-10,9-borazarophenanthrene XXVIII (R = CH_3) by reaction with dimethyl sulfate. The B-phenyl compound reacted analogously (34). Direct methylation was not possible; alkaline dimethyl sulfate did not react and diazomethane was catalytically decomposed by the boron compound to polymethylene.

In the presence of excess organolithium compound, a second mole was added on to give a colored solution (in ether) which probably contained the salt XXIX. Reaction of XXVII or XXIX with water gave back the original borazarophenanthrene (XXIII); reaction of XXIX with dimethyl sulfate gave 10,10-disubstituted-9,9-dimethyl-9,10-dihydro-10,9-borazarophenanthrenes (XXX). Carbonation of XXVII and hydrolysis gave back the borazarophenanthrene (XXIII), but the same reaction on XXIX gave 10,10-disubstituted-9,10-dihydro-10,9-borazarophenanthrenes (XXXI).



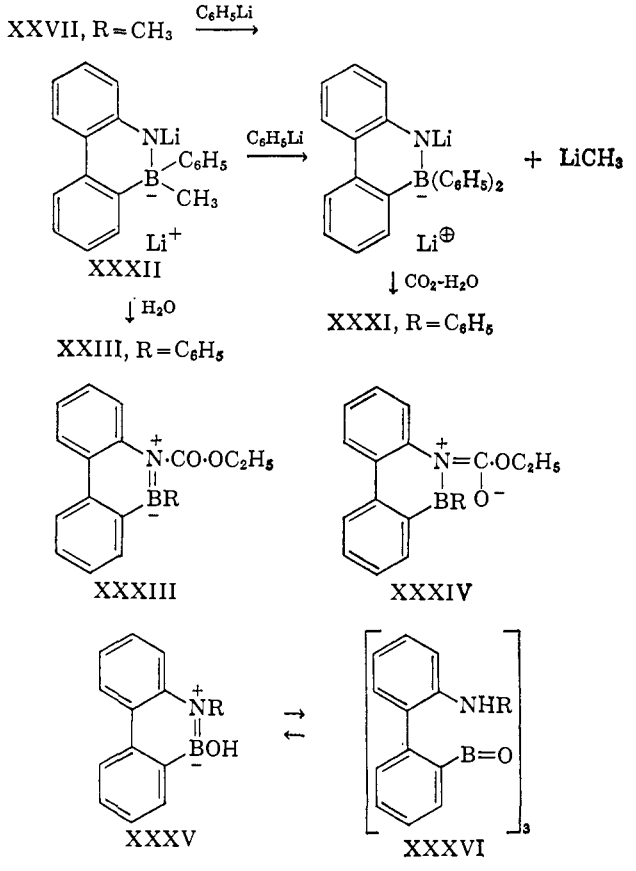
This latter reaction undoubtedly goes *via* the N-carboxylic acids which are unstable and decarboxylate spontaneously to give either the borazarophenanthrene or the dihydroborazarophenanthrene. The remarkable hydrolysis of XXIX to XXIII with loss of a B-alkyl or -aryl group must go in two stages: first a rapid hydrolysis of the ionic lithium salt, second a slow dismutation process



The dihydroborazarophenanthrenes XXX (R = CH_3, m.p. 108–109°; R = C_6H_5, m.p. 224–226°) and XXXI (R = CH_3, m.p. 136°; R = C_6H_5, m.p. 232°) are interesting compounds of a new type. They are quite stable thermally and do not disproportionate in the way which might be expected for XXXI (R = CH_3), which is really a substituted dimethylphenylborane. They do not undergo autoxidation and are not appreciably basic, though high concentrations of acid destroy them. These properties indicate that a very strong donor bond $-{}^{+}NR_2-{}^{-}BR'_2-$ must be present. Treatment of XXXI with excess organolithium gives XXIX which is hydrolyzed back to XXIII with water (34).

For these reactions to proceed normally R- in the organolithium must be the same as the substituent on the boron in the borazarophenanthrene. If they are different, then replacement reactions occur. Thus, the B-methylborazarophenanthrene was converted to the B-phenylborazarophenanthrene merely by adding 2 moles of phenyllithium to an ethereal solution, and hydrolyzing. When a large excess of phenyllithium was used and the product was carbonated before hydrolysis, the main product was 10,10-diphenyl-9,10-dihydro-10,9-borazarophenanthrene XXXI (R = C_6H_5). Since an X–C_{sp^2} bond, present in the B-phenyl compounds, is stronger than an X–C_{sp^3} bond, present in the B-methyl compounds (36), it is not unexpected that a phenyl will replace a methyl and also that in the intermediate XXXII, the methyl is hydrolyzed off in preference to the phenyl.

Reaction of 9-lithio-10,9-borazarophenanthrenes (XXVII) with ethyl chloroformate gave the 9-carbethoxy-10,9-borazarophenanthrenes (XXXIII) which were

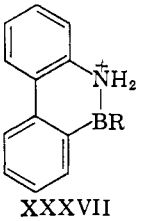


easily autoxidized with loss of the group R to give XXXV (R = $COOC_2H_5$). This reaction is analogous to the oxidation of 8-nitro-10-methylborazarophenanthrene (section IIIC (2a)) and is again due to the presence of a strong electrophilic group adjacent to the nitrogen, making structures of the type XXXIV important. The now unstabilized boron will be able to coördinate oxygen to give the autoxidized product after rearrangement. The product actually isolated was XXXVI (R = $COOC_2H_5$) which no longer had the hetero-ring intact. It is probable that there is always an equilibrium between the borazarophenanthrene XXXV and the substituted phenylboronic anhydride (XXXVI) in the 10-hydroxy-10,9-borazarophenanthrenes and that the position of the equilibrium depends on the nature of the substituent on the nitrogen; a strongly electrophilic group such as carbethoxy weakens the N–B bond so that the more stable structure is in fact the anhydride XXXVI (35).

Attempts to prepare the 9-benzoylborazarophenanthrenes failed; the only product isolated was the anhydride XXXVI (R = C_6H_5CO); presumably the 9-benzoylborazarophenanthrenes are too easily autoxidized to be stable. This is not unexpected since the benzoyl group is a stronger electrophile than the carbethoxy group (35).

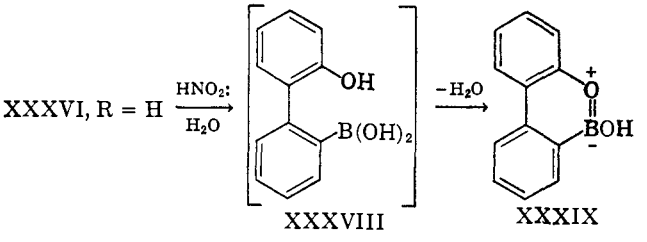
(*c*) *Other Reactions.*—The borazarophenanthrenes, provided that no strong destabilizing groups are present, are very stable to air, bases, acids and heat. 10-Hydroxy-10,9-borazarophenanthrene was recovered unchanged from boiling aqueous alkali (30) and 10,9-borazarophenanthrene itself, a substituted boron hydride, was stable in the solid to air for over a year at room temperature; it did, however, undergo both acid- and base-catalyzed hydrolytic oxidation readily in solution (26).

In strong acid (9 *N* hydrochloric) the borazarophenanthrenes underwent protonation, with loss of conjugation, probably forming XXXVII (33).



XXXVII

10 - Hydroxy - 10,9 - borazarophenanthrene XXXV (R = H) was converted into 10-hydroxy-10,9-boroxarophenanthrene (XXXIX) in 50% yield by treatment with nitrous acid in acetic acid followed by boiling water. The mechanism is not clear, but it may well go *via* the boronic anhydride XXXVI (R = H), a small amount of which is in equilibrium with the borazarophenanthrene; under the conditions of the reaction this would be converted into 2-hydroxy-2′-biphenylylboronic acid (XXXVIII) which spontaneously ring closes to the hydroxyboroxarophenanthrene (33).



D. 10,9-BOROXAROPHENANTHRENES

10,9-Boroxarophenanthrenes have been prepared from 2-hydroxybiphenyl by the general route for 2,1-borazarenes (section IIIB) and are included in Table 2. The only derivatives which are stable are those in which the boron carries a substituent such as hydroxy, which gives additional stabilization by internal coordination. The B–H and B–alkyl derivatives are unknown and even the 10-phenylboroxarophenanthrene readily underwent hydrolytic oxidation in solution. 10-Hydroxy-10,9-boroxarophenanthrene (XXIX) gave 2-hydroxybiphenyl on fusion with potassium hydroxide, and 2,2′-dihydroxybiphenyl on oxidation with hydrogen peroxide; it was stable to aqueous acids and alkalies and was unaffected by air (23).

This compound is also the most strongly acidic hydroxyborazarene and the only one which showed an increase in acidity on addition of mannitol. Models show that the boroxarophenanthrene ring is more strained than the borazarophenanthrene ring; this explains the lower stability of the former and suggests that in alkali or in the presence of mannitol the hydroxyboroxarophenanthrene gives the more stable tetrahedral borate ion (see section VID (2)) (25).

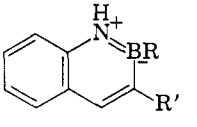
Bromination of XXXIX in glacial acetic acid gave 6,8-dibromo-10-hydroxy-10,9-boroxarophenanthrene; excess bromine gave the 2,6,8-tribromo compound. This is similar to the substitution pattern of 10-hydroxy-10,9-borazarophenanthrene (23).

E. 2,1-BORAZARONAPHTHALENES AND 1,2-BOROXARONAPHTHALENES

The preparation of the borazaronaphthalenes already has been mentioned (section IIIB); in their properties such as stability and the relationship of their ultraviolet spectra to those of the isoconjugate naphthalenes, the borazaronaphthalenes parallel the borazarophenanthrenes. The parent compound XL (R = H) is stable to acids, in contrast to 10,9-borazarophenanthrene (22). The derivatives of this ring system which are known have been summarized in Table 4.

TABLE 4

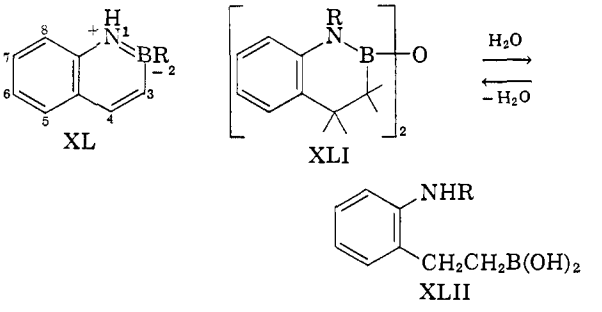
2,1-BORAZARONAPHTHALENES



R′	R	M.p., °C.	References
H	H	100–101	22, 26
H	CH_3	73–74	22, 26
H	C_6H_5	137.5–139	22
H	Cl	72–74	22
H	O/2	198–200	22
H	OCH_3	57–58	26
Cl	CH_3	119–120.5	24
Cl	OCH_3	88–89.5	24
Br	CH_3	128–129.5	24

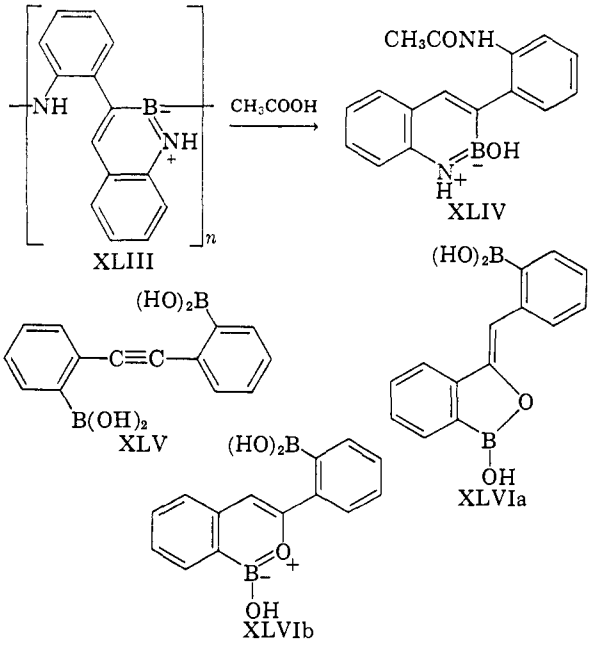
2-Methyl-2,1-borazaronaphthalene XL (R = CH_3) was brominated in the 3-position; a small amount of *o*-amino-ω-bromostyrene was obtained as a by-product. Chlorination proceeded analogously, with the formation of a greater amount of *o*-amino-ω-chlorostyrene as by-product. It has been suggested that substitution occurs *via* the formation of a π-complex between the borazaronaphthalene and the bromonium or chloronium ion (24).

Bis - (2,1 - borazaro - 2 - naphthyl) anhydride XL (R = O/2) was resistant to conditions which normally reduce styrenes (sodium in ethanol) but was reduced to bis-(3,4-dihydro-2,1-borazaro-2-naphthyl) anhydride XLI (R = H), m.p. 87.5–89°, by sodium in butanol. This compound formed an N-acetyl derivative on treatment with acetic anhydride XLI (R = CH_3CO), m.p. 280–282°, a reaction not undergone by the borazaronaphthalenes. With water both of these compounds underwent a reversible ring opening to give *o*-amino- and *o*-acetamidophenethylboronic acids XLII (R = H and CH_3CO), respectively (25). The unsaturated, aromatic borazaronaphthalenes are resistant to acids and alkalies, illustrating the great difference in reactivity between the borazarenes and the cyclic amides.

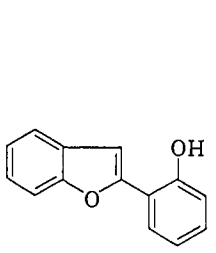


Attempts to carry out a double cyclization on *trans*-2,2′-diaminostilbene gave only 3-substituted borazaronaphthalenes (section IIIB); using boron trichloride a polymer, probably XLIII, was obtained after hydrolysis, which was converted into 3-(*o*-acetamidophenyl)-2-hydroxy-2,1-borazaronaphthalene (XLIV) by acetic acid. Treatment of 3-(*o*-aminophenyl)-2-phenyl-2,1-borazaronaphthalene XXII (R = C_6H_5) with aluminum chloride in tetralin at high temperatures led to dephenylation and gave the polymer XLIII after hydrolysis. This unusual reaction probably goes by exchange of groups between the aluminum and the boron (16).

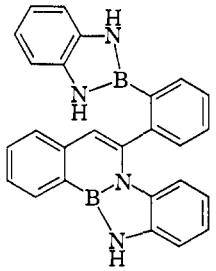
Letsinger and Nazy (72) found that 2,2′-tolanediboronic acid (XLV) isomerized in the presence of alkali



or tartrate ion to give a stable new heterocyclic compound which they formulated as XLVIa by analogy with the 1,3 - dihydro - 1 - hydroxy - 2,1 - benzoxaboroles (section VIB). It was deboronated by hydrogen peroxide to give 2-(*o*-hydroxyphenyl)-benzofuran (XLVII) and gave desoxybenzoin on treatment with water at 200°. Dewar and Dietz (23) have pointed out that the structure XLVIb, incorporating an aromatic hetero-ring, is more in keeping with the properties of the compound. Reaction of XLVI with *o*-phenylenediamine gave a derivative, m.p. 227.5–228°, which should presumably be formulated as XLVIII. The isomerization did not occur with 2-tolaneboronic acid, *o*-styrylboronic acid and *cis*-2,2′-stilbenediboronic acid (69).



XLVII



XLVIII

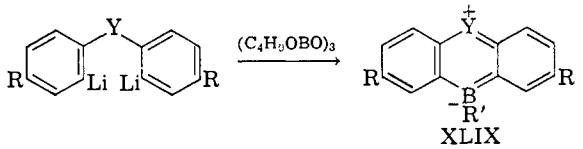
F. 4,10-DIBORA-5,9-DIAZAROPYRENES AND 2,7-DIBORA-1,8-DIAZAROANTHRACENES

Derivatives of the above ring systems, XX and XXI, have been prepared (section IIIB), and their ultraviolet spectra determined (14, 16).

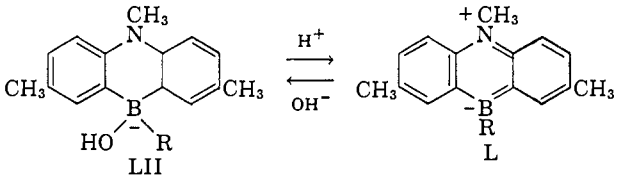
G. 4,1-BORAZARENES (10,9-BORAZAROANTHRACENES AND 10,9-BOROXAROANTHRACENES)

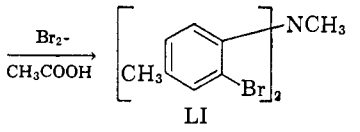
Only two types of 4,1-borazarene are known, the derivatives of 10,9-borazaroanthracene XLIX (R = R′ = H, Y = NH) and 10,9-boroxaroanthracene XLIX (R = R′ = H, Y = O). They were prepared by action of *n*-butyl metaborate on the 2,2′-dilithiodiphenylamine or -diphenyl ether. This reaction gave 10 - hydroxy - 10,9 - boroxaroanthracene XLIX (R = H, R′ = OH, Y = O), m.p. 285° (21), from diphenyl ether, and bis-3,6,9-trimethyl-10,9-borazaro-10-anthracenyl) ether L (R = O/2), m.p. 244–245° (ethanolamine derivative L (R = $OCH_2CH_2NH_2$), m.p. 223–224°) from the diphenylamine LI. Reaction of L (R = O/2) with phenylmagnesium bromide gave 10-phenyl-3,6,9-trimethyl-10,9-borazaroanthracene L (R = C_6H_5), m.p. 114–115° (79).

The ultraviolet spectra of 10-hydroxy-10,9-boroxaroanthracene and of the 10,9-borazaroanthracenes (L)



XLIX





are similar to xanthone (21) and acridines and anthracenes (79), respectively.

The borazaroanthracenes are less stable than the borazarophenanthrenes; thus the B–H and B–alkyl derivatives could not be prepared owing to the ease with which they underwent autoxidation (to give L, R = O/2); even the B-phenyl compound underwent rapid hydrolytic oxidation in solution to give the same compound (see the 10,9-boroxarophenanthrenes, section IIID). The action of bromine in acetic acid on L (R = O/2) caused deboronation and gave 2,2′-dibromo-4,4′,N-trimethyldiphenylamine (LI). Addition of alkali to an ethanolic solution of either the anhydride L (R = O/2) or the B-phenyl compound L (R = C_6H_5) caused a large bathochromic shift in the ultraviolet spectrum. This reaction is reversible on addition of acid and has been ascribed to the addition of hydroxide ion to the boron, giving a complex (LII) in which the boron is now tetrahedral and removed from conjugation (79). This reaction also occurred in the boroxaroanthracene XLIX (R = H, R′ = OH, Y = O), but did not occur in the 2,1-borazarenes, all of which show a slight bathochromic shift on addition of alkali. This suggests that boron in a heteroaromatic ring is considerably more stabilized by the presence of an adjacent NH (or oxygen) than by one removed from it by a double bond.

Since the boroxarophenanthrenes are less stable than the borazarophenanthrenes, it is to be expected that the boroxaroanthracenes will be found to be even less stable than the borazaroanthracenes.

H. AROMATICITY OF THE BORAZARENES

The aromatic stabilization of these ring systems is quite clearly shown by the unusual stability of trigonal boron here toward reagents with which it usually undergoes a ready reaction, by their ultraviolet spectra and by the typically aromatic reactions such as electrophilic substitution which they undergo. It is clear that the most stable ones are those with the stabilizing heteroatom adjacent to the boron; nitrogen is a more effective stabilizer than oxygen. This is not unexpected, as oxygen, being more electronegative than nitrogen, cannot take part in structures such as —$^{+}$O=$^{-}$BR— as readily as nitrogen. Stabilization by the nitrogen

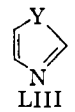
can be reduced greatly by substituting strongly electrophilic groups for the imino hydrogen which decrease the importance of structures such as $-^{+}NR=^{-}BR'-$ and makes the substituents on the boron more susceptible to hydrolytic oxidation. The impossibility of preparing stable B–H or B–alkyl compounds of the boroxarophenanthrenes and the borazaroanthracenes is again due to the lack of stabilization of the boron here; unless the substituent on the boron can give additional back-conjugative stabilization, it will be oxidized away.

In general it appears that the most stable compounds are those in which boron is attached to two carbon atoms and one nitrogen in a heteroaromatic ring. Compounds with boron attached to one carbon and two other hetero atoms are less stable and easily undergo B–X ring scission (section IV). There is also good reason for supposing that B-hydroxy-2,1-borazarenes such as 10-hydroxy-10,9-borazarophenanthrene may, to a small extent at least, exist in a noncyclic form.

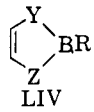
IV. Unsaturated Rings Containing Boron and Two Other Heteroatoms (1,3,2-Diheteroboroles and Boradiheterazarenes)

A. 1,3,2-Diheteroboroles: Introduction

By analogy with the aromatic imidazoles, oxazoles, and thiazoles LIII (Y = NH, O or S), five-membered rings of the type LIV (Y, Z = NH, O or S) where each heteroatom can donate two π-electrons should show aromatic characteristics. Only two monocyclic systems are known, but a number of benzo derivatives have been prepared and investigated. Although little quantitative work has been done on these compounds a few conclusions are possible. They are usually prepared by reaction of *o*-diamino-, *o*-dihydroxy-, etc., benzenes with boronic acids, and are, strictly speaking, cyclic esters and amides of the boronic acids, especially as their properties differ from those of the cyclic esters and amides (section VI) more in degree than in kind. The 1,3,2-benzodiheteroboroles (LVII) are not nearly as stable as the borazarenes; they are all readily solvolyzed and undergo autoxidation with rupture of the B–Y and B–Z bonds. The similarity of the properties of these compounds to those of the cyclic esters and amides suggests that aromatic stabilization is small here, because of the weakness of B–N and B–O bonds compared to B–C bonds, and the increased localization of charge by comparison to the borazarenes (see section IIIH). There are, however, good grounds for supposing these compounds to possess some aromatic character, such as the relationship of the ultraviolet spectra to those of the isoconjugate nonboron-containing heterocycles (31); hence they will be considered separately from the cyclic esters and amides.



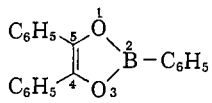
LIII



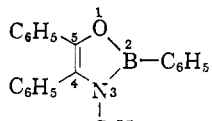
LIV

B. 1,3,2-Dioxaborole and 1,3,2-Oxazaborole

2,4,5-Triphenyl-1,3,2-dioxaborole (LV), m.p. 112–113°, was made by azeotroping a mixture of benzoin and phenylboronic acid in toluene (71). The ultraviolet spectrum indicated some aromatic character in the ring, but the compound was oxidized to benzil more rapidly than benzoin. It was fairly resistant to hydrolysis and did not react with *o*-phenylenediamine (to give LVII, Y = Z = NH, R = C_6H_5), or with aniline to give LVI.



LV

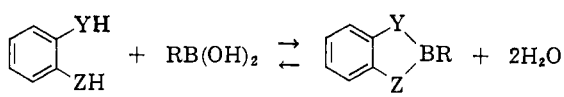


LVI

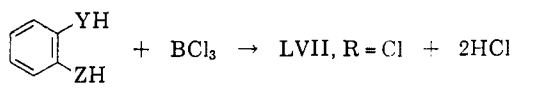
2,3,4,5 - Tetraphenyl - 1,3,2 - oxazaborole (LVI), m.p. 183–185°, together with a small amount of LV was obtained from the reaction of benzoin and aniline with phenylboronic acid in toluene (71). This compound was autoxidized easily and underwent hydrolysis on crystallization from aqueous ethanol, giving phenylboronic acid and benzoin monoanil; the latter did not react with phenylboronic acid to give back LVI.

C. 1,3,2-Benzodiheteroboroles

1. Preparation.—(*a*) These compounds (LVII) are most easily prepared from an *o*-disubstituted benzene such as *o*-phenylenediamine, *o*-aminophenol, catechol, or thiocatechol and the appropriate boronic acid (13, 70, 86). The reaction is reversible and it is sometimes necessary to remove the water formed as an azeotrope with benzene or toluene; in many cases, however, good yields are obtained by mixing solutions of the components.

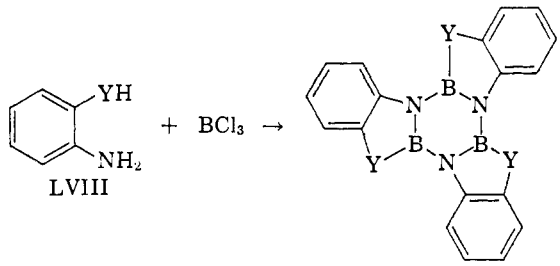


LVII



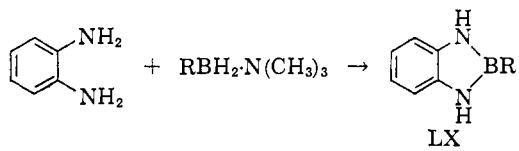
(*b*) *o*-Phenylenediamine, catechol, and similar substances containing active hydrogens react with boron trichloride in the cold to form complexes; on heating they lose two moles of hydrogen chloride and give the benzoborole LVII (R = Cl). The chlorine in LVII (Y = Z = NH, R = Cl) is very reactive and can be replaced by alkyl or aryl groups with the appropriate Grignard reagent (53). Phenylboron dichloride has been

used in place of boron trichloride and gives the B-phenylbenzoborole LVI (R = C_6H_5) directly (31). If the complex from an *o*-substituted aniline (LVIII) and boron trichloride is heated in chlorobenzene, both of the amino hydrogens react giving, for example, with LVIII (Y = NH), 5H, 12H, 19H-tris-(benzo-1,3,2-diazaborolo)-borazine LIX, Y = NH) (90); these compounds are high-melting and insoluble in inert solvents below 120°. Reaction of borate esters with *o*-phenylenediamine at 150° also gave LIX (Y = NH) (8).

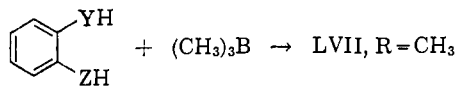


LVIII LIX

(*c*) Trimethylamine complexes of alkylboranes react with *o*-phenylenediamine to give 1,3,2-benzodiazaboroles (LX) (48). The B-methylbenzoboroles LVII (R = CH_3) have been prepared by treating trimethylborane with the appropriate disubstituted benzene derivatives at 280–300° in a sealed tube (105).



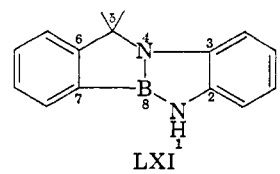
LX



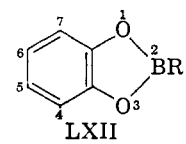
(*d*) The diethyl tartrate ester of phenylboronic acid reacts readily in the cold with *o*-phenylenediamine to give 2-phenyl-1,3,2-benzodiazaborole LX (R = C_6H_5) (70). This transesterification reaction is capable of much expansion.

2. 1,3,2-Benzodiazaboroles (LX).—The spectrum of 2-phenyl-1,3,2-benzodiazaborole LX (R = C_6H_5), resembles that of 2-phenylbenziminazole (31). Changing the nature of the 2-substituent changes primarily the intensity of the main bands and has only a secondary effect on their positions (86). Substitution in the 5-position causes greater variations; electron-donating groups give bathochromic shifts and electron-withdrawing groups give hypsochromic shifts. This effect has been interpreted as due to changes in the bond order of the B–N bonds caused by these differing substituents (86).

The benzodiazaboroles have been used for isolating and characterizing alkylboronic acids as they are more stable than the acids. The melting points of all the 1,3,2-benzodiheteroboroles are summarized in Table 5. 2-Phenyl-1,3,2-benzodiazaborole LX (R = C_6H_5) is readily solvolyzed, especially in the presence of acid; in contrast to the 1,3,2-diazaboracycloalkanes (section VIE) though, it is not split by dry hydrogen chloride in toluene, but forms a dihydrochloride instead (70). It is air-stable in contrast to the B-methyl compound LX (R = CH_3), which is slowly autoxidized (105). 1,4,5,8 - Tetrahydro - 2,3,6,7 - dibenzo - 1,4,8 - diazaborapentalene (LXI), m.p. 245°, was obtained in low yield from α-bromo-2-tolylboronic acid and *o*-phenylenediamine (46).



LXI



LXII

3. 1,3,2-Benzodioxaboroles.—An infrared study of the benzodioxaboroles LXII showed that the B–O bond order was greater than usual for borate esters, indicating that electron delocalization was greater in the former as a result of the presence of a heteroaromatic ring; this did not appear to be true for the B-phenyl compound (5). 2-Chloro-1,3,2-benzodioxaborole LXII (R = Cl) showed considerable thermal stability but reacted readily with compounds containing active hydrogen such as amines and alcohols to give B-amino- and B-alkoxy-benzodioxaboroles. With water it gave 2-hydroxy-1,3,2-benzodioxaborole LXII (R = OH), which was unusually stable for a compound of this type (41).

4. Other 1,3,2-Benzodiheteroboroles.—A number of related systems LVII (Y = NH, Z = O, R = CH_3 or C_6H_5; X = S, Y = NH, R = C_6H_5; Y = Z = S, R = C_6H_5) have been prepared and their ultraviolet spectra investigated (31, 105).

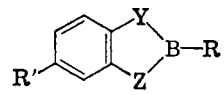
D. COMPOUNDS CONTAINING ONE BORON AND TWO OTHER HETEROATOMS IN A SIX-MEMBERED RING (BORADIHETERAZARENES)

Structures LXIII and LXIV have been ascribed to the products obtained by the action of hydroxylamine on *o*-formylphenylboronic acid (94), and by reduction of *o*-nitrophenylboronic acid in acetic acid (95), respectively.

Compounds LXV, LXVI, and LXVII, which it was hoped might be effective in cancer therapy (62), or as antimetabolites in neoplastic cells (especially LXVI, a borapurine), were prepared from the appropriate aminocarboxamide (LXVIII). The boraquinazoline LXV and the borapurine LXVI were obtained on mixing solutions of the aminocarboxamide and phenylboronic acid; the borazapurine LXVII was prepared by heating dibutyl phenylboronate with the aminophenyl-

TABLE 5

1,3,2-BENZODIHETEROBOROLES



Y	Z	R'	R	M.p., °C., or b.p., °C.	Mm.	References
NH	NH	H	H	79–80		53
NH	NH	H	Cl	320		53
NH	NH	H	CH_3	94, 98–99		53, 105
NH	NH	H	n-C_3H_7	92–94, 102–103		48, 86
NH	NH	H	i-C_3H_7	124–126		48
NH	NH	H	n-C_4H_9	86–86.5, 66–67		48, 53, 70
NH	NH	H	s-C_4H_9	61–62		48
NH	NH	H	i-C_4H_9	90–92		48
NH	NH	H	t-C_4H_9	93–95		48
NH	NH	H	n-C_5H_{11}	69–71		48
NH	NH	H	n-C_6H_{13}	96–97		48
NH	NH	H	C_6H_{11}	78–80		48
NH	NH	H	$C_6H_5CH_2$	54–56		48
NH	NH	H	C_6H_5	204–6, 212–4, 215–6		31, 53, 70, 86
NH	NH	CH_3	C_6H_5	224–225		86
NH	NH	CH_3O	C_6H_5	138–140		86
NH	NH	Cl	C_6H_5	183–184		86
NH	NH	NO_2	C_6H_5	203–204		86
NH	NH	COOH	C_6H_5	209–210		86
NH	NH	H	2,4,6-$(CH_3)_3C_6H_2$	141		45
NH	NH	H	p-$CH_3OC_6H_4$	258–258.5, 242–243		70,86
NH	NH	H	p-BrC_6H_4	232–233		70
NH	NH	H	p-ClC_6H_4	219–221		86
NH	NH	H	p-$NO_2C_6H_4$	218–219		86
NH	NH	H	p-HOOC·C_6H_4	281–282		86
NH	NH	H	8-Quinolinyl	188–189		68
NH	NH	H	2-(Carbethoxyamino)-2′-biphenylyl	156–157		35
NH	NH	H	$(p$-$C_6H_4)_{1/2}$	—		95
NH	O	H	CH_3	32–34		105
NH	O	H	C_6H_5	105–106		31, 100
NH	S	H	C_6H_5	154–156		31
O	O	H	CH_3	–7		105
O	O	H	C_6H_5	109–110		31, 63
O	O	H	Cl	64	10	41
O	O	H	Br	76	9	41
O	O	H	OH	70–75	—	41
O	O	H	CH_3O	81	10	41
O	O	H	C_6H_5O	91	10	41
O	O	H	n-C_3H_7O	105	10	41
O	O	H	n-C_4H_9O	104	5	41
O	O	H	i-C_4H_9O	100	5	41
O	O	H	s-C_4H_9O	97	5	41
O	O	H	n-$C_5H_{11}O$	116	5	41
O	O	H	n-$C_8H_{17}O$	124	0.05	41
O	O	H	n-C_4H_9S	80–84	0.1	41
O	O	H	n-$C_8H_{17}S$	142	0.05	41
O	O	H	O/2	160	0.1	41
O	O	H	C_6H_5O	40–44		41
O	O	H	$C_6H_{11}O$	55–59		41
S	S	H	C_6H_5	154–156		41

triazolecarboxamide. These compounds are all derived from the potentially aromatic 2-boraropyrimidine LXIX; however, they showed no aromatic stability, presumably owing to the presence of the lactam group. This is not unexpected as heterocycles containing lactam groups show no aromatic character due to cross-conjugation being preferred to cyclic conjugation. These compounds were readily solvolyzed, the most stable being LXV and the least LXVII (12, 14).

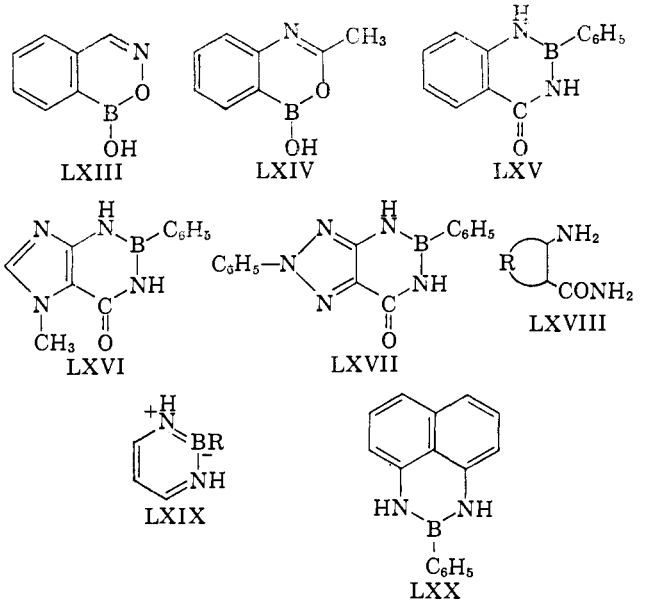
2-Phenyl-2-boradihydroperimidine (LXX) was also not aromatic, as shown by the difference between its ultraviolet spectrum and that of 2-phenylperimidine; it showed surprising stability to solvolysis but was readily autoxidized (14).

V. BORACYCLOALKANES

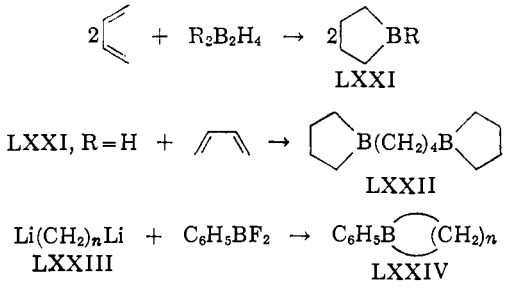
The first boracycloalkane was prepared in 1954 (103); since then the field has grown rapidly and a large number are now known. As with the other boron compounds, the boracycloalkanes differ most from the acyclic alkylboranes in their increased stability.

A. Monocyclic Systems

1. Preparation.—(*a*) Acyclic dienes such as 1,3-butadiene react readily with diborane, alkylboranes, or their adducts with tertiary bases at moderate temperatures to give the boracycloalkane, LXXI (47, 49, 57, 58, 91). This is a particular case of the general reaction of olefins with boranes giving the alkylborane.

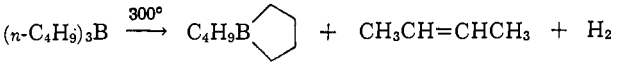


Using diborane and an excess of the diene, the boracycloalkane LXXI (R = H) is not isolated as it reacts immediately with a further mole of the diene to give, in this case, 1,1'-tetramethylene-bis-(borolane) (LXXII).

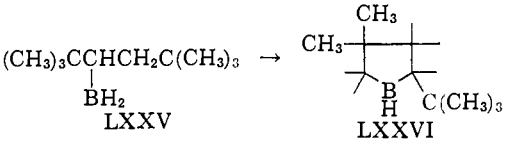


(*b*) Reaction of α,ω-dilithioalkanes LXXIII (n = 4, 5) with phenylboron difluoride gave the 1-phenylboracycloalkanes LXXIV (n = 4, 5) (103).

(*c*) Trialkylboranes with four or more carbon atoms in an unbranched chain undergo disproportionation on heating to give cyclic compounds, olefins and hydrogen; 5-, 6-, and 7-membered boracycloalkanes have been prepared by this route (60, 91, 17), *e.g.*



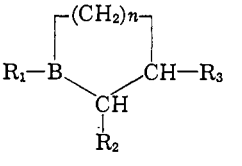
In this case the butyl group attached to the borolane also underwent isomerization in part; the product was shown to be a mixture of 85% *n*-butylborolane and 15% *sec*-butylborolane (60). A mechanism has been suggested for this reaction (110); it has been noted, however (60), that all compounds of the type $B_2H_{6-n}R_n$ (n = 1 to 4) where R, the alkyl group, has the requirements mentioned, undergo this reaction. In an attempt to carry out a hydroboration isomerization reaction (10) on a very hindered molecule, it was observed that 1-(1,2-di-*tert*-butyl)-ethylborane (LXXV) did not isomerize but instead evolved hydrogen and formed a cyclic compound, probably 2-*tert*-butyl-4,4-dimethyl-1-borolane (LXXVI) (76).



2. Properties. The properties of the known boracycloalkanes have been summarized in Table 6. B-Alkylboracycloalkanes are unusual among mixed alkylboranes in that they are thermally very stable and do not in general undergo disproportionation on heating. However, on prolonged heating at 160–175° it was found that 2-methylboracyclopentanes isomerized to boracyclohexanes and that boracycloheptanes isomerized to 2-methylboracyclohexanes. This suggests that six-membered boracycloalkanes are thermally more stable than the five- or seven-membered ones (91).

TABLE 6

BORACYCLOALKANES

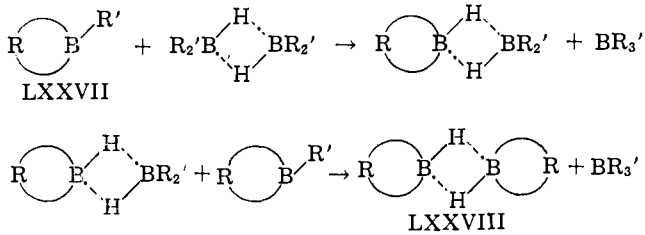


R_1	R_2	R_3	n	B.p., °C.	Mm.	Reference
H	H	H	2	—	—	58
H	H	CH_3	2	95	12	58
C_3H_7 (mixt. of isomers)	H	H	2	137–141	760	57
n-C_4H_9	H	H	2	—	—	17
C_4H_9 (mixt. of isomers)	H	H	2	54–57	14	60
t-C_4H_9	H	H	2	55	55	49
t-C_4H_9	H	CH_3	2	67	54	49
C_5H_{11}	CH_3	H	2	29–30	0.3	110
C_6H_5	H	H	2	105–107	11	103
$((CH_2)_4)_{0.5}$	H	H	2	55	0.1	57
CH_3O	H	H	2	—	—	57
n-C_4H_9	H	H	3	—	—	17
-C_4H_9	H	H	3	44	12	49
C_6H_{13}	CH_3	H	3	34–36	0.25–0.3	110
C_6H_{13}	H	CH_3	3	—	—	60
C_6H_5	H	H	3	105–107	11	103
$((CH_2)_5)_{0.5}$	H	H	3	—	—	91
$((CH_2)_6)_{0.5}$	CH_3	H	3	—	—	91
$((CH_2)_6)_{0.5}$	H	H	4	—	—	91

The alkyl group R' in LXXVII could be exchanged for another by reaction with trialkylalanes, or for alkoxy by reaction with trialkyl borates at 200° (58). Most of the boracycloalkanes are spontaneously inflammable in air and all are oxidized quantitatively by alkaline hydrogen peroxide to boric acid and α,ω-diols. This method has been used to determine the structures of these compounds.

B-Alkylboracycloalkanes (LXXVII) underwent hy-

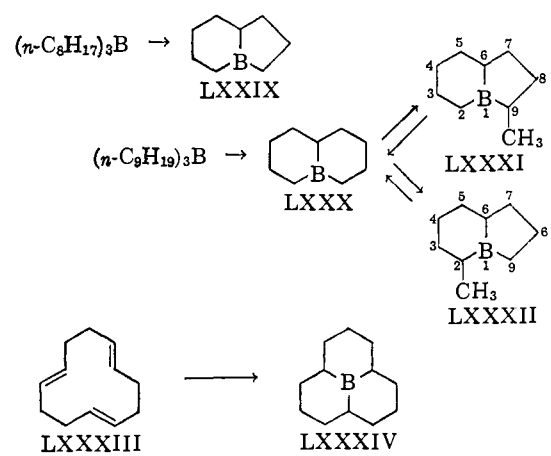
dride exchange with dialkylboranes at room temperature to give the parent boracycloalkanes LXXVIII. The latter also have been prepared from the diolefin and diborane directly. They are more stable than dialkylboranes, do not fume in air, are dimeric and can be distilled *in vacuo* without dissociation. Reaction with alcohols did not begin below 100°, whereas alkylboranes normally undergo complete alcoholysis at 70–80°; reactions with olefins and acetylenes did not proceed as readily as with the acyclic compounds (58).



LXXVII LXXVIII

B. POLYCYCLIC SYSTEMS

Alkylboranes or trialkylboranes having an unbranched chain of at least eight carbon atoms gave good yields of borabicycloalkanes on pyrolysis at 250–350°. Thus, 1-borabicyclo[4,3,0]nonane (LXXIX) and 1-borabicyclo[4,4,0]decane (LXXX) were obtained from tri-*n*-octylborane and tri-*n*-nonylborane, respectively (61). Monocyclic compounds were also obtained under these conditions which could be isomerized to the bicyclic compounds. It was shown by oxidation to the triols that 1-borabicyclo[4,4,0]decane (LXXX) isomerized at 150° to an equilibrium mixture which contained 80% (LXXX), 12% 9-methylborabicyclo-[4,3,0]nonane (LXXXI) and 8% 2-methylborabicyclo-[4,3,0]nonane (LXXXII).

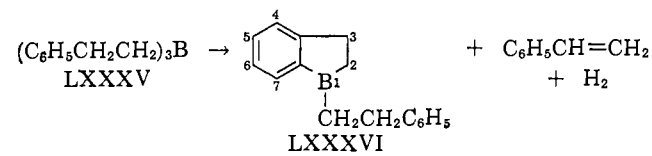


LXXIX LXXXI LXXX LXXXII LXXXIII LXXXIV

Perhydro-9b-boraphenalene (LXXXIV), b.p. 131° (16 mm.), was prepared by treating 1,5,9-cyclododecatriene (LXXXIII) with triethylamine-borane at elevated temperatures. It was thermally stable, could not be hydrogenated, did not react with olefins, but was easily oxidized to 1,5,9-cyclododecanetriol by alkaline hydrogen peroxide and was spontaneously inflammable in air (56). It formed 1:1 adducts with ammonia and piperidine but none with tetrahydrofuran or triethylamine; it was not soluble in water (44).

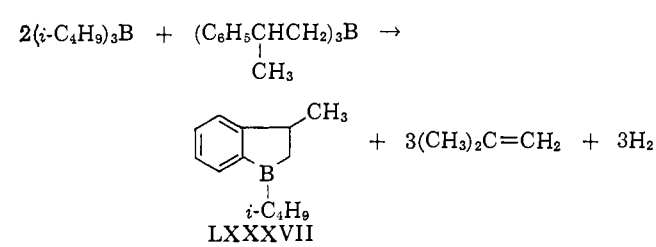
C. BENZO- AND DIBENZO-BORACYCLOALKANES

On heating to 250°, triphenethylborane (LXXXV) underwent a cyclization reaction similar to those described above, giving 1-(β-phenethyl)-1-benzoboracyclopentene (LXXXVI), styrene and hydrogen (59)



LXXXV LXXXVI

This reaction proceeded more readily using a mixture of one mole of triphenethylborane (or a derivative thereof) and two moles of a trialkylborane, and gave in this case 1-alkyl-1-benzoboracyclopentenes, *e.g.*, LXXXVII

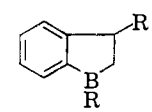


LXXXVII

Hydrogenation under pressure at 160° caused replacement of the B-alkyl group by hydrogen, and gave the parent benzoboracyclopentenes, which were dimeric and crystalline. The properties are summarized in Table 7.

TABLE 7

2,3-BENZO-1-BORACYCLOPENTENES

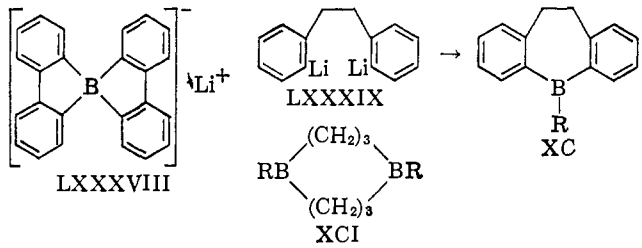


R	R'	M. p. or b. p., °C.	Mm.	Reference
H	H	132	—	59
H	CH_3	119	—	
$C_6H_5(CH_2)_2$	H	175	11	
C_2H_5	CH_3	98	11	
i-C_4H_9	CH_3	109	11	
$C_6H_4CH(CH_3)CH_2$	CH_3	126	0.5	

Reaction of 2,2′-dilithiobiphenyl with boron trifluoride etherate gave lithium bis-(2,2′-biphenylylene) borate(1⁻) (LXXXVIII) (111). This, in common with other tetraaryl borates, was very stable even in solution. Dilute acid hydrolyzed it to *o*-biphenylylboronic acid.

Hydrolysis of the product from the reaction of 2,2′-dilithiobibenzyl (LXXXIX) with tributyl borate

gave 5-hydroxy-10,11-dihydro-5H-dibenzo[b,f]borepin XC (R = OH), isolated as the ethanolamine ester XC (R = $OCH_2CH_2NH_2$), m.p. 195–196°. Hydrolysis of the latter, then dehydration, gave the anhydride XC (R = O/2), m.p. 145–146°; bromination of this in acetic acid gave 2,2′-dibromobibenzyl and alkaline hydrogen peroxide oxidation gave 2,2′-dihydroxybibenzyl, showing that ring formation had occurred (75). The conversion of XC to the dibenzoborepin has already been mentioned (section IIB).



D. DIBORACYCLOALKANES

Derivatives of only one such system, 1,5-diboracyclooctane XCI (R = H), have been reported (83). Triallylborane reacted at 130–140° with triisobutylborane to give butene and a polymer; the latter when heated with an alcohol was broken down to give 1,5-dialkoxy-1,5-diboracycloöctanes XCI (R = O-alkyl). Replacement of both alkoxy groups has been reported to occur even when a deficiency of phosphorus pentachloride was used for chlorination. The chloro groups in XCI (R = Cl) are very reactive and could be replaced by ethylamino groups. All the diboracyclooctanes were spontaneously inflammable; their boiling points are presented in Table 8.

TABLE 8

1,5-DIBORACYCLOÖCTANES (XCI) (83)

R	B.p., °C. (2 mm.)	n_D^{20}
n-C_4H_9O	106–107	1.4510
C_2H_5O	53–54	1.4444
n-$C_6H_{13}O$	150–152	1.4511
Cl	45–47	—
C_2H_5NH	71–73	1.4701

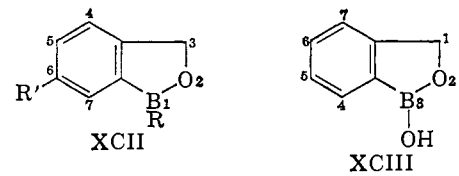
VI. SATURATED RINGS CONTAINING CARBON, BORON, AND ONE, TWO, OR THREE OTHER HETEROATOMS (CYCLIC BORATE ESTERS)

A. INTRODUCTION

The compounds which fall into this category are those in which aromatic stabilization of the hetero-ring cannot occur, and mainly consist of rings in which the heteroatoms are adjacent, which are cyclic borate esters or amides. Some of the former have been covered in the review by Lappert (64).

B. 1,2-HETEROBOROLANES

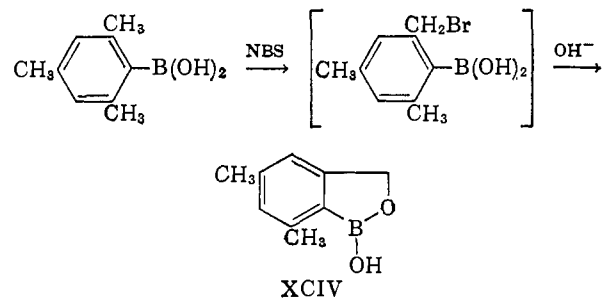
The only compounds known with a boron and one oxygen adjacent in an unsaturated ring are the derivatives of 1,3-dihydro-2,1-benzoxaborole (XCII); the name "boronophthalide" and the numbering as shown has been used for 1-hydroxy-1,3-dihydro-2,1-benzoxaborole (XCIII). The systematic nomenclature and numbering will be used here.



Hydrolysis of α-bromo-2-tolylboronic acid did not give the expected α-hydroxy-2-tolylboronic acid, but the cyclic ester 1,3-dihydro-1-hydroxy-2,1-benzoxaborole XCII (R′ = H, R = OH), m.p. 97–98° (104). It has been suggested that this reaction may occur by internal displacement of Br^- by $>B-O^-$, rather than by hydrolysis followed by dehydration (67).

1,3 - Dihydro - 1 - hydroxy - 2,1 - benzoxaborole is very stable to hydrolysis, both acid and base catalyzed; ring cleavage at the B–O bond does not occur appreciably and deboronation is very slow. In contrast to most borinic acids it did not form an anhydride on dehydration (94). It underwent mononitration in fuming nitric acid at −35 to −40° to give 1,3-dihydro-1-hydroxy-6-nitro-2,1-benzoxaborole XCII (R = OH, R′ = NO_2), m.p. 191°. This was reduced to the 6-amino compound XCII (R = OH, R′ = NH_2), m.p. 157° dec., by hydrogen and Raney nickel, which could be diazotized and coupled with 2-naphthol-3-carboxylic acid. 1,3-Dihydro-1-hydroxy-2,1-benzoxaborole did not react with ammonia under pressure or with benzylamine; the B–O bond was stable to *o*-phenylenediamine which splits many other borate esters (67). It was also unaffected by selenium dioxide in dioxane. The stability of this compound is unusual.

Mesitylboronic acid on treatment with N-bromosuccinimide, followed by alkali, gave the homolog 1,3 - dihydro - 5,7 - dimethyl - 1 - hydroxy - 1,1-benzoxaborole (XCIV) (45).

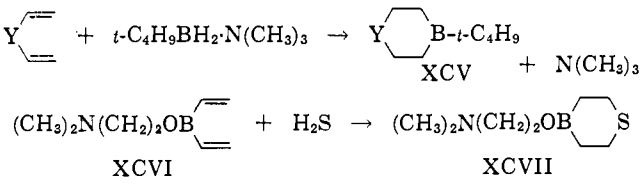


The reactions of derivatives of 1,2-benzazaboracyclohexene (3,4 - dihydro - 2,1 - borazaronaphthalene) have been discussed (section IIIE).

c. 1,4-heteroborinanes

Reaction of divinyl ether with trimethylamine-*tert*-butylborane gave the very unstable 4-*tert*-butyl-1,4-oxaborinane (XCV, Y = O), b.p. 90° (56 mm.); analogously, dimethyldivinylsilane gave 4-*tert*-butyl-1,1-dimethyl-1,4-silaborinane (XCV, Y = $(CH_3)_2Si$), b.p. 44° (2 mm.) (47, 49).

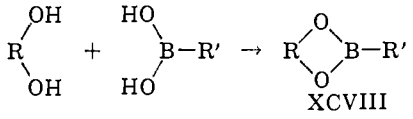
(2-Dimethylaminoethoxy)-divinylborane (XCVI) reacted with hydrogen sulfide in boiling benzene to give a polymer which was cracked by heating to 160–200° and gave 4-(2-dimethylaminoethoxy)-1,4-thiaborolane (XCVII) (81).



d. 1,3,2-dioxaboracycloalkanes

The only dioxaboracycloalkanes known are the cyclic borate esters of boric and boronic acids (XCVIII. Many of the methods of preparation of these compounds and their properties resemble those of the 1,3,2-benzodioxaboroles (section IVC(1)).

1. Preparation.—(*a*) The most usual preparatory route is directly from the diol and the boronic or boric acid. Reactions in which six-membered rings (1,3,2-dioxaborinanes, XCVIII, R = $(CH_2)_3$) are formed proceed easily, even in aqueous solution; formation of five-membered rings (1,3,2-dioxaborolanes XCVIII, R = $(CH_2)_2$) is more difficult and does not usually proceed under aqueous conditions unless the product is very insoluble. The water formed in the latter reaction is usually removed as an azeotrope (88, 96, 100, 102).



(*b*) A modification of the above reaction uses the borate ester and a diol; transesterification occurs on heating and removal of the alcohol. No catalysts are necessary (40, 73).

(*c*) Reaction of a diol with boron trichloride in an inert solvent gives the 2-chloro-1,3,2-dioxaboracycloalkanes XCVIII (R′ = Cl); the chlorine can be replaced by primary or secondary amines or alcohols (3, 4, 9, 18, 38). Alkoxydichloroboranes have been used in place of boron trichloride (3).

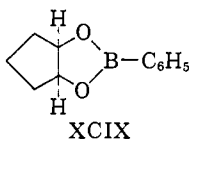
(*d*) B-Methyldioxaborolanes have been prepared by heating 1,2-diols with trimethylborane at 340° (105).

(*e*) Cyclic borate esters and their complexes with sodium borate were formed in the reduction of 1,2- and 1,3-diketones by sodium borohydride (19).

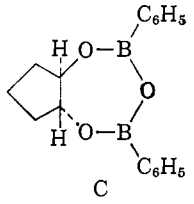
Five-, six- and seven-membered rings are all readily formed from diols in which there is no restriction to rotation about the carbon–carbon bonds. The six-membered ester of phenylboronic acid and 2,3-butanediol was formed in higher yield than the five- and seven-membered esters from other butanediols, suggesting that the former is more easily formed (100). Dale, Hubert and Hargitay (19, 20, 54) have confirmed earlier suggestions that the six-membered esters of boric acid are more easily formed and more stable than the five-membered esters by competitive esterifications between boric acid and ethylene and 1,3-propylene glycols. The former esters can be prepared by mixing aqueous solutions of the diol and boric acid, whereas five-membered esters cannot be formed in this way. These, on dissolution in water, slowly hydrolyze and deposit boric acid. The difference in stability is due to the greater strain present in five-membered rings by comparison with the six-membered ones, leading to a considerable distortion of the bond angles in the former with consequent decrease of the stabilizing —O⇌B< back-coördination.

Differences in the ease of formation of esters between *meso*- and racemic diols have also been observed. This has been used to separate such diols (19, 20).

When there is no free rotation about the carbon–carbon bonds as in the 1,2-cyclopentanediols, the products depend on the conformation of the diol. Thus, *cis*-1,2-cyclopentanediol gave the normal ester XCIX with phenylboronic acid, whereas *trans*-1,2-cyclopentanediol gave a seven-membered ring (C). In the latter case, formation of the normal ester is not possible without great strain since the hydroxy groups are on opposite sides of the plane of the ring. 1,2-Cyclohexanediols behave similarly (100).



XCIX

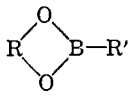


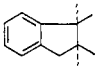
C

2. Properties.—Cyclic borate esters are mostly liquids, stable to air but usually quite readily hydrolyzed; the rates of hydrolysis of a number of these compounds have been measured (96). Their properties are summarized in Table 9. On standing, the five-membered esters of boric acid polymerize to open-chain polymers, the formation of the latter reducing the ring strain. On heating (distillation) they once more revert to the liquid cyclic form (54, 102). It is noteworthy that the borate esters of catechol are more stable and do not exhibit this behavior, probably due to aromatic char-

TABLE 9

1,3,2-DIOXABORACYCLOALKANES (CYCLIC BORATE ESTERS)

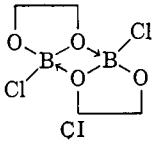


Parent diol	R	R′	M.p. or b.p., °C.	Mm.	References
1,2-Diols					
Ethylene glycol	$-CH_2CH_2-$	CH_3	70	760	105
		n-C_4H_9	78–79	66	73
		$ClCH{=}CH$	Below 200	760	66
		Cl	28–31	0.5	3, 9
		OH	114–118	—	3
		C_2H_5O	38	0.1	3
		n-C_4H_9O	84 (0.7); 108	30	3, 9, 54, 73
		i-C_4H_9O	56	0.8	3
		s-C_4H_9O	45–50	0.8	3
		n-$C_5H_{11}O$	106	12	102
		$C_6H_{11}O$	119	10	102
		C_6H_5O	123–127	5	
			112–114	0.5	3, 102
		(OCH_2CH_2O)	128	—	102
		n-C_4H_9S	26	0.002	4
		$(CH_3)_2N$	55–62	60	9, 18
		$(C_2H_5)_2N$	36	0.4	4
		CH_3COO	77		4
		CH_2ClCOO	—		4
		CF_3COO	—		4
1,2-Propanediol	$-CH(CH_3)CH_2-$	CH_3NH	38	10	18
		$(CH_3)_2N$	45	20	18
		$C_5H_{10}N$	40	5–10	18
2,3-Butanediol	$-CH(CH_3)CH(CH_3)-$	OH (?)	112–117	<1	88
		n-C_4H_9O	92	13	54
		C_6H_5	75–77	1	100
Pinacol	$-C(CH_3)_2C(CH_3)_2-$	CH_3	—		105
		C_6H_5	29–30		63
cis-1,2-Cyclopentanediol		C_2H_5	80–82	1	100
cis-1,2-Cyclohexanediol		C_6H_5	95	0.3	100
cis-1,2-Indanediol		C_6H_5	107.5–108.5		63
Diethyl tartrate	$-CH(COOEt)CH(COOEt)-$	C_6H_5	46–48		63, 70
1,3-Diols				—	
1,3-Propyleneglycol	$-CH_2CH_2CH_2-$	Cl	25	0.05	38
		n-C_4H_9O	98	12	38, 54
Isobutylene glycol	$-CH_2CH(CH_3)CH_2-$	OH (?)	76–79	<1	88
1,3-Butanediol	$-CH(CH_3)CH_2CH_2-$	OH (?)	107–109	<1	88
		n-C_4H_9O	101	13	54
		C_6H_5	85–86	1	100
2-Methyl-2,4-pentanediol	$-CH(CH_3)CH_2C(CH_3)_2-$	C_2H_5O	182–185	760	40
		$-(OCH(CH_3)CH_2C(CH_3)_2O-$	143–149	2	96
2,4-Dimethyl-2,4-pentanediol	$-C(CH_3)_2CH_2C(CH_3)_2$	C_2H_5O	186–189	760	40
Glycerol	$-CH_2CHOHCH_2-$	O/2	271–272	760	42, 87
1,4-Diols					
1,4-Butanediol	$-(CH_2)_4-$	C_6H_5	90–95	1	100
		OH (?)	147–151	3	88

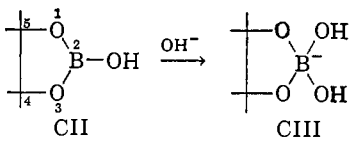
BISPHENYLBORONATES OF SUGARS AND TRISPHENYLBORONATES OF SUGAR ALCOHOLS (112)

Sugar	M.p., °C.	Sugar	M.p., °C.
L-Arabinose	166	L-Fucose	109.5
D-Ribose	140–142	L-Rhamnose	107.5
D-Xylose	137	Mannitol (tris)	134–135
L-Lyxose	109–110	Sorbitol (tris)	187–190

acter in the dioxaborole ring (102). Molecular weight determinations on some dioxaborolanes and dioxaborinanes in benzene showed that the latter were always monomeric while some of the former were associated. In particular, 2-chloro-1,3,2-dioxaborolane is dimeric and the structure CI has been suggested for the dimer (9).



CI

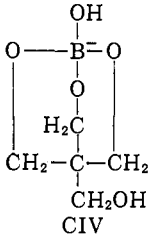


CII CIII

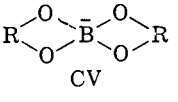
Mixed acyclic borates $(RO)_2BOR'$ are unknown

as they disproportionate too rapidly to permit isolation; however, a number of cyclic borates XCVIII (R′ = alkoxy) have been prepared and found to be stable (3, 38, 73, 102). 2-Hydroxy-1,3,2-dioxaborolane has also been prepared, whereas dialkoxyborinic acids are unknown (3).

2-Hydroxy-1,3,2-dioxaborolanes (CII) readily add a hydroxide ion giving complexes of the type CIII; the same products are obtained from sodium borate and 1,2-diols. Boric and boronic acids are acids in the Lewis sense, since the addition of a hydroxide ion converts the boron from the trigonal to the very stable tetrahedral form, whereas release of a proton gives no such stabilization. In the five-membered dioxaborolanes this leads to a decrease in the bond angles and to a consequent lessening of the ring strain and hence is very much favored. The increase in acidity of boric and boronic acids on addition of 1,2-diols is explained by the ready formation of the complexes CIII (19, 20, 77). Since the ring strain in 1,3,2-dioxaborinanes is much less than in 1,3,2-dioxaborolanes, they are not, in general, as acidic and do not have the tendency to add a hydroxide ion; therefore 1,3-diols have no effect on the acidity of boric and boronic acids. The difference in acidity between hydroxy-dioxaborolanes and -dioxaborinanes was confirmed by measurements of the relative heats of formation of complexes with benzylamine or pyrrolidine (54). The anomalous behavior of pentaerythritol is due to the formation of the complex CIV in the presence of alkali (20). Spiran complexes (CV) suggested by Böeseken (6, 7) to account for the effect of 1,2-diols are not usually formed under the conditions used.



CIV

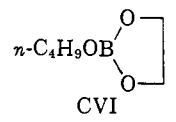


CV

A number of compounds such as sugar pentoses and sugar alcohols form bis- and tris-esters with phenylboronic acids. They are crystalline and have been used for characterizing sugars, but their exact structures are unknown (100, 112). The trisphenylboronate ester of mannitol dissolved in anhydrous solvents without decomposition but was hydrolyzed readily in moist acetone or pyridine.

The infrared spectra of some dioxaborolanes have been studied (5); the general rule that nitrogen is more effective in back-coördination than oxygen was followed in the B-aminodioxaborolanes.

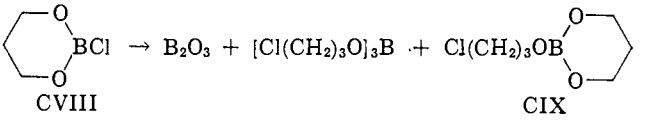
2-*n*-Butoxy-1,3,2-dioxaborolane (CVI) was cleaved by butylmagnesium bromide to give (ethylenedioxy)-bis-(dibutylborane) (CVII) (73).



CVI

$$(n\text{-}C_4H_9)_2BO(CH_2)_2OB(n\text{-}C_4H_9)_2$$

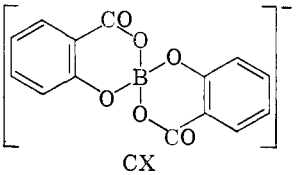
CVII



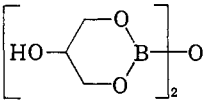
CVIII

CIX

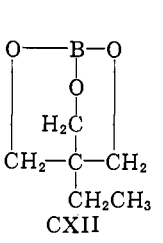
Pyrolysis of 2-chloro-1,3,2-dioxaborinane (CVIII) at 160° gave boric anhydride, tri-(3-chloropropyl) borate and 2-(3-chloropropoxy)-1,3,2-dioxaborinane (CIX) (38). This latter type of product was not formed in the pyrolysis of 2-chloro-1,3,2-dioxaborolane (4).



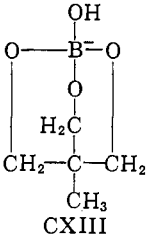
CX



CXI



CXII



CXIII

Reaction of salicylic acid with boric acid gave the complex anion, bis-(salicylato-O,O′)-borate(1⁻) (CX); this formed salts with sodium, silver, etc. The 1-strychnine salt was resolved into optical isomers (6).

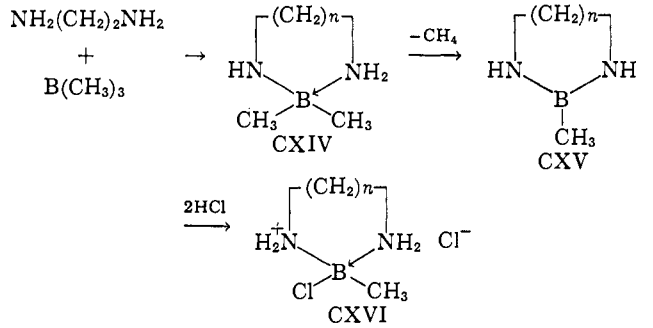
"Glyceryl borate" (87) has been reformulated as CXI (42).

Brown and Fletcher (11) attempted to prepare CXII by removal of water from a mixture of boric acid and 1,1,1-tris-(hydroxymethyl)-propane, but only obtained a polymer. Calculations showed that the energy needed to force normally trigonal boron into the tetrahedral configuration needed in the cage structure CXII is too great and is not offset by any gain in stability as the stabilization energy from >B⇐O back-coördination is lost. It has also been shown that trigonal boron can only link up with two hydroxy groups; in the presence of alkali, however, the bicyclic complex anion CXIII was formed from 1,1,1-tris-(hydroxymethyl)-ethane and boric acid (20).

E. 1,3,2-DIAZABORACYCLOALKANES

2-Methyl-1,3,2-diazaborolidine CXV (n = 2), m.p. 43.5°, and 2-methyl-1,3,2-diazaboracyclohexane CXV (n = 3), b.p. 132°, have been prepared from ethylene and 1,3-propylene diamine, respectively, by heating their 1 : 1 adducts with trimethylborane. At 220° one mole of methane was evolved, giving $(CH_3)_2B\cdot NH(CH_2)_nNH_2$, which is probably stabilized as CXIV.

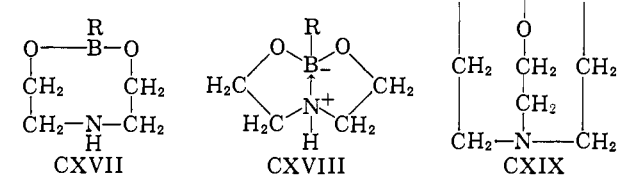
These compounds, on heating to 370°, lose more methane to give CXV. In air both the borolidine and the boracyclohexane turn brown and become polymeric; they also add two moles of hydrogen chloride at room temperature to give CXVI (43).



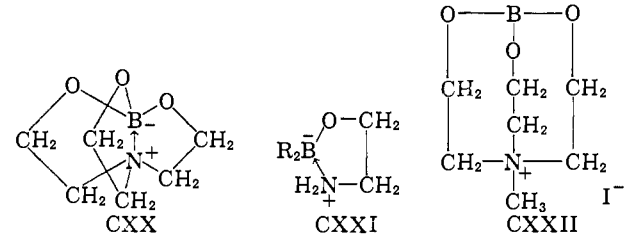
CXIV CXV CXVI

F. DIOXAZABORACYCLOALKANES AND TRIOXAZABORABICYCLOALKANES (BOROXAZOLIDINES)

Two classes of compound come into this group; those derived from 1,3,6,2-dioxazaboracycloöctane CXVII (R = H) and those from 2,8,9,5,1-trioxazaborabicyclo[3,3,3]undecane (triethanolamine borate) (CXIX). There is, however, good evidence that both these groups of compounds are additionally stabilized by the formation of a —N→B— transannular bond, and thus they have been referred to in their bicyclic (CXVIII) and tricyclic (CXX) forms as diptych- and triptych-boroxazolidines, respectively.



CXVII CXVIII CXIX



CXX CXXI CXXII

1. Diptych-boroxazolidines.—The diptych-boroxazolidines (CXVIII) are crystalline compounds easily prepared from diethanolamine and a boronic acid. In contrast to the alkylboronic acids, which are readily hydrolyzed and autoxidized by moist air, these derivatives are quite stable, because of the formation of the tetrahedral boron. They can be reconverted into the boronic acids by alkaline or acid hydrolysis and hence have been used extensively as derivatives (65). Analogous derivatives (CXXI) are formed by boronous acids and ethanolamine; these also exist in a cyclic chelated form (74).

Musgrave and Park have measured the N–H stretching frequencies of substituted B-phenyl-diptych-boroxazolidines and have found that by comparison with the frequencies of normal secondary N–H groups, the former showed a large shift in the 3100 cm.$^{-1}$ region due to the formation of tetrahedral nitrogen. The nature of the substituents on the phenyl affects this frequency as shown by these values: CXVIII, R = *p*-anisyl, 3135 cm.$^{-1}$; R = *p*-tolyl, 3110 cm.$^{-1}$; R = phenyl, 3100 cm.$^{-1}$; R = *p*-bromophenyl, 3090 cm.$^{-1}$; and R = *m*-nitrophenyl, 3090 cm.$^{-1}$. The existence of a bond between the boron and the nitrogen to transmit the effect is thus implied.

The N–H stretching frequencies of a number of B-alkyl-diptych-boroxazolidines have also been studied (65); again large differences (180–200 cm.$^{-1}$) between the N–H absorption of the free amine and of the boroxazolidines were observed. However, it was pointed out that the shift is only 0–50 cm.$^{-1}$ in true coördination complexes, such as $R_2BH \cdot BF_3$, by comparison with the free amines; this indicates that the effect in the boroxazolidines cannot be due wholly to the formation of the transannular bond but that intermolecular hydrogen bonding must also be important.

The dipole moments of triptych-boroxazolidine, B-phenyl-diptych-boroxazolidine CXVIII (R = C_6H_5) and of the ethanolamine ester of diphenylboronous acid CXXI (R = C_6H_5) are all nearly the same (8.6 *D*). This probably is due to one electron being transferred from the nitrogen to the boron in each case to form the transannular bond (39).

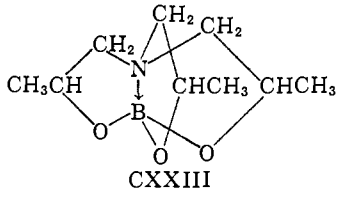
Weidmann and Zimmerman (106, 113) have investigated the solubilities of various boroxazolidines and their rates of hydrolysis in various media. They consider the first step in the hydrolysis to be rupture of the N→B bond, both in acid, alkaline and neutral media, and have proposed a mechanism for the reaction. The infrared spectra of the boroxazolidines also have been discussed (107).

2. Triptych-boroxazolidines.—Triethanolamine borate (CXIX), m.p. 236.5–237.5°, was formed by heating triethanolamine with boric acid (11, 52, 89). It is monomeric in nitrobenzene, forms salts with some acids and complexes with a number of metal salts (50). A large number of 3-substituted triptych-boroxazolidines and related compounds have been prepared by transesterification between tributyl borate and the appropriate trialkanolamine (92).

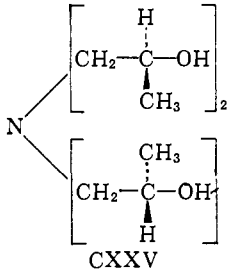
Bicyclic tertiary amines with a bridgehead nitrogen such as quinuclidine react faster with methyl iodide than acyclic tertiary amines to form the quaternary iodides, owing to lack of steric hindrance in the former case. Brown and Fletcher (11), however, found that triethanolamine reacted 1700 times as fast with methyl

iodide as did triethanolamine borate; the energy of activation of the latter reaction, giving CXXII, was approximately 6 kcal. This, together with the fact that triethanolamine borate could not be titrated with strong acids, suggested that there was a bond between the nitrogen and the boron, as in the triptych form CXX, and that additional energy was needed to break this bond before reaction could occur. The actual reaction path for formation of the quaternary salt CXXII is still in doubt. It may proceed either by primary rupture of the N→B bond, followed by attack by CH_3^+, or by attack by CH_3^+ followed by breakage of the N→B bond. Either path is compatible with the observed kinetics (11).

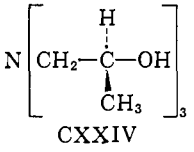
It has been found that a mixture of equimolar solutions of triethanolamine and boric acid, at equilibrium, contains 18–19% CXX (78). Triethyl borate was found to hydrolyze 130 times as fast as triethanolamine borate (96). Triisopropyl borate hydrolyzed *ca.* 10^7 times faster than triisopropanolamine borate (CXXIII) (96, 97); however, commercial triisopropanolamine is a mixture of two diastereoisomers and the borates derived from these hydrolyze at very different rates. It was suggested that the two isomers of triisopropanolamine present are the symmetric CXXIV and the unsymmetric CXXV and that the borate derived from the latter probably is the one which hydrolyzes more slowly due to the greater methyl–methylene interactions which are present here leading to greater N→B interaction. The rate of hydrolysis of this form is also more influenced by the polarity of the medium.



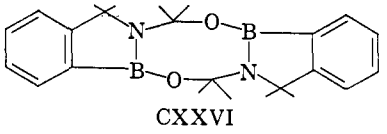
CXXIII



CXXV



CXXIV



CXXVI

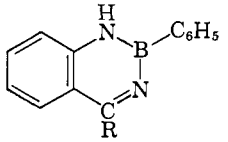
G. OTHER COMPOUNDS

The structure CXXVI has been proposed for one of the products obtained from a Sommelet reaction on α-bromo-2-tolylboronic acid (94).

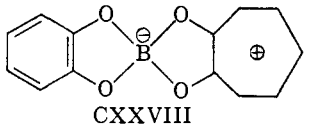
VII. APPENDIX

Molecular orbital parameters for boron in the borazarophenanthrenes and related systems (section IIIH) have been estimated from the spectra of charge transfer complexes of these compounds which were prepared with *s*-trinitrobenzene and tetracyanoethylene (117, 118).

A number of new 1,3,2-dioxaboroles (section IVB) have been prepared (121) and 2-isopropyl-4,5-dimethyl-1,3,2-dioxaborole has been shown to have a small absorption at 3000 Å. due to the heterocyclic ring (126). Some new benzo- and pyrido-diheteroboroles (section IVC) have been prepared from phenylboronic acid and the appropriate diamine or diol (124). The synthesis of 2-boradihydroperimidine (section IVD), m.p. 97–99°, has been reported; it undergoes methanolysis and autoxidation readily (116). New compounds of the general type LXVII and some analogous ring systems have been prepared (127). It was found that reaction of LXVII with phosphorus oxychloride, followed by mild ethanolysis and treatment with aqueous ammonia gave 2-phenyl-4-amino-2-boraroquinazoline (CXXVII, R = NH_2); use of sodium bicarbonate in place of ammonia gave the 4-ethoxy compound (CXXVII, R = OEt).



CXXVII



CXXVIII

During attempts to synthesize 4,5-benzoborepin some new benzoboracycloalkanes (section VC) have been prepared (115).

The synthesis and reactions of 1,3,2-dioxaborolane XCVIII (R = $(CH_2)_2$, R′ = H) (125), and of the novel compound CXXVIII, from β-methyltropone and 2-*n*-butoxy-1,3,2-benzodioxaborole (114) have been reported. The effect of acid on the formation of 2-butyl-1,3,2-dioxaborepane has been studied (122) and a number of 2-substituted 4,4,6-trimethyl-1,3,2-dioxaborinanes synthesized (123). Further studies on 2-chloro-1,3,2-dioxaborinane (CVIII) have also appeared (119, 120).

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