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XXVIII *. CONVENIENT PROCEDURES FOR THE SYNTHESIS OF BORINANE

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Summary

Convenient syntheses of the six-ring boracyclane, borinane, have been developed. Hydroboration of 1,4-pentadiene with two molar equivalents of 9-borabicyclo-[3.3.1]nonane (9-BBN) in a suitable solvent, followed by reaction of the resulting trialkylborane with one molar equivalent of the borane-tetrahydrofuran complex ($BH_3 \cdot THF$) or the borane-dimethyl sulfide complex ($BH_3 \cdot SMe_2$, BMS), leads to the cyclization of the pentadiene moiety, forming borinane with the regeneration of two molar equivalents of 9-BBN. Complete separation of the two dialkylboranes by fractional crystallization from solvents such as THF, 1,2-dimethoxyethane (DME), 1,3-dioxolane, n-hexane, n-pentane and hexane plus dioxolane was unsuccessful. Treating the reaction mixture in hexane with the requisite amount of triethylamine (Et_3N) led to selective complexation with borinane. By cooling the reaction mixture to $-78°C$, it was now possible to crystallize out the uncomplexed 9-BBN almost quantitatively (98%). Alternatively, borinane could be precipitated selectively from the hexane reaction mixture as its bis-adduct with either *N,N,N',N'*-tetramethylethylenediamine (TMED) or 1,4-diazabicyclo[2.2.2]octane (DABCO). Free borinane was readily liberated from its amine adducts by treatment with boron trifluoride etherate ($BF_3 \cdot OEt_2$). Finally, the two dialkylboranes were readily separated by fractional distillation, using a specially designed reaction setup. Distillation at about 70–80°C and 0.01 mm pressure led to the clean distillation of borinane, leaving the 9-BBN, as a residue, readily recycled in subsequent preparations. Alternatively, once free borinane has been obtained, it can be used to hydroborate 1,4-pentadiene in place of 9-BBN. Treatment of the product with $BH_3 \cdot THF$ or $BH_3 \cdot SMe_2$ converts two moles of borinane into three, without the formation of a by-product.

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* For Part XXVII see ref. 26.

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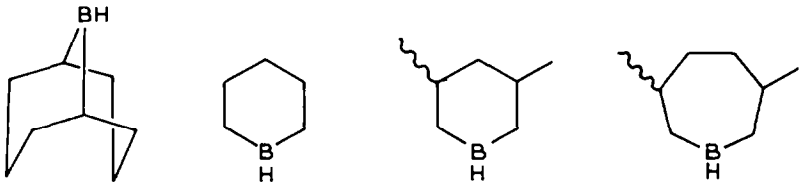
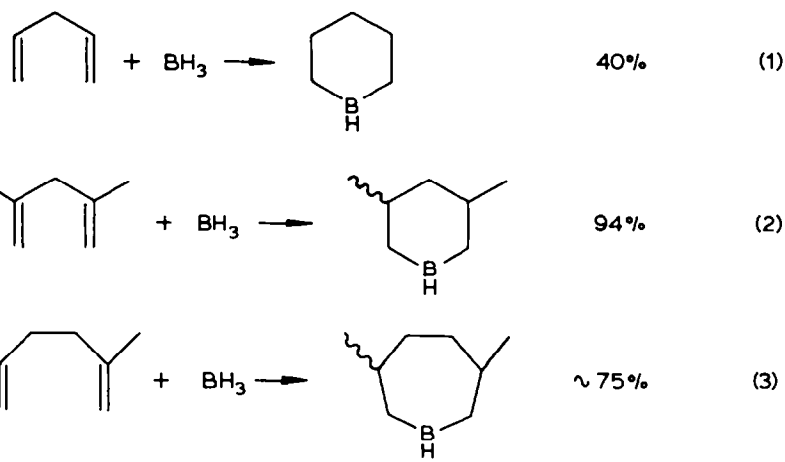
Introduction

9-BBN (I) is an extremely versatile, valuable reagent, immensely useful in organic synthesis [1]. Its remarkable thermal and air stability, combined with its exceptionally high regio- and stereoselectivity in hydroboration as well as its low migratory aptitude, have made it a unique hydroborating agent with wide applicability for synthesis via borane chemistry. Many reactions of trialkylboranes involve the utilization of only one of the three alkyl groups attached to boron. In such cases, it is economically desirable as well as conceptually appealing to avoid the loss of valuable alkyl groups. This has been achieved in many reactions by using 9-BBN as a blocking group (as, for example, in the carbonylation [2–4] and α-alkylation reactions [5–7]). However, in certain reactions involving free radical mechanisms, as in the conjugate addition of organoboranes to α,β-unsaturated carbonyl compounds [8–11], 9-BBN proved unsatisfactory. Here the problem was overcome by utilization of boracyclanes, such as borinane (II), 3,5-dimethylborinane (III), and 3,6-dimethylborepane (IV) [12].

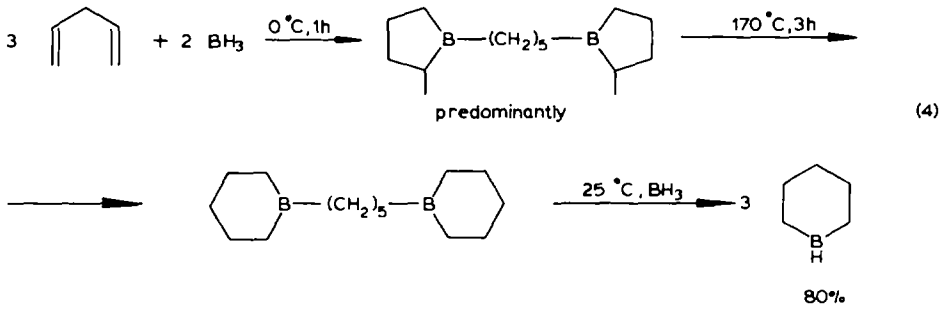


(I) (II) (III) (IV)

These compounds have been prepared earlier by the cyclic hydroboration of the corresponding dienes (eqs. 1–3) [12–14]. The yield of borinane was later improved by incorporating an isomerization step in the reaction sequence (eq. 4) [15,16].



During the elucidation of the course of hydroboration of 1,5-hexadiene with $BH_3 \cdot THF$, it was discovered in our laboratory that the dumbbell-shaped compounds, such as V, are cleanly converted to boracyclanes on treatment with



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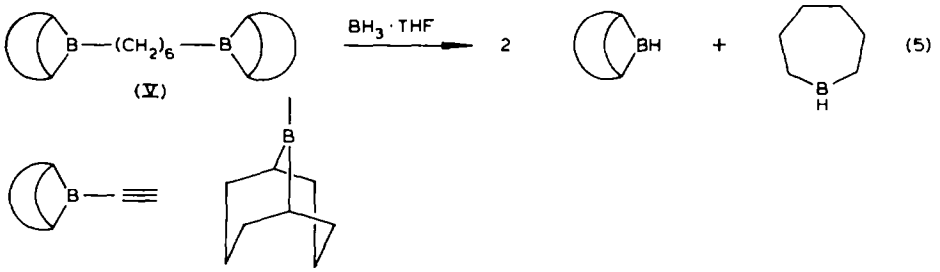
$BH_3 \cdot THF$ (eq. 5) [17]. We decided to investigate the generality of this method as a way of converting α,ω-dienes into cyclic compounds, Herein we discuss our success



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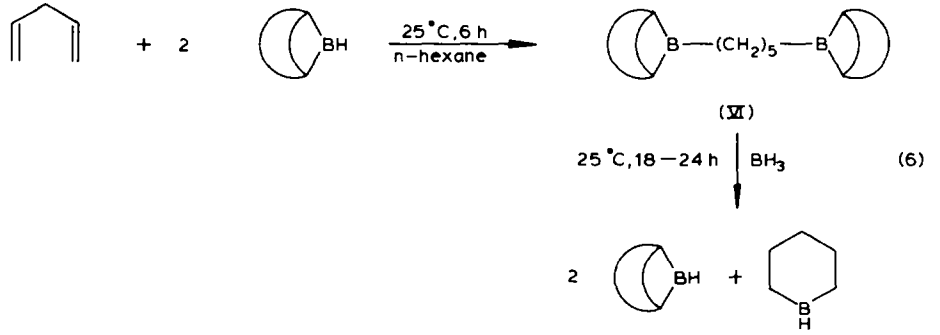
in applying this method to 1,4-pentadiene. The results of our studies with other diens will be the subject of a future communication.

Results and discussion

Hydroboration of 1,4-pentadiene at room temperature with 9-BBN cleanly forms the dumbbell-shaped compound VI without any regioisomers. Treatment of VI with either $BH_3 \cdot THF$ or BMS leads to cyclization, with the formation of borinane and regeneration of 9-BBN (eq. 6). The reaction is best followed by ^{11}B NMR. During



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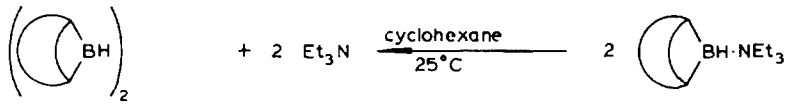
the initial hydroboration, one can see both R_2BH and R_3B peaks (δ 27 and 84 respectively). Following completion of the hydroboration, only the R_3B peak is present. During the cyclization stage, both R_3B and BH_3 (δ −20 when BMS was used) are apparent initially. When the redistribution is complete, both of these peaks vanish and only the R_2BH peak is observed.

The reaction product consists of a mixture of 9-BBN and borinane in the molar ratio 2/1. The separation of the two compounds and isolation of borinane in pure form presented considerable difficulty. Fortunately, we found it possible to overcome these difficulties.

Initially we attempted to achieve the separation by fractional crystallization. The solubility of 9-BBN in various ethereal, hydrocarbon and halocarbon solvents is known [18]. At 25°C it ranges from a high of 1.01 *M* in chloroform to a low of 0.073 *M* in 1,3-dioxolane. On the contrary, borinane is highly soluble in most solvents, easily forming 2 *M* solutions. Cooling the reaction mixture to −78°C, however, failed to effect a complete precipitation of 9-BBN. Typically on cooling a reaction mixture, 0.5 *M* in 9-BBN and 0.25 *M* in borinane, only 60–74% of the 9-BBN present crystallized out in pure form. Cooling to lower temperatures (or concentrating and cooling the mother liquor to various temperatures) resulted in the simultaneous precipitation of both 9-BBN and borinane. Possibly, the two reagents form a mixed dimer of lower solubility than that of borinane itself.

Having failed to achieve a separation by this simple method, we turned our attention towards chemical methods. The structures of 9-BBN and borinane suggest that there might be a significant difference in their steric requirements which would affect their abilities to coordinate with appropriate amines. The ability of 9-BBN to form adducts with various amines was known from earlier research in our laboratory [19]. We carried out a similar study for borinane and discovered some significant differences between the coordinating properties of the two cyclic boranes [20]. For example, 9-BBN does not form an adduct with Et_3N in cyclohexane solution [19,21]. On the contrary, borinane is about 80% associated with Et_3N under comparable conditions (eqs. 7, 8).



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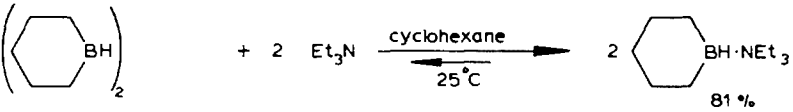

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Consequently, it appeared that selective complexation with Et_3N should be possible and might facilitate the separation by crystallization. Accordingly, a hexane reaction mixture was treated with 100% excess of Et_3N with respect to the contained borinane. Examination of the solution by ^{11}B NMR showed a peak at δ −2 (attributed to $R_2BH \cdot$ amine) in addition to the original R_2BH peak (δ 27). The two were in the ratio 2/1 [22], implying essentially complete conversion of borinane to its amine complex, with the 9-BBN remaining uncomplexed. Cooling this reaction mixture to −78°C resulted in the almost quantitative (98%) precipitation of pure 9-BBN. The mother liquor contained the borinane-triethylamine complex (with a small amount of 9-BBN). Free borinane was liberated from this complex by treatment with $BF_3 \cdot OEt_2$. (This complex was also directly used in the synthesis of borinane without going through the BF_3 treatment [23].) The separation was proba-

bly facilitated either by the higher solubility of borinane · NEt_3 complex or by the breaking up by Et_3N of the mixed dimer between 9-BBN and borinane.

Both 9-BBN and borinane form bis-adducts with difunctional amines like TMED and DABCO in non-polar solvents (eqs. 9, 10). Both adducts precipitate quantita-

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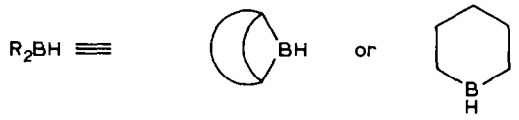
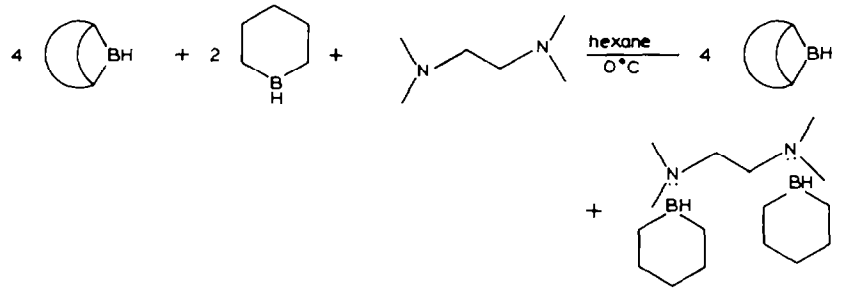


tively from hexane solutions of the boranes at 0°C. However, there is a large difference in the two complexation rates. Whereas 9-BBN takes a couple of hours to react with TMED, borinane reacts almost instantaneously. We exploited this kinetic difference between 9-BBN and borinane in the rate of adduct formation to separate the two. Thus, treating the reaction mixture in hexane at 0°C with the quantity of TMED calculated to react with the borinane present resulted in the selective complexation of borinane and the almost quantitative precipitation of the bis adduct (VII). Similar reaction with DABCO led to the precipitation of the DABCO bis adduct (VIII) (eqs. 11, 12).



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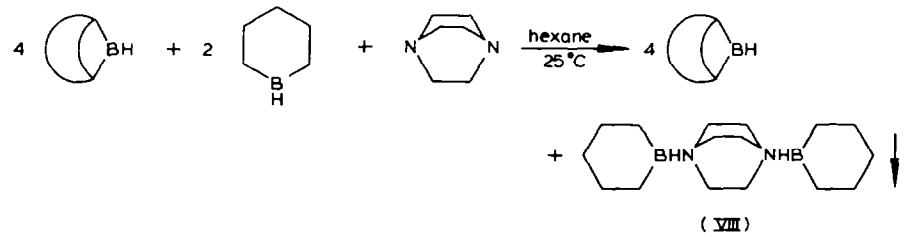

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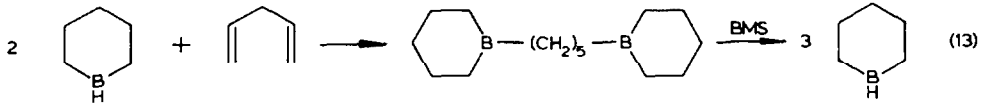
(VIII)

In both cases, the 9-BBN used in the synthesis remained in solution and could be recycled for subsequent syntheses. As before, free borinane could be liberated from

its amine complexes by reaction with $BF_3 \cdot OEt_2$.

Even though the use of amines solved the separation problem, it still added two undesirable additional steps to the synthesis of borinane. Consequently, we sought for still easier methods to achieve the separation. It is known that 9-BBN exists as a strongly hydrogen bridged dimer and even distills as the dimer (b.p. 190°C/12 mm Hg) [24]. Borinane also exists as a dimer in solution, as evidenced by its IR absorption (1560 cm^{-1}), but has a much lower boiling point (78–80°C/2 mmHg). It also seemed to possess fairly good thermal stability. So we concentrated on a separation of the two by distillation and, after some exploration, developed the right conditions to achieve this. It was found that borinane is extremely air-sensitive. Even slight exposure to air causes deterioration of the product. Similarly, heating the compound close to 100°C also causes some undesirable changes and contaminates the distilled product with foreign impurities. However, by exercising due care, it proved straightforward to distill pure borinane from 9-BBN in ~ 100% purity and greater than 90% yield at a pot temperature of 60–70°C and 0.01 mm pressure. This provided the simplest method for the desired separation. Borinane was distilled over as a low-melting solid, leaving 9-BBN as a solid pot residue. The 9-BBN could be conveniently recycled for later syntheses.

With pure borinane in hand, it is a simple matter to prepare additional material by the reaction shown in eq. 13. This gives three moles, starting from two moles, and eliminates the separation problem.



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Conclusions

The present study constitutes an extremely simple synthesis of a useful boracyclane-borinane.

Experimental

General comments

All glassware was dried overnight at 140°C, assembled hot, and allowed to cool under argon or nitrogen. All reactions were carried out under a static pressure of argon or nitrogen. The liquids and solutions were transferred with hypodermic syringes fitted with stainless steel needles.

Materials

Solid 9-BBN and BMS were obtained from the Aldrich Chemical Company. 1,4-Pentadiene was obtained from ChemSampCo and used without further purification. TMED and Et_3N were dried by distillation from CaH_2 under N_2. DABCO was sublimed prior to use and handled in a N_2-filled glovebag. Anhydrous solvents were prepared as described elsewhere [25].

Analysis

Proton NMR spectra were obtained on a Varian T-60 spectrometer. ^{11}B and ^{13}C

spectra were scanned on a Varian FT-80A spectrometer. IR measurements were conducted on a Perkin–Elmer 700 spectrophotometer. GC analyses were performed using a Hewlett-Packard 5750 research chromatograph on 6′ × 1/4″ 10% Apiezon L on Chromosorb W 60/80 column. The diols were analyzed as their bis-trimethylsilyl ethers. Peak areas were calculated using the HP 3380S digital integrator. Distillation of borinane was done in a Kügelrohr oven.

Preparation of a stock solution of borinane

An oven-dried, 250-ml, round-bottom flask fitted with septum-capped sidearm, connecting tube and magnetic stirring bar was cooled to room temperature in a stream of nitrogen. The flask was charged with 8.8 g (72 mmol) of solid 9-BBN (9-BBN can be handled in air for a short time; however, for quantitative work, the use of a N_2-filled glovebag is advisable). The flask was thoroughly flushed with N_2 and ~ 50 ml of n-hexane was added to the flask. The flask was immersed in an ice bath and 1,4-pentadiene (3.7 ml, 36 mmol) was added to the flask. The ice bath was removed and the reaction allowed to proceed at room temperature. Initially, all of the 9-BBN does not dissolve but it goes into solution as the reaction progresses. On completion of the reaction, as evidenced by ^{11}B NMR (3–6 h), 3.67 ml of 9.8 *M* (36 mmol) BMS was added to the flask and the reaction continued at room temperature for 18–24 h. The reaction mixture was transferred to a 100-ml volumetric flask fitted with a Teflon stopcock and the volume made up to the mark. Estimation by hydride analysis (THF · methanol) gave its strength as 1.1 *M* within experimental error.

Oxidation and GC analysis of diols

5 ml of the stock solution was transferred to a N_2-flushed flask containing a known amount of tridecane (GC internal standard). The solution was diluted with 5 ml of THF and hydrolyzed by dropwise addition of water. The contents were then oxidized by the addition of 4 ml of 3 *M* sodium hydroxide and 3 ml of 30% hydrogen peroxide. After 1 h, 7 g of solid potassium carbonate was added to saturate the aqueous layer. About 1 ml of organic layer was transferred to a vial containing anhydrous magnesium sulfate. The vial was shaken, and after a while, centrifuged. The diols present in the clear supernatant solution were converted to their bis trimethylsilyl ethers by adding 100 μl of this solution to 100 μl of neat *N*,*O*-bistrimethylsilylacetamide. After 0.5 h at room temperature, the silyl ethers were analyzed on 6′ × 1/4″ 10% Apiezon L column, 80–220°/10°/min, carrier gas helium, 35 ml/min. The GC analysis showed only 1,5-pentanediol and *cis*-1,5-cyclooctanediol in 1/2 ratio. Combined yield of diols > 98%.

Fractional crystallization studies

10 ml of the stock solution was transferred to a dry, nitrogen-filled, 50-ml centrifuge vial. The solvent was pumped off and replaced with the desired solvent. The vial was immersed in a cold bath kept at the desired temperature. After about 1 h, the vial was quickly centrifuged, reimmersed in the cold bath and the supernatant solution decanted with a double-ended needle. The residue was washed once with a small amount of the solvent at the same temperature. The residue, as well as the supernatant, was oxidized as described above and the diols analyzed by GC to determine their composition. See Table 1 for a summary of the results.

TABLE 1

FRACTIONAL CRYSTALLIZATION OF 9-BBN FROM VARIOUS SOLVENTS

Solvent	Strength of the reaction mixture with respect to 9-BBN	Temperature (°C)	Composition [a] BH / Borinane	
			Mother liquor	Residue
Hexane	0.5 *M*	−78	30/70	100/0
Pentane	0.5 *M*	−78	35/65	100/0
1,2-Dimethoxyethane	1.0 *M*	0	33/67	100/0
		−23	8/92	100/0
		−78	10/90	87/13
1,3-Dioxolane	0.5 *M*	0	22/78	100/0
		−18	16/84	100/0
		−23	9/91	100/0
		−45	0/100	70/30
		−55 to −65	0/100	50/50

[a] Composition was determined by adding Et_3N and integrating R_2BH vs. $R_2BH \cdot$amine peaks in ^{11}B NMR. In some cases results were confirmed by oxidation and GC analysis of diols.

Isolation of borinane by triethylamine procedure

An oven-dried, 50-ml centrifuge vial containing a magnetic stirring bar was capped with a rubber septum and cooled to room temperature under nitrogen. 25 ml of stock solution were transferred to the vial and it was concentrated to about 10 ml. Triethylamine (2.5 ml, 18 mmol) was added to the vial and it was cooled to −78°C in a dry ice-acetone bath. After 1 h, the vial was centrifuged quickly, reimmersed in the bath, and the supernatant solution decanted with a double-ended needle. The residue was washed at −78°C once with a small amount of n-hexane and the washing transferred to the mother liquor. The residue was dried and weighed: 2.15 g (98%). A small amount of residue was oxidized and the diol analyzed by GC. It showed only 1,5-cyclooctanediol. The mother liquor was treated with 2.20 ml of $BF_3 \cdot OEt_2$ (18 mmol). After 5 min the vial was cooled to 0°C and the clear upper layer was decanted using a double-ended needle. More hexane was added to the vial and the mixture was thoroughly stirred, allowed to settle and the hexane layer decanted. This was repeated again. The combined hexane layers were stripped off the solvent to obtain a white solid: 0.74 g. GC analysis showed it to contain 96% 1,5-pentanediol and 4% 1,5-cyclooctanediol.

Isolation of borinane by TMED procedure

As above, 13.8 ml of stock solution was added to a centrifuge vial. It was diluted by adding 6 ml of n-hexane and cooled to 0°C. TMED (0.38 ml, 2.5 mmol) was added dropwise to the vial with vigorous stirring. After 5 min the vial was centrifuged, recooled to 0°C and the supernatant solution decanted. The residue was dried and weighed: 1.06 g. Examination by ^{11}B NMR and oxidation showed that it was contaminated with a small amount (~ 8%) of 9-BBN. It was washed a couple of

times with cold hexane to remove the 9-BBN and recrystallized from THF to obtain fairly air-stable, long white needles, m.p. 140–142°C (N_2 filled sealed capillary). ^1H NMR ($CDCl_3$): δ 3.0 (s, 4H), 2.5 (s, 12H), 2.2–0.4 (complex, 20H); ^{11}B NMR ($CDCl_3$): δ −5 (broad); ^{13}C ($CDCl_3$) proton decoupled: 17–19, 27.8, 30.5, 47.5, 54.4 Regeneration of borinane was carried out as described above in ether suspension of the complex. Recovery: 84%. The loss occurred due to the difficulty of extracting borinane from the voluminous $(BF_3)_2 \cdot$ TMED complex.

Isolation of borinane by DABCO procedure

The reaction was carried out exactly as in the case of TMED except DABCO was added as THF solution at 25°C. Quantitative precipitation occurred without any contamination from 9-BBN: m.p. 183–187° (N_2 filled capillary). ^1H NMR (Me_2SO-d_6): δ 2.9 (brS, 12H), 2–0.4 (complex, 20H); ^{11}B NMR (Me_2SO-d_6): δ −2 (slightly resolved doublet); ^{13}C NMR (Me_2SO-d_6) proton decoupled δ 17.2, 27.2, 30.2, 46.9.

Isolation of borinane by distillation

A cylindrical vial of 20-cm length and 4.5-cm diameter equipped with a sidearm and standard joint was fitted with a bent adapter. A receiver flask fitted with a sidearm carrying Teflon stopcock was attached to the other end of the adapter. The assembly was flamed under a stream of argon and then cooled to room temperature. 50 ml of the stock solution was added to the vial and the solvents carefully pumped off using an oil pump at about 1 mm pressure. The pressure was then reduced to 0.01 mm and the vial heated in a Kügelrohr oven to 70–80°C. Borinane distilled over and collected in the receiver. The adapter was gently heated periodically to melt any solidified borinane. Towards the end of distillation, a small amount of 9-BBN also started to sublime.

Distillation was stopped at this stage. Typically ~ 99% pure borinane can be collected as distillate before this happens. Following the completion of distillation, the vacuum was broken with argon, the receiver detached in a rapid stream of argon, and capped with a septum. Using a previously weighed receiver flask, the weight of borinane was determined. Hexane was added to the flask to dissolve borinane and it was quantitatively transferred to a volumetric flask and the volume made up to the mark. The strength of the solution as determined by hydride analysis (MeOH · THF), the weight of distillate, and oxidation and GC analysis of diols gave excellent correspondence: m.p. 52–55°C (N_2 filled sealed capillary). IR: (n-hexane): 1560 cm^{-1}. Yield ~ 90%.

Preparation of borinane

As described earlier, 10 mmol of 1,4-pentadiene was hydroborated with 20 mmol borinane in hexane. The hydroboration was over in ~ 15 min. 10 mmol of BMS was added and the reaction carried out for 18 h. ^{11}B NMR now showed only an R_2BH peak. The solution was transferred to a suitable septum-capped volumetric flask, made up to the mark, and estimated by hydride analysis and oxidation. Both showed that borinane was formed in quantitative yield. This cycle was repeated several times without any adverse effect.

Acknowledgement

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References

1 H.C. Brown and C.F. Lane, Heterocycles, 7 (1977) 453; G.W. Kramer and H.C. Brown, Heterocycles, 7 (1977) 487.
2 H.C. Brown, E.F. Knights and R.A. Coleman, J. Amer. Chem. Soc., 91 (1969) 2144, 4606.
3 H.C. Brown, J.L. Hubbard and K. Smith, Synthesis, 701 (1979).
4 H.C. Brown, T.M. Ford and J.L. Hubbard, J. Org. Chem., 45 (1980) 4067.
5 H.C. Brown, H. Nambu and M.M. Rogić, J. Amer. Chem. Soc., 91 (1969) 6852, 6854, 6855.
6 H. Nambu and H.C. Brown, J. Amer. Chem. Soc., 92 (1970) 1761.
7 H. Nambu and H.C. Brown, Organomet. Chem. Syn., 1 (1970) 95.
8 H.C. Brown, M.M. Rogić, M.W. Rathke and G.W. Kabalka, J. Amer. Chem. Soc., 89 (1967) 5708, 5709.
9 H.C. Brown, G.W. Kabalka, M.W. Rathke and M.M. Rogić, J. Amer. Chem. Soc., 90 (1968) 4165, 4166.
10 G.W. Kabalka, H.C. Brown, A. Suzuki, S. Honma, A. Arase and M. Itoh, J. Amer. Chem. Soc., 92 (1970) 710.
11 H.C. Brown and G.W. Kabalka, J. Amer. Chem. Soc., 92 (1970) 712, 714.
12 E. Negishi and H.C. Brown, J. Amer. Chem. Soc., 95 (1973) 6757.
13 R. Köster, Angew. Chem., 72 (1960) 626.
14 R. Köster, Advan. Organometal. Chem., 2 (1964) 257.
15 H.C. Brown and E. Negishi, J. Organometal. Chem., 26 (1971) C67.
16 E. Negishi, P.L. Burke and H.C. Brown, J. Amer. Chem. Soc., 94 (1972) 7431.
17 P.L. Burke, E. Negishi and H.C. Brown, J. Amer. Chem. Soc., 95 (1973) 3654.
18 J.A. Soderquist and H.C. Brown, J. Org. Chem., 46 (1981) 4599.
19 H.C. Brown and K.K. Wang, Rec. Trav. Chim., 98 (1979) 117.
20 H.C. Brown and G.G. Pai, J. Org. Chem., 46 (1981) 4713.
21 In THF solution there is about 15% association. H.C. Brown and S.U. Kulkarni, Inorg. Chem., 16 (1977) 3090.
22 In general, quantitative integration of peaks is not possible in ^{11}B NMR. However, in this case, the ^{11}B NMR result was found to be in agreement with the value obtained by GC analysis of the diols.
23 H.C. Brown and G.G. Pai, Heterocycles, 17 (1982) 77.
24 E.F. Knights and H.C. Brown, J. Amer. Chem. Soc., 90 (1968) 5280.
25 H.C. Brown, G.W. Kramer, A.B. Levy and M.M. Midland, Ch. 9, Organic Syntheses via Boranes; Wiley-Interscience, New York, 1975.
26 H.C. Brown, A.K. Mandal, N.M. Yoon, B. Singaram, J.R. Schwier and P.K. Jadhav, J. Org. Chem., 47 (1982) 5069.