1072 *J. Org. Chem.* **1984**, *49*, 1072–1078

Hydroboration. 67. Cyclic Hydroboration of Acyclic α,ω-Dienes with 9-Borabicyclo[3.3.1]nonane/Borane–Dimethyl Sulfide

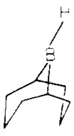
Herbert C. Brown,* Ganesh G. Pai,[1] and Ramachandra G. Naik[2]

Richard B. Wetherill Laboratory, Purdue University, West Lafayette, Indiana 47907

Received August 25, 1983

Hydroboration of acyclic α,ω-dienes, 1,3-butadiene, 1,4-pentadiene, 1,5-hexadiene, 1,6-heptadiene, 1,7-octadiene, 1,8-nonadiene, 1,9-decadiene, 1,11-dodecadiene, and 1,13-tetradecadiene, with 2 molar equiv of 9-borabicyclo[3.3.1]nonane (9-BBN), followed by redistribution of the resulting dumbbell-shaped trialkylboranes with 1 molar equiv of borane–methyl sulfide complex (BMS), has been investigated. With 1,3-butadiene, the initial redistribution product, the five-membered boracyclane, borolane, underwent a rapid ring-opening reaction to give the known 1,6-diboracyclodecane. 1,4-Pentadiene and 1,5-hexadiene afforded the corresponding boracyclanes, borinane and borepane, in quantitiative yields. With all other dienes, the initial redistribution products were polymeric. They were converted to the methyl esters by treatment with methanol, and these products were depolymerized into cyclic derivatives in 88–98% yield by vacuum distillation at 175–200 °C. In every case the cyclization was accompanied by varying amounts of isomerization so that the major products were both the parent *B*-methoxyboracyclane and the corresponding *B*-methoxy-2-*n*-alkylborinane. Thus, 1,6-hepatdiene afforded *B*-methoxyborocane and *B*-methoxy-2-ethylborinane in 3:1 ratio and a total yield of 95%. With 1,7-octadiene, 1,8-nonadiene, 1,9-decadiene, and 1,11-dodecadiene, the isomerized product constituted the major constituent of the distillate. 1,13-Tetradecadiene afforded the parent boracyclane and the isomer in a 47:53 ratio and a combined yield of 82%. The *B*-methoxyboracyclanes were converted to the corresponding cyclic ketones by the DCME reaction in 55–65% yield.

In the past few years, the cyclic hydroboration of dienes has been actively investigated.[3] This has led to highly efficient syntheses of valuable boracyclanes such as 9-borabicyclo[3.3.1]nonane (9-BBN, 1),[4,5] borinane (2),[6-10]



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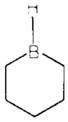

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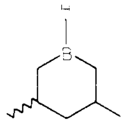

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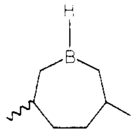

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3,5-dimethylborinane (3),[11] 3,6-dimethylborepane (4),[11] *B*-chloroborepane,[12a] *B*-methoxyborepane[13] and *B*-halo-9-borabicyclo[3.3.1]nonanes.[10c] The discovery of carbonylation,[14-17] cyanidation,[18] and the dichloromethyl methyl ether reaction (the DCME reaction)[19,20] permits ready conversion of these boracyclanes into the corresponding cyclic ketones, thus making it a new, powerful annelation reaction.[21-23]

Of the various reagents used for cyclic hydroboration such as BH_3·THF,[4,11,24-26] thexylborane,[27-29] monochloroborane etherate,[12] 9-BBN/BH_3·THF,[13] and 9-BBN/BH_3·SMe_2,[9,10] the last seemed to be the most promising. Both 9-BBN and BH_3·SMe_2 (BMS) are commercially available,[30] stable reagents, are handled conveniently, and afford clean products. Recently, we published an efficient synthesis of borinane by this methodology.[9,10] We wanted to explore the scope of this reaction; therefore, we undertook a systematic study of the cyclic hydroboration of representative acyclic α,ω-dienes.

Results and Discussion

The hydroboration of the dienes was carried out at 25 °C in THF, by using 2 molar equiv of 9-BBN. On completion of hydroboration (3–6 h), 1 molar equiv of BMS was added and the reaction continued until the redistribution was complete, as evidenced by ^{11}B NMR (18–24 h at 25 °C or 3 h at reflux). The content of polymeric and

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(1) Postdoctoral research associate on Grant GM 10937-20 from the National Institutes of Health.

(2) Postdoctoral research associate on Grant CHE 79-18881 from the National Science Foundation.

(3) Brown, H. C.; Negishi, E. *Tetrahedron* **1977**, *33*, 2331.

(4) Brown, H. C.; Knights, E. F.; Scouten, C. G. *J. Am. Chem. Soc.* **1974**, *96*, 7765.

(5) Soderquist, J. A.; Brown, H. C. *J. Org. Chem.* **1981**, *46*, 4599.

(6) Köster, R. *Angew. Chem.* **1960**, *72*, 626.

(7) Brown, H. C.; Negishi, E. *J. Organomet. Chem.* **1971**, C67.

(8) Negishi, E.; Burke, P. L.; Brown, H. C. *J. Am. Chem. Soc.* **1972**, *94*, 7431.

(9) Brown, H. C.; Pai, G. G. *Heterocycles* **1982**, *17*, 77.

(10) Brown, H. D.; Pai, G. G. *J. Organomet. Chem.* **1983**, *250*, 13.

(11) Negishi, E.; Brown, H. C. *J. Am. Chem. Soc.* **1973**, *95*, 6757.

(12) (a) Brown, H. C.; Zaidlewicz, M. *J. Am. Chem. Soc.* **1976**, *98*, 4917. (b) Jadhav, P. K.; Kulkarni, S. U. *Heterocycles* **1982**, *18*, 169. (c) Brown, H. C.; Kulkarni, S. U. *J. Org. Chem.* **1979**, *44*, 2422.

(13) Burke, P. L.; Negishi, E.; Brown, H. C. *J. Am. Chem. Soc.* **1973**, *95*, 3654.

(14) Brown, H. C. *Acc. Chem. Res.* **1969**, *2*, 65.

(15) Brown, H. C.; Kramer, G. W.; Levy, A. B.; Midland, M. M. "Organic Syntheses via Boranes"; Wiley-Interscience: New York, 1975; pp 126–132.

(16) Pelter, A.; Smith, K. In "Comprehensive Organic Chemistry"; Barton, D. H. R., Ollis, Ollis, W. D., Eds.; Pergamon Press: Oxford, England, 1979; Vol. 3, pp 824–828.

(17) Negishi, E. In "Comprehensive Organometallic Chemistry"; Wilkins, G., Stone, F. G. A., Abel, E. W., Eds; Pergamon Press: Oxford, England, 1982; Vol. 7, pp 282–285.

(18) Pelter, A. In "Comprehensive Organic Chemistry", Barton, D. H. R., Ollis, W. D., Eds.; Pergamin Press: Oxford, England, 1979; Vol. 3, pp 888–891.

(19) Brown, H. C.; Kramer, G. W.; Levy, A. B.; Midland, M. M. "Organic Syntheses via Boranes"; Wiley-Interscience: New York, 1975; pp 133–135.

(20) Pelter, A.; Smith, K. In "Comprehensive Organic Chemistry", Barton, D. H. R., Ollis, W. D., Eds.; Pergamon Press: Oxford, England, 1979; Vol. 3, pp 829–830.

(21) Negishi, E.; Brown, H. C. *Synthesis* **1974**, 77.

(22) Bryson, T. A.; Pyle, W. E. *J. Org. Chem.* **1977**, *42*, 3214.

(23) Zaidlewicz, M. In "Comprehensive Organometallic Chemistry"; Wilkinson, G., Stone, F. G. A., Abel, E. W., Eds.; Pergamon Press: Oxford, England, 1982; Vol. 7, pp 209–214.

(24) Zweifel, G.; Nagase, K.; Brown, H. C. *J. Am. Chem. Soc.* **1962**, *84*, 183.

(25) Brown, H. C.; Negishi, E.; Burke, P. L. *J. Am. Chem. Soc.* **1971**, *93*, 3400.

(26) Brown, H. C.; Negishi, E.; Burke, P. L. *J. Am. Chem. Soc.* **1972**, *94*, 3561.

(27) Zweifel, G.; Brown, H. C. *J. Am. Chem. Soc.* **1963**, *85*, 2066.

(28) Brown, H. C.; Pfaffenberger, C. D. *J. Am. Chem. Soc.* **1967**, *89*, 5475.

(29) Brwon, H. C.; Negishi, E. *J. Am. Chem. Soc.* **1972**, *94*, 3567.

(30) Available from Aldrich Chemical Co.

0022-3263/84/1949-1072$01.50/0

monomeric species in the reaction product was established by the following procedure. The reaction mixture was methanolyzed and the amount of hydrogen evolved was measured. The solvents and excess methanol were pumped off under reduced pressure, and the resulting mixture of borinate esters was distilled under vacuum. The more volatile monomeric species (B-OCH$_3$-9-BBN and any B-methoxyboracyclane) were distilled out at relatively low temperataure (<100 °C). The temperature was then slowly raised to 175–200 °C to effect depolymerization. The distilled products were characterized by oxidation with alkaline hydrogen peroxide to the corresponding diols and by conversion to the corresponding cyclic ketones by the DCME reaction.[19,20] The cyclic ketones were characterized by mass spectra, IR, and ^{1}H and ^{13}C NMR spectroscopy.

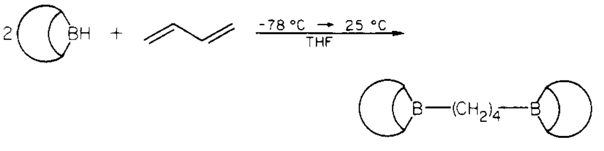
The nature of the redistribution product was dependent on the diene. Thus, with 1,3-butadiene, the initially formed boracyclane, borolane, underwent a rapid ring opening to form 1,6-diboracyclodecane. This is in accordance with the known instability of this compound.[31] With 1,4-pentadiene and 1,5-hexadiene, the redistribution products were the stable boracyclanes, borinane[9,10] and borepane,[13] respectively. The higher dienes yielded essentially polymeric products.

The depolymerization was accompanied by isomerization, and the depolymerized products consisted mostly of a mixture of the parent boracyclane and the corresponding 2-n-alkyl derivative. The extent of isomerization was in turn dependent on the diene. Thus, 1,6-heptadiene yielded the parent compound, B-methoxyborocane, and the isomer B-methoxy-2-ethylborinane in a nearly 3:1 ratio. With other higher dienes, the ratio favored the isomer. On the other hand, the longer chain derivative, 1,13-tetradecadiene, afforded the parent compound and the isomer in almost equal amounts.

The results obtained with individual dienes are described below.

1,3-Butadiene. The hydroboration of 1,3-butadiene has been extensively investigated by several workers in the past.[3] It has been established that the initial product of hydroboration is polymeric and that it undergoes cyclization on depolymerization at 140 °C. Köster originally proposed the "bisborolane" (**5**) structure for this compound.[32] This was shown to be incorrect, and, currently, the "1,6-diboracyclodecane" (**6**) structure, proposed by Brown and co-workers,[24] has been accepted as the correct structure.[33-35]

In the present study, hydroboration of 1,3-butadiene was carried out by adding the diene to a slurry of 9-BBN (2 molar equiv) in THF at −78 °C (eq 1). The reaction mixture was slowly warmed to 25 °C and the reaction continued until the ^{11}B NMR indicated the completion of hydroboration (4 h). BMS was added, and the redistribution was carried out at 25 °C for 14–18 h. On completion of reaction, the solvents were pumped off under aspirator vacuum and the residue was distilled under vacuum. The compound that distilled (bp 41–42 °C (2 mm)) was not the desired bisborolane **5** but the dimer 1,6-diboracyclodecane (**6**) (eq 1–3). This is not surprising, since it is known that



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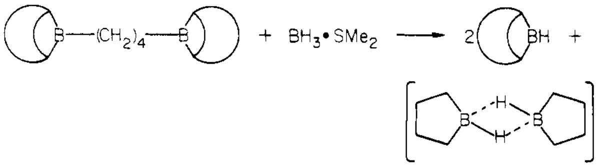

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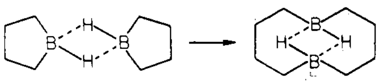
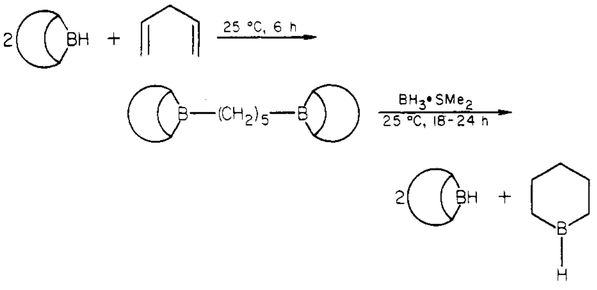


(3)

5 **6**

the borolane ring system is highly unstable ($t_{1/2} \approx 15$ min at 25 °C) and that it readily dimerizes to **6**.[31] A major advantage of the present procedure is its avoidance of the formation of a considerable amount of byproduct of 1,3-dibora derivatives.

1,4-Pentadiene. The hydroboration of 1,4-pentadiene with diborane was first reported by Köster.[6] An exhaustive study of the cyclic hydroboration of this diene with BH$_3$·THF was conducted in our laboratory, which led to a practical synthesis of borinane **2**.[7,8,24,26] However, hydroboration of 1,4-pentadiene with 9-BBN and redistribution with BMS provides the most convenient synthesis of this useful reagent[9,10] (eq 4). Borinane is isolated from



(4)

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the reaction mixture by careful distillation. The 9-BBN remaining as pot residue can be conveniently recycled. Alternatively, borinane itself can be used for hydroboration in place of 9-BBN, generating 3 mmol of reagent from 2 mmol. This also obviates the need for distillation.

1,5-Hexadiene. In the past, several workers have studied the hydroboration of 1,5-hexadiene with borane (or diborane,[6,24,26,36-38] monochloroborane etherate,[12a] thexylborane,[28,29] 9-BBN/BH$_3$·THF,[13] and 9-BBN/B(OCH$_3$)$_3$).[13] The last two reagents afforded the borepane ring system in quantitative yields. Thus, 9-BBN/BH$_3$·THF gave a mixture of 9-BBN and borepane in solution (which could not be separated), and 9-BBN/B(OCH$_3$)$_3$ afforded B-methoxyborepane and B-OCH$_3$-9-BBN (which could be separated by fractional distillation). In the present study, directed mainly at the separation of borepane from 9-BBN, we used the more readily available BMS instead of BH$_3$·THF. As with 1,4-pentadiene, the hydroboration of 1,5-hexadiene with 9-BBN and redistribution of the dumbbell-shaped compound with BMS led to the formation of borepane (**7**) and the regeneration of 9-BBN (eq 5). But, just like the previous workers, we failed in our attempt to separate the two. None of the methods attempted, such as fractional crystallization from different

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[31] Brown, H. C.; Negishi, E. *J. Am. Chem. Soc.* **1971**, *93*, 6682.

[32] Köster, R. *Angew. Chem.* **1959**, *71*, 520.

[33] Breuer, E.; Brown, H. C. *J. Am. Chem. Soc.* **1969**, *91*, 4164.

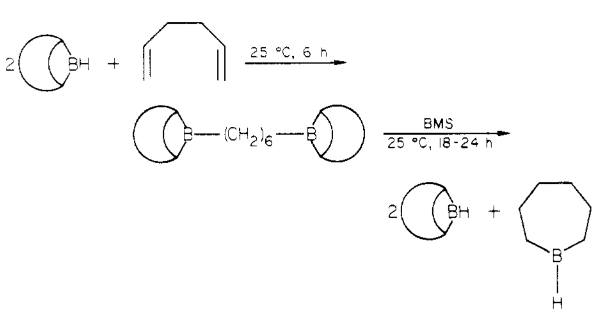
[34] Young, D. E.; Shore, S. G. *J. Am. Chem. Soc.* **1969**, *91*, 3497.

[35] Saturino, D. J.; Yamauchi, M.; Clayton, W. R.; Nelson, R. W.; Shore, S. G. *J. Am. Chem. Soc.* **1975**, *97*, 6063.

[36] Saegebarth, K. W. *J. Am. Chem Soc.* **1960**, *82*, 2081.

[37] Mikhailov, B. M.; Vasil'ev, L. S.; Safonva, E. *Izv. Akad. Nauk SSSR, Ser. Kim.* **1962**, *147*, 630.

[38] Zakharkin, K. I.; Kovredov. A. I. *Izv. Akad. Nauk SSSR, Ser. Khim.* **1962**, *147*, 106.



(5)

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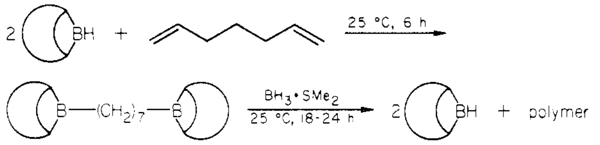
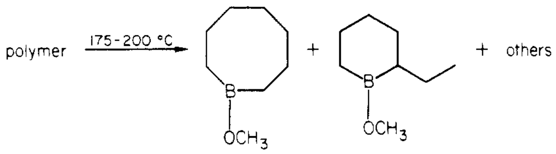
solvents, selective complexation with amines, or distillation, could effect a complete separation of the two boracyclanes. Most disappointing was the failure of distillation, which had proved so convenient for the isolation of borinane. Borepane appears to be thermally unstable, and attempted distillation resulted in deterioration of the compound, presumably due to polymerization. Fractional crystallization from ethereal solvents such as THF, DME, and ether resulted in simultaneous precipitation of both 9-BBN and borepane. From hydrocarbon solvents such as *n*-pentane, *n*-hexane, and toluene pure 9-BBN (~70–75% of that used in the reaction) precipitated at −78 °C. But cooling the mother liquor to −78 °C did not achieve any further enrichment, due to the coprecipitation of borepane (see Table I). Possibly the situation is complicated by the formation of mixed dimers. Earlier we had succeeded in separating borinane from 9-BBN by exploiting their different complexation abilities with suitable amines such as triethylamine, *N,N,N',N'*-tetramethylethylenediamine (TMED), and triethylenediamine (TED). This method also failed in the present case.

1,6-Heptadiene. The hydroboration of this diene with 9-BBN and redistribution of the dumbbell-shaped compound with BMS resulted in the regeneration of the 9-BBN, but no cyclization. Instead, a polymer was obtained (eq 6). This was established as follows: the reaction mixture, from which the polymer had separated out as a white globular species, was methanolyzed and the amount of hydrogen evolved was measured within experimental error. The theoretical amount of hydrogen was evolved, indicating that the all of the B–H species in the reaction product were active. The solution was transferred to a distillation setup, and the solvent and excess methanol were pumped off. The distillation setup was then evacuated to 0.01-mm pressure and slowly heated to 90 °C. In this manner all of the B-OCH$_3$-9-BBN and any monomeric species arising from 1,6-heptadiene was collected. Oxidation and GC analysis of the diols, as their bis(trimethylsilyl) ethers, showed that the distillate consisted of only B-OCH$_3$-9-BBN and just traces of *B*-methoxyborocane (**8**). The residue left in the distillation apparatus was heated to a temperataure of 175–200 °C under vacuum. Under these conditions, the polymeric species underwent depolymerization and cyclization. The cyclized species distilled over and was collected in a dry ice–acetone cooled receiver. Examination of the distillate by ^{11}B NMR showed only one signal at δ +56 (R$_2$BOCH$_3$). This shows that the distilled species must be a boracyclane. If it consisted of a linear monomer, the ^{11}B NMR would have shown a signal at δ +32, corresponding to RB(OCH$_3$)$_2$.



(6)

This fact was conclusively proven by applying the DCME reaction. Cyclooctanone and 2-ethylcyclohexanone were formed in a 3:1 ratio. The presence of 2-ethylcyclohexanone indicates that the depolymerization was accompanied by isomerization. This was also revealed by oxidation of the distillate, providing mainly two diols, 1,7-heptanediol and 1,5-heptanediol, arising from *B*-methoxyborocane (**8**) and *B*-methoxy-2-ethylborinane (**9**), respectively (eq 7). The fact that the isomerization occurs during the depolymerization and not during the redistribution or the methanolysis was established by analysis of the methanolyzed product before distillation. The GC analysis of the diols in this case showed the presence of only *cis*-1,5-cyclooctanediol (from B-OCH$_3$-9-BBN) and 1,7-heptanediol (from the linear polymer) in a 2:1 ratio.



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Other Dienes. The hydroboration–redistribution of the higher α,ω-dienes such as 1,7-octadiene, 1,8-nonadiene, 1,9-decadiene, 1,11-dodecadiene, and 1,13-tetradecadiene was studied as described earlier for 1,6-heptadiene. In every case, 9-BBN and a linear polymer were obtained. Methanolysis, removal of B-OCH$_3$-9-BBN, and depolymerization at the 175–200 °C under reduced pressure afforded the boracyclanes as before. But unlike the 1,6-heptadiene experiment, in all cases, except 1,13-tetradecadiene, the isomerized product comprised the major portion of the distillate (see Table II). In the case of 1,13-tetradecadiene, the parent 15-membered boracyclane and its isomer were obtained in nearly equal amounts.

The structures of the isomers obtained from the reaction mixture of 1,8-nonadiene and 1,9-decadiene were established as follows: the distilled boracyclanes were converted to the corresponding cyclic ketones by the DCME reaction. The desired isomers were isolated by preparatiave gas chromatography. A mass spectral analysis of these compounds showed the correct molecular weights (154 and 168, respectively). A ^{13}C NMR analysis (fully decoupled) showed the required number of carbon signals. An APT (Attached Proton Test) ^{13}C analysis established the presence of only one CH$_3$ group and only one tertiary carbon atom. ^{1}H NMR spectra at high fields (470 MHz and/or 200 MHz) showed the CH$_3$ signal as a distorted triplet (J = 6.1–6.7 Hz). All of these facts suggested that the compounds must be straight-chain alkyl-substituted cyclic ketones but gave no information about the size of the ring or the length of the alkyl chain.

To obtain a positive structure proof, we resorted to the recently developed,[39,40] "INADEQUATE" (Incredible Natural Abundance Double Quantum Transfer Experiment) ^{13}C NMR experiment. This experiment is a unique method for studying carbon–carbon couplings in natural abundance compounds. Thus, one can obtain unperturbed satellite spectra by suppressing the strong signals (200 times stronger since the natural abundance of ^{13}C is 1.1%) from molecules with isolated ^{13}C nuclei. Since an INADEQUATE spectrum recorded with the pulse timing set for the detection of one-bond couplings represents the sum of nothing but AB- and/or AX-spectra, each corresponding

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(39) Bax, A.; Freeman, R.; Kempsell, S. P. *J. Am. Chem. Soc.* **1980**, *102*, 4849.

(40) Bax, A.; Kempsell, S. P. *J. Magn. Reson.* **1980**, *41*, 349.

Table I. Fractional Crystallization of 9-BBN from its Mixture with Borepane from Various Solvents

solvent	strength of the reaction mixture with respect to 9-BBN, M	temp, °C	composition[a] 9-BBN:borepane mother liquor	residue
tetrahydrofuran	0.5	−78	35:65	86:14
1,2-dimethoxyethane	0.38	0	51:49	50:50
ether	0.33	−40	40:60	
		−78	34:66	92:8
pentane	1.0[b]	−78	32:68	100:0[c]
		−116	36:64	
		−130	32:68	
hexane	0.5	−35	59:41	
		−78	27:73[d]	100:0[e]
toluene	0.66	−78	38:62	99:1

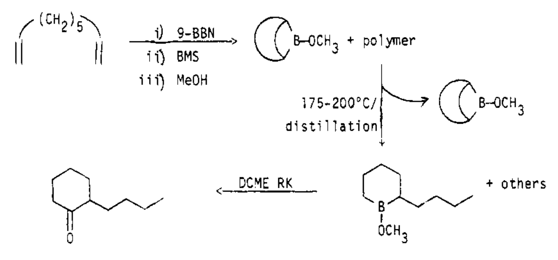
[a] Determined by oxidation and GC analysis of the diols. [b] Partially heterogeneous reaction mixture. [c] ~70% of the 9-BBN used in the reaction. [d] Further concentration and cooling of the reaction mixture resulted in simultaneous precipitation of both borepane and 9-BBN. [e] ~74% of the 9-BBN used in the reaction.

Table II. Hydroboration-Redistribution-Depolymerization of Representative Dienes with 9-BBN·BMS

diene	depolymerization temp, °C	total yield of boracyclanes, %	% composition[a] parent boracyclane	2-alkyl derivative	other isomers
1,5-hexadiene		100	100		
1,6-heptadiene	175-180	95	75	25	<2
1,7-octadiene	185-190	93	11	67	22
1,8-nonadiene	190-200	98	15	71	14
1,9-decadiene	175-180	88	12	65	23
1,11-dodecadiene	180-185	91	0	65	35
1,13-tetradecadiene	175-195	95	38	44	18

[a] Determined by oxidation and GC analysis of the diols.

Chart I



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XL-200 C O S M I C
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 VERSION 4/27/81 RR

SAMPLE:   Pai-1
LIMIT FOR COUPLING:       0.30 HZ
LIMIT FOR A-B TEST:       1.00 HZ

SATELLITE ANALYSIS:
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 BOND  SAT     JCC   ISO-SHIFTS

 1- 5 25 12   36.63 -0.49/-0.47
 1- 3 34 13   30.47 -0.54/-0.56
 2- 6 13 13   29.97 -0.34/-0.58
 4- 8 12 13   34.55 -0.43/-0.40
 6- 7 24 13   32.96 -0.35/-0.42
 7- 3 24 24   32.87 -0.47/-0.25
 8- 9 24 12   34.66 -0.37/-0.24

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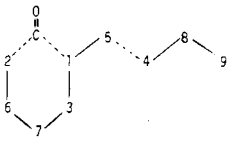
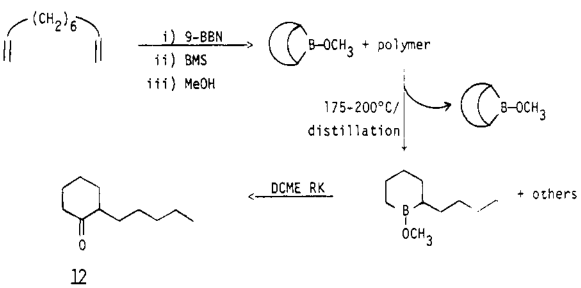


Chart II



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XL-200 C O S M I C
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 VERSION 4/27/81 RR

SAMPLE  Naik-1
LIMIT FOR COUPLING.       0.30 HZ
LIMIT FOR A-B TEST:       1.00 HZ

SATELLITE ANALYSIS:
===================

 BOND  SAT     JCC   ISO-SHIFTS

 2- 6 14 13   29.95 -0.44/-0.72
 3- 8 14 24   32.94 -0.45/-0.62
 4- 9 13 13   34.43 -0.33/-0.52
 5- 1 13 14   36.37 -0.62/-0.61
 5- 7 24 13   35.09 -0.41/-0.56
 6- 8 24 13   33.03 -0.56/-0.48
 7- 4 24 24   34.67 -0.52/-0.67
 9-10 24 12   34.68 -0.53/-0.47

NOT ASSIGNED SAT  2 OF SIGNAL 1
NOT ASSIGNED SAT. 3 OF SIGNAL 1
NOT ASSIGNED SAT. 2 OF SIGNAL 2
NOT ASSIGNED SAT. 3 OF SIGNAL 2
NOT ASSIGNED SAT  2 OF SIGNAL 3
NOT ASSIGNED SAT  3 OF SIGNAL 3
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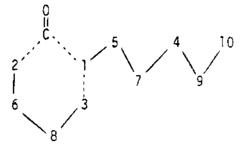


to a specific C–C bond, it offers the unique possibility of tracing the whole carbon connectivity pattern of organic compounds.

Such an analysis of the isomers isolated from the 1,8-nonadiene and 1,9-decadiene reactions unequivocally established that they were 2-*n*-butylcyclohexanone and 2-*n*-pentylcyclohexanone, respectively (Charts I and II). The dotted bonds in the structures represent the bonds not assigned by this analysis. Their connectivities are, however, easy to guess. The satellite lines arising from the coupling between the carbonyl carbon and its neighboring carbons (carbons 1 and 2) are not observed due to the fact that in the ^{13}C spectra the carbonyl carbon is located far away from the transmitter, which is centered on the aliphatic region, and also due to the long relaxation time of

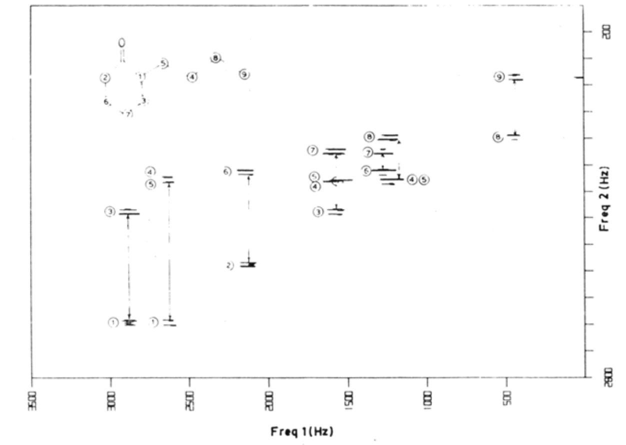
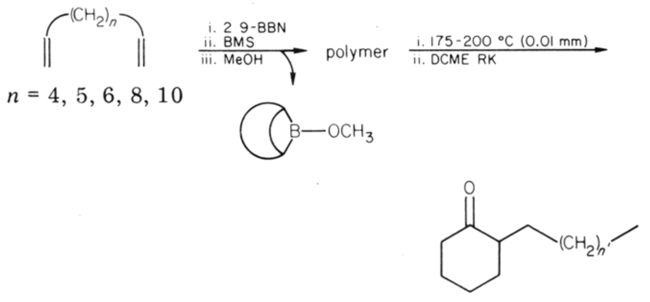


Figure 1. ^{13}C 2D INADEQUATE analysis of 1,8-nonadiene reaction mixture.

Scheme I



10, $n' = 1$
11, $n' = 2$
12, $n' = 3$
13, $n' = 5$
14, $n' = 7$
(major product)

the former. Similarly, the bond between carbons 4 and 5 (Chart I) was not assigned because they form a strongly coupled AB system (The equation $\tau = (2n + 1)/4J_{cc}$; $n = 0, 1, 2...$ used for this analysis is not strictly applicable for strongly coupled AB systems.[41]).

Even this minor uncertainty was settled for the 1,8-nonadiene reaction sample by conducting a 2D INADEQUATE ^{13}C analysis (Figure 1), which unequivocally established structure **11** (Chart I) for this isomer. Also, there is a literature precendent for the formation of six-membered boracyclanes during thermal depolymerization. It was observed that during the depolymerization of the hydroboration product of 1,7-octadiene with $BH_2Cl{\cdot}OEt_2$, *B*-chloro-2-*n*-propylborinane was the major isomer formed.[12a]

The isomers isolated from the reaction mixture of other dienes, 1,7-octadiene, 1,11-dodecadiene, and 1,13-tetradecadiene, exhibited similar ^{13}C and ^{1}H NMR behavior. So, by analogy, we assigned them 2-*n*-propyl-, 2-*n*-heptyl-, and 2-*n*-nonylcyclohexanone structures (Scheme I, compounds **10**, **13**, and **14**, respectively). As said previously, the last diene also gave the 15-membered boracyclane (and ketone) in 36% GC yield. Its structure was proven by GC comparison with an authentic sample of cyclopentadecanone and lack of CH_3 signal in the ^{1}H NMR spectrum.

In an earlier study of the cyclic hydroboration of the α,ω-dienes with monochloroborane etherate,[12a] it was reported that the initial reaction mixture consisted of monomer and polymer. The polymer could be depolymerized by heating under vacuum. But the depolymerization temperature increased with the size of the diene. In the present study we did not observe any such effect. In all cases, the depolymerization proceeded at an acceptable rate at 175–200 °C.

It is conceivable that the undesirable isomerization will be minimized if the depolymerization can be carried out at lower temperature. We attempted to catalyze the depolymerization by adding a catalytic amount (5 mol %) of BMS. This did not facilitate the depolymerization. In fact, the reaction mixture was more complex in this case, showing the presence of R_3B species. One of the reasons for the lack of catalytic effect may be the conversion of R_2BOCH_3 species to R_2BH species by BMS. Even though we did not characterize it, during distillation, a small amount of solid was seen to collect and was ascribed to 9-BBN.

Conclusions

The hydroboration of α,ω-dienes with 9-BBN and redistribution of the trialkylborane so formed with BMS leads to the formation of six- and seven-membered boracyclanes in excellent yield. The isolation of the six-membered boracyclane, borinane, is possible, but the seven-membered boracyclane could not be separated from its admixture with 9-BBN. The initial product of this reaction with 1,3-butadiene, borolane, undergoes a rapid dimerization to yield 1,6-diboracyclodecane in quantitative yield. With all higher dienes, the reaction products are polymeric. These could be cyclized by methanolysis and thermal depolymerization at 175–200 °C under vacuum. The depolymerization is accompanied by isomerization, and varying amounts of the parent boracyclane and the corresponding 2-*n*-alkylborinane are obtained as the major products, depending on the size of the diene. Attempts to effect the depolymerization at lower temperatures by using a catalytic amount of BMS gave unsatisfactory results.

Since the boracyclanes can be readily converted to the corresponding cyclic ketones, the present study offers great promise as a new, powerful annelation reaction.

Experimental Section

Materials. 9-BBN and BMS were obtained from the Aldrich Chemical Co. The commercially available dienes were used without further purification. All glassware were dried at 140 °C overnight, assembled hot, and cooled to room temperature in a stream of argon or nitrogen. All reactions involving organoboranes were carried out under a static pressure of argon or nitrogen. The liquids were transferred with syringes fitted with stainless steel needles. The solvents were dried as described elsewhere.[42]

Proton NMR spectra were scanned on a Varian XL-200 or a Nicolet NT-470 NMR spectrometer. The ^{11}B NMR spectra were obtained on a Varian FT-80A spectrometer. The ^{13}C NMR spectra were scanned on a Varian FT-80A or a Varian XL-200 spectrometer. The APT, the INADEQUATE, and the 2D ^{13}C experiments were run on a Varian XL-200 spectrometer. The IR measurements were conducted on a Perkin-Elmer 700 spectrophotometer or a Perkin-Elmer 1420 Ratio Recording IR spectrophotometer. GC analyses were performed on a Hewlett-Packard 5750 research chromatograph, on 6 ft × $^{1}/_{4}$ in 10% Apiezon L or 10% SE-30 columns. The diols were analyzed by converting them to their bis(trimethylsilyl) ethers by treatment with excess *N*,*O*-bis(trimethylsilyl)acetamide. Peak integration was done by using a Hewlett-Packard 33805 digital integrator.

Oxidation of Organoboranes and the GC Analysis of the Diols. The procedure described for the oxidation of borinane

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(41) Bax, A.; Freeman, R. *J. Magn. Reson.* **1980**, *41*, 507.

(42) Reference 19, Chapter 9.

is typical. Five milliliters of the reaction mixture containing a total of 5 mmol of boranes was transformed 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 (this step is unnecessary if the methanolyzed product is used). The contents were then oxidized by the addition of 4 mL of 3 M NaOH solution and 3 mL of 30% H_2O_2. After 1 h, 7 g of solid K_2CO_3 was added to saturate the aqueous layer. About 1 mL of organic layer was transferred to a vial containing $MgSO_4$. The vial was shaken and, after awhile, 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*-bis(trimethylsilyl)-acetamide. After 15 min at room temperature, the silyl ethers were analyzed on a 6 × $^1/_4$ in. 10% Apiezon L column, 80–220 °C/10 °C/min, carrier gas He, 35 mL/min. The diols were characterized by coinjection with authentic *cis*-1,5-cyclooctanediol and 1,5-pentanediol.

Hydroboration–Redistribution of Dienes. The following method is representative. An oven-dried, 50-mL, round-bottomed flask fitted with a septum-capped side arm, a reflux condenser, a connecting tube, and a magnetic stirring bar was cooled to room temperature in a stream of N_2. The flask was charged with 2.5 g of solid 9-BBN (20 mmol, 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 18 mL of THF and 1.34 mL (10 mmol) of 1,6-hepatadiene were added. The hydroboration was followed by ^{11}B NMR and, on completion of reaction (~3 h), 1.12 mL of 9.4 M BMS (10.5 mmol, 5% excess) was added and the reaction continued at room temperature. As the redistribution progressed, the polymeric species started to separate from the solution. The redistribution was complete in 18 h at room temperature or 3 h at reflux, as evidenced by the ^{11}B NMR of the clear solution. The reaction mixture was carefully methanolyzed, and the amount of H_2 evolved was measured by using a gas buret. On completion of methanolysis, an aliquot was examined by ^{11}B NMR. It showed a single peak at δ +56.

Oxidation of a small amount of the reaction mixture showed only *cis*-1,5-cyclooctanediol and 1,7-heptanediol in 2:1 ratio. The reaction mixture was transferred to a specially designed distillation setup consisting of a cylindrical vial of 20-cm length and 4.5-cm diameter fitted with a side arm, a bent-tube, and a receiver fitted with a Teflon stopcock. The solvent and excess methanol were pumped off under aspirator vacuum. The distillation assembly was connected to the oil pump, and the vial was heated by using a Kügelrohr oven to 90 °C. The distillate was collected in the receiver cooled to −78 °C. After complete removal of volatile materials, the vacuum was broken with N_2 and the distillate was withdrawn with a syringe and weighed. Oxidation and GC analyses showed that it was almost pure *B*-OCH_3-9-BBN containing <1.5% of *B*-methoxyborocane; yield 100%. The flask was reevacuated and the vial heated to 175–200 °C. After 3–4 h, the depolymerization was complete. The distillate was weighed and a part of it was oxidized. It consisted of *B*-methoxyborocane (**8**) and *B*-methoxy-2-ethylborinane (**9**) in 75:25 ratio; yield 94%. Traces of other isomers and *B*-OCH_3-9-BBN were also present.

A part of the distillate was subjected to the DCME reaction. The ketones, cyclooctanone and 2-ethylcyclohexanone, were isolated in 60% yield. They were separated by preparative GC and characterized by comparison of their ^{1}H NNR, ^{13}C NMR, IR, and GC behavior with authentic samples.

1,3-Butadiene. To a suspension of 2.5 g (20 mmol) of 9-BBN in THF was added the diene at −78 °C. The reaction mixture was slowly warmed to room temperature and reaction continued for 3–4 h. BMS was added (1.11 mL of 9.4 M liquid) and reaction continued overnight. THF was removed under aspirator suction and the 1,6-diboracyclodecane (**6**) was isolated from the reaction mixture by distillation: bp 41–42 °C (2 mm); ^{11}B NMR δ +28; IR 1612 cm^{-1}; $n\mathrm{D}^{21}$ 1.4835 [lit. $n\mathrm{D}^{20}$ 1.4886]; yield 92%. 9-BBN remained as pot residue and could be recycled.

1,4-Pentadiene. Synthesis of borinane has been described by this method elsewhere.[10]

1,5-Hexadiene. Fractional Crystallization Studies. An oven-dried, 50-mL centrifuge vial was cooled to room temperature in a stream of N_2 and capped with a septum. Forty milliliters of a 0.5 M 9-BBN solution was added to the flask, followed by 1.19 mL (10 mmol) of 1,5-hexadiene. After 6 h, 1.06 mL of 9.4 M BMS was added and the reaction carried on overnight. The ^{11}B NMR spectrum at this time indicated complete reaction, as evidenced by the absence of R_3B and BMS (δ +80 and −20, respectively) and the presence of an R_2BH signal at δ +27. The vial was cooled to 0 °C and then to −78 °C. After 1 h, it was centrifuged quickly and reimmersed in the cold bath, and the clear supernatant liquid was transferred into another similar vial with a double-ended needle. The precipitate was washed once with a small amount of hexane and centrifuged, and the washing was added to the mother liquor. The residue was dried under vacuum and weighed: 1.88 g (77%). Oxidation and GC analysis gave only *cis*-1,5-cyclooctanediol, thus indicating it to be pure 9-BBN. A similar analysis of the mother liquor showed that it was a mixture of borepane and 9-BBN in the ratio 68:32. The mother liquor was concentrated to half its volume and cooled to −78 °C. The precipitate and supernatant were analyzed as above and found to have the following compositions (9-BBN:borepane): precipitate, 78:22; supernatant, 26:74.

1,6-Heptadiene. Depolymerization at 175–180 °C (0.01 mm): yield of boracyclanes 95%; ^{11}B NMR δ +56. Oxidation showed 1,7-heptanediol and 1,5-heptanediol in a ratio of 3:1; minor isomers <2%. The DCME reaction gave a mixture of cyclooctanone and 2-ethylcyclohexanone; yield 60%. The ketones were separated by preparative GC on 10% SE-30/115 °C/isothermal. Cyclooctanone: IR (thin film) 1720 cm^{-1}; ^{13}C NMR ($CDCl_3$) δ 24.91, 25.77, 27.35, 41.99, 195.38. Identical with an authentic sample on coinjection.

1,7-Octadiene. Depolymerization at 185–190 °C (2 mm): yield of boracyclanes 93%; ^{11}B NMR δ +56. Oxidation showed 1,8-octanediol (11%), 1,5-octanediol (67%), and another four isomers (22%). The DCME reaction gave a mixture of ketone; yield 58%. The major isomer (80% of the mixture) was isolated by preparative GC on 10% SE-30/95 °C/isothermal: IR (thin film) 1715 cm^{-1}; ^{13}C NMR ($CDCl_3$) δ 14.10 (q in off-resonance), 20.27, 24.78, 28.00, 31.62, 33.81, 41.87, 50.48, 199.26; ^{1}H NMR ($CDCl_3$) δ 0.90 (t, J = 6.7 Hz), 1.28 (m), 1.66 (m), 2.06 (m), 2.37 (m).

1,8-Nonadiene. Depolymerization carried out at 190–200 °C (0.01 mm): yield of boracyclanes 98%; ^{11}B NMr δ +56. Oxidation showed 1,9-nonanediol (15%), 1,5-nonanediol (71%), and other isomers (14%). The DCME reaction afforded a mixture of ketones; yield 65%. The major isomer was purified by preparative GC on 10% SE-30/130 °C/isothermal: IR (thin film) 1712 cm^{-1}; ^{13}C NMR ($CDCl_3$) δ 14.04, 23.07, 25.15, 28.20, 29.42, 29.66, 34.18, 42.00, 50.78, 201.40; ^{1}H NMR ($CDCl_3$) δ 0.89 (t, J = 6.7 Hz), 1.29 (m), 1.62 (m), 2.07 (m), 2.27 (m).

1,9-Decadiene. Depolymerization carried out at 175–200 °C (0.01 mm): yield of boracyclanes 88%; ^{11}B NMR δ +56. Oxdiation showed 1,10-decanediol (12%), 1,5-decanediol (65%), and other isomers (23%). The DCME reaction afforded a mixture of ketones from which the major isomer (72% of the mixture) was isolated by preparative GC on 10% SE-30 column/125 °C/isothermal: IR (thin film) 1715 cm^{-1}; ^{13}C NMr ($CDCl_3$) δ 13.91, 22.51, 24.79, 26.84, 27.98, 29.41, 31.96, 33.86, 41.87, 50.72, 199.51; ^{1}H NMR ($CDCl_3$) δ 0.88 (t, J = 6.7 Hz), 1.27 (m), 1.66 (m), 2.27 (m).

1,11-Dodecadiene. Depolymerization at 180–185 °C (0.01 mm): yield of boracyclanes 91%; ^{11}B NMR δ +56. Oxidation showed one major peak (65%) and a mixture of four other isomers (35%). The DCME reaction gave a mixture of ketones (55% yield) from which the major isomer (47%) was purified by preparative GC on 10% SE-30 column/160 °C/isothermal: IR (thin film) 1720 cm^{-1}; ^{13}C NMr ($CDCl_3$) δ 14.07, 22.60, 25.11, 27.26, 27.81, 29.18, 29.51, 29.76, 31.83, 33.86, 41.56, 50.45, 203.31; ^{1}H NMR ($CDCl_3$) δ 0.88 (t, J = 6.7 Hz), 1.27 (m), 166 (m), 2.36 (m).

1,13-Tetradecadiene. Depolymerized at 175–195 °C (0.01 mm): yield of boracyclanes 95%; ^{11}B NMR δ +56. Oxidation showed 1,14-tetradecanediol (38%), another diol (44%) that was not coincident with 1,13-tetradecanediol, and three other isomers (18%). The DCME reaction afforded a mixture of ketones in 66% yield. The two major isomers were isolated by preparative GC on 20% SP-2100 column (200 °C/isothermal). The minor isomer was identified as cyclopentadecanone by coinjection with an authentic sample: ^{1}H NMR ($CDCl_3$) δ 1.30 (m, 20 H), 1.65 (t, J

= 6 Hz, 4 H), 2.43 (t, J = 6 Hz, 4 H). The other isomer showed the following ^{1}H NMR signals: ($CDCl_3$) δ 0.88 (t, J = 6.8 Hz), 1.26 (m), 1.57 (m).

Acknowledgment. We thank David N. Whittern for conducting the INADEQUATE and the 2D NMR analyses on a Varian XL-200 spectrometer (NSF Grant CHE-8004246). We also thank the Purdue University Biochemical Magnetic Resonance Laboratory for the use of NT-470 NMR spectrometer (NIH Grant RR-01077). The financial assistance from the National Institutes of Health (GM-10937-20) and the National Science Foundation (Grant CHE 79-18881) is gratefully acknowledged.

Registry No. 1, 280-64-8; 6, 5626-20-0; 7, 4480-56-2; 8, 60579-50-2; 9, 60579-58-0; 10, 94-65-5; 11, 1126-18-7; 12, 32362-97-3; 13, 3313-59-5; 14, 16556-72-2; BMS, 13292-87-0; 1,7-heptanediol, 629-30-1; 1,5-heptanediol, 60096-09-5; cyclooctanone, 502-49-8; 2-ethylcyclohexanone, 4423-94-3; 1,8-octanediol, 629-41-4; 1,6-octanediol, 4066-76-6; 1,9-nonanediol, 3937-56-2; 1,5-nonanediol, 13686-96-9; 1,10-decanediol, 112-47-0; 1,5-decanediol, 4203-48-9; 1,14-tetradecanediol, 19812-64-7; cyclopentadecanone, 502-72-7; *B*-methoxy-2-propylborinane, 60579-70-6; *B*-methoxy-2-butylborinane, 88703-65-5; *B*-methoxy-2-pentylborinane, 88703-66-6; *B*-methoxy-2-heptylborinane, 88729-57-1; *B*-methoxy-2-nonylborinane, 88703-67-7; 1,3-butadiene, 106-99-0; 1,5-hexadiene, 592-42-7; 1,6-heptadiene, 3070-53-9; 1,7-octadiene, 3710-30-3; 1,8-nonadiene, 4900-30-5; 1,9-decadiene, 1647-16-1; 1,11-dodecadiene, 5876-87-9; 1,13-tetradecadiene, 21964-49-8; 1,4-butanediyl-*B*,*B*′-bis(9-borabicyclo[3.3.1]nonane), 88703-68-8; 1,5-pentanediyl-*B*,*B*′-bis(9-borabicyclo[3.3.1]nonane), 81547-70-8; 1,6-hexanediyl-*B*,*B*′-bis(9-borabicyclo[3.3.1]nonane), 88703-69-9; 1,7-heptanediyl-*B*,*B*′-bis(9-borabicyclo[3.3.1]nonane), 88703-70-2; BH_3, 13283-31-3.

Ortho Metalation Directed by α-Amino Alkoxides

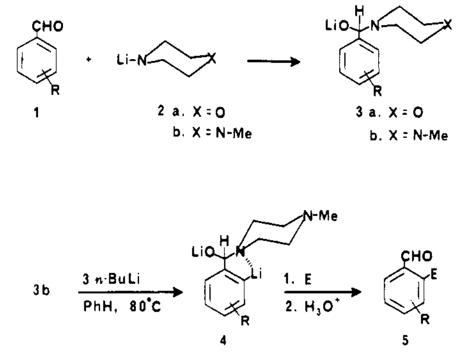
Daniel L. Comins* and Jack D. Brown

Department of Chemistry and Biochemistry, Utah State University, Logan, Utah 84322

Received August 2, 1983

The addition of aromatic aldehydes to certain lithium dialkylamides in benzene or tetrahydrofuran gave α-amino alkoxides which were ortho lithiated with excess *n*-butyllithium. Subsequent alkylation and hydrolysis provided ortho-substituted aromatic aldehydes via a one-pot reaction. The ortho metalation of α-amino alkoxides derived from 1- and 2-naphthaldehyde and various substituted benzaldehydes was examined. When *N*,*N*,*N*′-trimethylethylenediamine was used as the amine component of the α-amino alkoxide, metalation could be carried out at lower temperatures. This rate increase is due to an intramolecular TMEDA-like assisted metalation. The synthetic utility of this ortho metalation, including how varying the amine component of the α-amino alkoxide affects the regiochemistry and metalation rate, is discussed.

In recent years there has been considerable interest in the area of ortho metalation.[1] A variety of ortho-directing groups have been utilized on various aromatic rings to direct regiospecific metalation in the ortho position. Carbonyl-derived directing groups include $CONR_2$,[2] CONHR,[3] oxazolines,[4] α-amino alkoxides[5] (prepared from tertiary amides and RLi), $CH(OR)_2$,[6] imidazolidines,[7] cyclohexylimines,[8] and α-amino alkoxides[9] (prepared from aromatic aldehydes and lithium *N*-methylpiperazide). We recently reported an in situ protection of aromatic and aliphatic aldehydes in high yield via the formation of α-amino alkoxides.[10] The α-amino alkoxides **3** are prepared by the addition of an aromatic aldehyde (**1**) to certain



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(1) For reviews, see: Gschwend, H. W.; Rodriguez, H. R. *Org. React.* **1979**, *26*, 1–360. Omae, I. *Chem. Rev.* **1979**, *79*, 287–321. $CONEt_2$: Snieckus, V. *Heterocycles* **1980**, *14*, 1649. Beak, P.; Snieckus, V. *Acc. Chem. Res.* **1982**, *15*, 306–312.

(2) Beak, P.; Brown, R. A. *J. Org. Chem.* **1977**, *42*, 1823–1824. de Silva, S. O.; Reed, J. N.; Snieckus, V. *Tetrahedron Lett.* **1978**, 5099–5102. de Silva, S. O.; Snieckus, V. *Ibid.* **1978**, 5103–5106. de Silva, S. O.; Ahmad, I.; Snieckus, V. *Ibid.* **1978**, 5107–5110. Beak, P.; Brown, R. A. *J. Org. Chem.* **1979**, *44*, 4463–4464. de Silva, S. O.; Watanabe, M.; Snieckus, V. *Ibid.* **1979**, *44*, 4802–4808. de Silva, S. O.; Ahmad, I.; Snieckus, V. *Can. J. Chem.* **1979**, *57*, 1598–1605. Watanabe, M.; Snieckus, V. *J. Am. Chem. Soc.* **1980**, *102*, 1457–1460. Beak, P.; Brown, R. A. *J. Org. Chem.* **1982**, *47*, 34–46. Iwao, M.; Reed, J. N.; Snieckus, V. *J. Am. Chem. Soc.* **1982**, *104*, 5531–5533. Harvey, R. G.; Cortez, C.; Jacobs, S. A. *J. Org. Chem.* **1982**, *47*, 2120–2125. Mills, R. J.; Snieckus, V. *Ibid.* **1983**, *48*, 1565–1568. Beak, P.; Chen, C-W. *Tetrahedron Lett.* **1983**, *24*, 2945–2948. Reed, J. N.; Snieckus, V. *Ibid.* **1983**, *24*, 3795–3798. Billedean, R. J.; Sibi, M. P.; Snieckus, V. *Ibid.* **1983**, *24*, 4515–4518.

(3) Puterbaugh, W. H.; Hauser, C. R. *J. Org. Chem.* **1964**, *29*, 853–856. Slocum, D. W.; Jennings, C. A. *Ibid.* **1976**, *41*, 3653–3664. Katritzky, A. R.; Rahimi-Rastgoo, S.; Ponkshe, N. K. *Synthesis* **1981**, 127–129.

(4) Meyers, A. I.; Mihelich, E. D. *J. Org. Chem.* **1975**, *40*, 3158–3159. Gschwend, H. W.; Hamdan, A. *Ibid.* **1975**, *40*, 2008–2009. Meyers, A. I.; Lutomski, K. *Ibid.* **1979**, *44*, 4464–4466. Meyers, A. I.; Avila, W. B. *Ibid.* **1981**, *46*, 3881–3886. Meyers, A. I.; Rieker, W. *Tetrahedron Lett.* **1982**, *23*, 2091–2094. Smith, A. B., III; Schow, S. R.; Bloom, J. D.; Thompson, A. S.; Wizenberg, K. N. *J. Am. Chem. Soc.* **1982**, *104*, 4015–4018. Edgar, K. J.; Bradsher, C. K. *J. Org. Chem.* **1982**, *47*, 1585–1587. Newman, M. S.; Hussain, N. S. *Ibid.* **1982**, *47*, 2837–2840.

(5) Michael, U.; Gronowitz, S. *Acta Chem. Scand.* **1968**, 1353. Gronowitz, S. *Ark. Kemi.* **1970**, *32*, 283. Brasky, L.; Gschwend, H. W.; McKenna, J.; Rodriquez, H. R. *J. Org. Chem.* **1976**, *41*, 3651–3652.

(6) (a) Plaumann, H. P.; Key, B. A.; Rodrigo, R. *Tetrahedron Lett.* **1979**, 4921–4924. (b) Winkle, M. R.; Ronald, R. C. *J. Org. Chem.* **1982**, *47*, 2101–2108. (c) Napolitano, E.; Giannone, E.; Fiaschi, R.; Marsili, A. *Ibid.* **1983**, *48*, 3653–3657.

(7) Harris, T. D.; Roth, G. P. *J. Org. Chem.* **1979**, *44*, 2004–2007.

(8) (a) Ziegler, F. E.; Fowler, K. W. *J. Org. Chem.* **1976**, *41*, 1564–1566. (b) Murahashi, S-I, Tamba, Y.; Yamamura, M.; Yoshimura, N. *Ibid.* **1978**, *43*, 4099–4106.

(9) Comins, D. L.; Brown, J. D.; Mantlo, N. B. *Tetrahedron Lett.* **1982**, *23*, 3979–3982.

(10) Comins, D. L.; Brown, J. D. *Tetrahedron Lett.* **1981**, *22*, 4213–4216.

0022-3263/84/1949-1078$01.50/0