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ORGANOBORANES FOR SYNTHESIS. 9. RAPID REACTION OF ORGANOBORANES WITH IODINE UNDER THE INFLUENCE OF BASE. A CONVENIENT PROCEDURE FOR THE CONVERSION OF ALKENES INTO IODIDES *VIA* HYDROBORATION[1,2]

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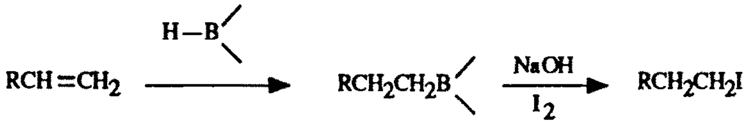
Abstract - The reaction of organoborane with iodine is strongly accelerated by sodium hydroxide. Organoboranes derived from terminal alkenes react with the utilization of approximately two of the three alkyl groups attached to boron, providing a maximum of 67% yield of alkyl iodide. Thus, hydroboration-iodination of 1-decene gives a 60% yield of *n*-decyl iodide. Secondary alkyl groups, derived from internal alkenes, react more sluggishly and only one of the three alkyl groups attached to boron is converted to the iodide. Thus, the procedure applied to 2-butene provides a 30% yield of 2-butyl iodide. The use of disiamylborane *bis*-(3-methyl-2-butylborane, Sia_2BH) as hydroborating agent increases the yield of iodides from terminal alkenes since the primary alkyl groups react in preference to the secondary siamyl groups. Consequently, hydroboration of 1-decene with Sia_2BH, followed by iodination gives a 95% yield of *n*-decyl iodide. The use of methanolic sodium methoxide in place of sodium hydroxide provides alkyl iodides in considerably higher yields. The combination of hydroboration with iodination in the presence of a base provides a convenient method for the *anti*-Markovnikov hydroiodination of alkenes. The base-induced iodination of organoboranes proceeds with the inversion of configuration at the reaction center, as shown by the formation of *endo*-2-iodonorbornane from tri-*exo*-norbornylborane.

The hydroboration of alkenes provides a convenient synthesis for organoboranes. Oxidation of organoboranes with alkaline hydrogen peroxide gives the corresponding alcohols, providing a simple procedure for the overall *anti*-Markovnikov hydration of the double bond.[4] A similar reaction of organoboranes with iodine would be expected to give the corresponding alkyl iodides, providing a simple procedure for the overall *anti*-Markovnikov hydroiodination of alkenes. However, reports in the literature indicated that organoboranes react with iodine very sluggishly.[5,6] Thus, the reaction of tri-*n*-propylborane with iodine at 150°C can convert only one of the three alkyl groups to *n*-propyl iodide. Nevertheless, it is evident that the ability to convert organoboranes into alkyl iodides would open up several new synthetic possibilities for these versatile reagents. Kinetic studies have indicated that the reaction of phenylboronic acid with bromine is accelerated by bases.[7] Consequently, it occurred to us that use of a base should enhance the reactivity of organoboranes toward iodine. Accordingly, we undertook to carry out a systematic investigation of the reaction of organoboranes with iodine.

RESULTS AND DISCUSSION

We have observed that organoboranes undergo a very rapid reaction with iodine under the influence of sodium hydroxide, the reaction being essentially complete in less than 5 min at 25°C. This makes possible a simple procedure for the conversion of terminal alkenes into primary iodides (eq 1).



$$RCH{=}CH_2 \xrightarrow{H-B<} RCH_2CH_2B< \xrightarrow[I_2]{NaOH} RCH_2CH_2I \qquad (1)$$

Initially, we established the conditions necessary for efficient iodination using tri-*n*-butylborane as a representative trialkylborane.

Reaction of Tri-*n*-butylborane with Iodine. A tetrahydrofuran solution of this organoborane, containing a hydrocarbon standard for GC analysis, was treated with an equivalent amount of iodine. The progress of the reaction at room temperature was followed by withdrawing aliquots, removing excess iodine with sodium thiosulfate, and injecting directly into the GC. A slow formation of *n*-butyl iodide was observed. Approximately three days were required for complete reaction of one of the three butyl groups attached to boron.

The reaction was repeated under essentially the same conditions except that an aqueous solution of sodium hydroxide was added to the reaction mixture immediately after the addition of iodine. An almost instantaneous decolorization of iodine resulted and GC analysis indicated an essentially complete conversion of one of the three butyl groups to *n*-butyl iodide (eq 2).

$$n\text{-}Bu_3B + I_2 + NaOH \longrightarrow n\text{-}BuI + n\text{-}Bu_2BOH + NaI \qquad (2)$$

Doubling the amounts of base and iodine resulted in the conversion of nearly two butyl groups to iodide (eq 3).

$$n\text{-}Bu_3B + 2I_2 + 2NaOH \longrightarrow 2n\text{-}BuI + n\text{-}BuB(OH)_2 + 2NaI \qquad (3)$$

Further increases in the amounts of base and iodine did not improve the yield of butyl iodide. Replacement of sodium hydroxide solution with aqueous sodium acetate gave a much slower reaction, requiring 12 h for conversion of one of the butyl groups. Use of methanolic sodium hydroxide as the accelerating base was investigated in some detail (Table 1).

Table 1. Reaction of Tri-*n*-butylborane with Iodine in THF[a]

Iodine mmol	Base (mmol)	Reaction Time	*n*-BuI Yield, %[b]
10	none	72 h	30
10	$NaOH/H_2O$ (10)	5 min	32
10	$NaOAc/H_2O$ (10)	12 h	30
10	$NaOH/CH_3OH$ (10)	5 min	33
20	$NaOH/CH_3OH$ (20)	5 min	65
30	$NaOH/CH_3OH$ (30)	5 min	65
30[c]	$NaOH/CH_3OH$ (30)	5 min	60
30[d]	$NaOH/CH_3OH$ (30)	5 min	64

[a] Reaction of 10 mmol disiamylalkylborane with 11 mmol iodine and 11 mmol methanolic sodium hydroxide. [b] GC yields, isolated yields in parentheses. The yields are based on the amount of starting alkene.

Even with an excess of base and iodine, only two of the three butyl groups were found to react at room temperature. Using inverse addition, adding the iodine to a solution of the organoborane and methanolic sodium hydroxide gave slightly lower yields of *n*-butyl iodide. Raising the temperature of the reaction mixture to 67°C prior to addition of the base gave no increase in the yield.

In all of the above reactions, the isomeric purity of the *n*-butyl iodide was greater than 99%, even though oxidation of a sample of the tri-*n*-butylborane with alkaline hydrogen peroxide gave the usual ratio of 94% *n*-butyl alcohol and 6% *sec*-butyl alcohol.

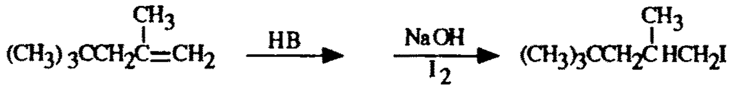
Reaction of Representative Organoboranes with Iodine. Based on the results with tri-*n*-butylborane (Table 1), a standard procedure for the conversion of alkenes into alkyl iodides was devised. The alkene was treated with the appropriate amount of diborane in tetrahydrofuran to form the trialkylborane. The solution was then treated with iodine and methanolic sodium hydroxide in slight excess of the amounts required for complete conversion of two of the three alkyl groups to iodide. The yield of product was determined by GC using an internal standard. In a representative number of cases, the products were isolated by distillation. The results are shown in Table 2.

Table 2. Conversion of Alkenes into Alkyl Iodides *via* Hydroboration-Iodination[a]

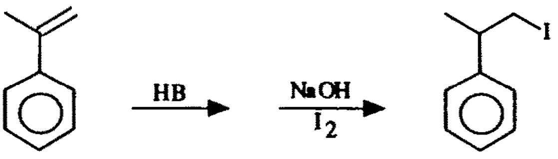
Alkene	Product	Yield, %[b]
1-decene	$CH_3(CH_2)_8CH_2I$	65
isobutylene	$(CH_3)_2CHCH_2I$	63
2,4,4-trimethyl-1-pentene	$(CH_3)_3CCH_2CH(CH_3)CH_2I$	63 (54)
α-methylstyrene	$C_6H_5CH(CH_3)CH_2I$	63 (50)
β-pinene	*cis*-myrtanyl iodide	60 (40)
cyclopentene	iodocyclopentane	33
2-butene	$CH_3CH_2CH(CH_3)I$	30

[a] Reaction of 10 mmol organoborane with 22 mmol iodine and 22 mmol methanolic sodium hydroxide at 25°C. [b] GC yields; isolated yields in parentheses. The yields are based on the amount of starting alkenes.

The reaction of iodine with simple organoboranes, such as tri-*n*-butylborane, is quite slow, in agreement with the results of earlier workers. However, the reaction is remarkably accelerated by sodium hydroxide. Under these conditions, essentially complete reaction is achieved in a matter of minutes at room temperature and distillation of the reaction mixture provides good yields of the corresponding alkyl iodides. Organoboranes derived from terminal alkenes react with the formation of two moles of alkyl iodide per mole of trialkylborane. The third alkyl group is unreactive under these conditions and remains attached to boron. The reaction appears to be generally applicable, as shown by the following transformations (eq 4-6).



$$\mathrm{(CH_3)_3CCH_2\overset{CH_3}{\overset{|}{C}}{=}CH_2} \xrightarrow{\mathrm{HB}} \xrightarrow[\mathrm{I_2}]{\mathrm{NaOH}} \mathrm{(CH_3)_3CCH_2\overset{CH_3}{\overset{|}{C}}HCH_2I} \qquad (4)$$



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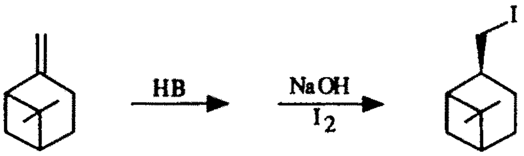

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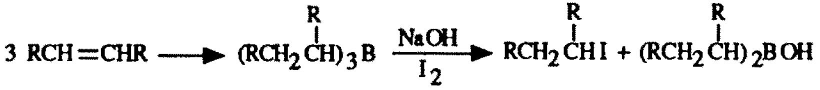
Secondary alkyl groups, derived from internal alkenes, react more sluggishly and only one of the three groups on boron is converted to alkyl iodide (eq 7).



$$3\ RCH{=}CHR \longrightarrow (RCH_2\overset{R}{\overset{|}{C}}H)_3B \xrightarrow[I_2]{NaOH} RCH_2\overset{R}{\overset{|}{C}}HI + (RCH_2\overset{R}{\overset{|}{C}}H)_2BOH \qquad (7)$$

Consequently, using this procedure, the yield of alkyl iodides from terminal alkenes, such as 1-butene, is restricted to a maximum of 67%, while the yields from internal alkenes, such as cyclopentene or 2-butene, are restricted to maximum of 33%.

The sluggishness of secondary alkyl groups toward iodination has been utilized in the selective iodination of *bis* (3-methyl-2-butyl)alkylboranes.

Reactions of Disiamylalkylboranes with Iodine. The use of disiamylborane rather than diborane as hydroborating agent was investigated as a means of increasing the yields of primary iodides obtained from terminal alkenes. Hydroboration of 1-decene with disiamylborane, followed by treatment of the reactant, disiamyl-*n*-decylborane, with iodine and methanolic sodium hydroxide in amounts slightly greater than required for conversion of only one alkyl group, gave a 95% yield of *n*-decyl iodide. Results with other terminal alkenes were equally good (Table 3)

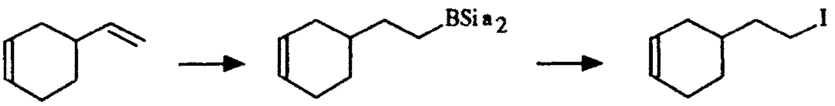
For these reactions, it was found advantageous to oxidize the residual boron compounds with alkaline hydrogen peroxide prior to isolation of the iodides. Thus, the use of disiamylborane in the hydroboration step circumvents the difficulty with terminal alkenes.

The greater sluggishness of secondary alkyl groups towards reaction with iodine as compared to primary alkyl groups is indicated not only by the lower yields of iodides obtained from these derivatives but also by the high isomeric purity (> 99%) of the primary iodides obtained from organoboranes containing approximately 6% of secondary alkyl groups. Consequently, the iodination of disiamylalkylboranes was expected to give preferred migration of a primary alkyl group rather than the secondary siamyl groups (eq 8).

$$RCH{=}CH_2 + Sia_2BH \longrightarrow RCH_2CH_2BSia_2 \longrightarrow RCH_2CH_2I + Sia_2BOH \qquad (8)$$

The procedure does in fact give excellent yields of primary iodides, as shown by the results in Table 3.

It is evident that disiamylborane can accommodate a number of common organic functional groups in an alkene under hydroboration conditions.[8-10] The functional group tolerance, combined with selectivity in the hydroboration of dienes,[11] renders Sia_2BH a valuable reagent for selective hydroiodination of such functionally substituted alkenes and dienes. Some indication of its versatility is provided by the ready conversion of 4-vinylcyclohexene to the unsaturated primary iodide (eq 9).



(9)

If a yield of approximately 65% is adequate, the simpler hydroboration with diborane can be utilized. However, if yields approaching 100% are desired, or if the structure requires a more selective hydroboration, then the procedure utilizing disiamylborane is preferable.

Table 3. Conversion of Terminal Alkenes into Primary Iodides *via* Hydroboration-Iodination Using Disiamylborane[a]

Alkene	Product	Yield, %[b]
1-hexene	$CH_3(CH_2)_4CH_2I$	95
1-decene	$CH_3(CH_2)_8CH_2I$	95
2,4,4-trimethyl-1-pentene	$(CH_3)_3CCH_2CH(CH_3)CH_2I$	92
4-vinylcyclohexene	4-(2-iodoethyl)cyclohexene	66 (60)

[a]Reaction of 10 mmol disiamylalkylborane with 11 mmol iodine and 11 mmol methanolic sodium hydroxide. [b]GCyields, isolated yields in parentheses. The yields are based on the amount of starting alkene.

An Improved Procedure for Iodination. The bromination procedure utilizes all three boron bound groups of trialkylboranes derived from the hydroboration of terminal olefins and two groups of trialkylboranes from internal and cyclic alkenes.[12] Unfortunately, however, the earlier iodination procedure utilizes only two groups from primary alkyl organoboranes and only one group from secondary alkyl organoboranes. The lower conversion realized in the iodine reaction could severely limit the synthetic utility of the reaction if a valuable olefin were to be converted into the corresponding iodide. In this study we have established that the substitution of sodium methoxide as the base in the reaction of organoboranes with iodine greatly improves the yields of the alkyl iodides.

The sodium methoxide induced iodination of trialkylboranes was examined employing tri-*n*-butyl- and tri-*s*-butylborane as representative organoboranes. Treatment of tri-*n*-butylborane in tetrahydrofuran at 25°C with three equivalents of iodine and three equivalents of methanolic sodium methoxide results in the rapid formation of two equivalents of *n*-butyl iodide. The third group reacts more slowly under these mild conditions, the reaction not being complete after three days. Nonetheless, this development would allow terminal olefins to be converted into the corresponding promary alkyl iodides in some 15% better yields than the previous iodination procedure using sodium hydroxide as the base. Treatment of tri-*sec*-butylborane under the same conditions also results in a fast reaction with the formation of two equivalents of *sec*-butyl iodide. Although the third *sec*-butyl group resists further reaction, utilization of two *sec*-butyl groups in the sodium methoxide iodination of organoboranes represents a major improvement over the sodium hydroxide-induced iodination sequence where only one alkyl group is utilized. The results are summarized in Table 4.

Table 4. The Reaction of Tri-*n*-butyl- and Tri- *sec*-butylborane with Iodine and Sodium Methoxide at 25°C[a].

Time (h)	Yield (%)[b,c] of *n*-C_4H_9I	Yield (%)[b] of *sec*-C_4H_9I
0.1	65	63
1.0	68	
4.0	75	65
24.0	79	
36.0	80	66
72.0	83	68

[a]Reaction of tri-*n*-butylborane (10 mmol) with I_2 (30 mmol) and $NaOCH_3$ (30 mmol).[b]Determined by GC. [c]Less than 1% *sec*-butyl iodide observed.

A study of this reaction was then undertaken to determine its generality and synthetic utility. The results of this iodination study using sodium methoxide as the base and a comparison with the previous procedure using sodium hydroxide as the base is found in Table 5.

Table 5. Conversion of Alkenes into Alkyl Iodides *via* Hydroboration-Iodination[a]

Alkene	Product	React. time, h	Yield (%)[c]	
			NaOH	NaOCH3
1-butene	n-C_4H_9-I	24	65	79
2-methyl-1-propene	i-C_4H_9-I	24	63	80
β-pinene	myrtanyl iodide	24	60	72
methyl 10-undecenoate	I-CH_2-$(CH_2)_9$-CO_2CH_3	24		80(68)
cis - 2-butene	I-$CH(CH_3)CH_2CH_3$	3	30	66
cyclopentene	iodocylopentane	3	33	64
cyclohexene	iodocyclohexane	3		72

[a]Reaction of R_3B (10 mmol) with I_2 (30 mmol) and $NaOCH_3$ (30 mmol) for the time indicated. [b]All products characterized by comparison with authentic samples. [c] Yields based on starting alkene, determined by GC (conditions: 10% Dow Corning on Chromosorb W; 6 ft x 0.25 in); value in parentheses refers to isolated product.

Clearly this procedure offers a substantial improvement over the use of sodium hydroxide. Significantly, the conversion of methyl 10-undecenoate into methyl 11-iodoundecanoate demonstrates that the hydroboration-iodination sequence may be applicable to a number of functionally substituted alkenes. The results also suggest that other organoborane conversion which are accelerated by sodium hydroxide may be even more strongly facilitated by the use of sodium methoxide.

Mechanism and Stereochemistry. We have not as yet carried out detailed investigation of the mechanism by which sodium hydroxide accelerates the reaction of organoboranes with iodine. For the present we can rationalize our results by the following scheme (eq 10).

$$R_3B + NaOH \rightleftharpoons R_3B^-OH\,Na^+ \xrightarrow{I_2} NaI + R_2BOH + RI \qquad (10)$$

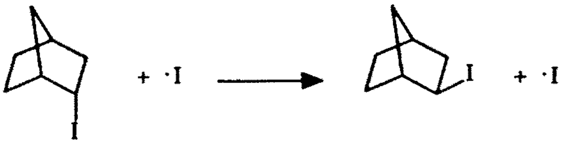
According to this mechanism, the base activates the alkyl groups by attaching to the boron atom, facilitating their oxidation by iodine. This mechanism suggests that many other reactions of organoboranes will be accelerated by base.

In view of the great synthetic potential of this reaction, it appeared desirable to examine the stereochemistry involved in the process. This might determine whether the unexpected stereochemistry observed in the sodium methoxide-induced bromination of tri-*exo*-norbornylborane is an anomalous observation peculiar to the bromine reagent or the norbornyl system, or whether a new mechanistic pathway is available for organoborane reactions. Such a study was undertaken to resolve these ambiguities. Initially, the iodination of tri-*exo*-norbornylborane was carried out using methanolic sodium hydroxide as the base. Room temperature treatment of 10 mmol of tri-*exo*-norbornylborane in tetrahydrofuran with 22 mmol of iodine followed by dropwise addition of 22 mmol of sodium hydroxide as a 3 *M* solution in methanol produces 9.2 to 9.8 mmol (31-33%) of 2-iodonorbornane by GC analysis.

Either GC or ^1H NMR examination indicates that, similar to bromination, the product consists of 75 ± 5% *endo*-2-iodonorbornane. Since only one of the norbornyl groups was utilized with sodium hydroxide as the base, the reaction was repeated using sodium methoxide as the base. Indeed, the yield of 2-iodonorbornane is increased to 60-70%. Unfortunately, the amount of the *endo* -2-iodonorbornane present in the mixture decreased to only 59-65 %. In one case, the amount of the endo isomer was only 40%. The erratic exo:endo isomer ratios prompted a study to investigate various conditions which would maximize the amount of *endo*-2-iodonorbornane.

It appears that an increase in the reaction time causes a decrease in the percentage of the *endo*-isomer. It was then considered that the *endo*-2-iodonorbornane might isomerize to the *exo*-isomer in the presence of light and excess iodine. Exchange and displacement reactions of alkyl iodides with iodine are known to be very facile.[13] This proposition was tested by reacting tri-*exo*-norbornylborane with iodine and sodium methoxide and following the composition of the 2-iodonorbornanes with time. Treatment of 30 mmol of tri-*exo*-norbornylborane in tetrahydrofuran at 0°C with 20 mmol of iodine followed by rapid addition of 20 mmol of sodium methoxide in methanol produces 11.8 mmol of 2-iodonorbornane after two minutes. The yield of 2-iodonorbornane is not increased very much with time, but the isomer distribution changes remarkably with time.

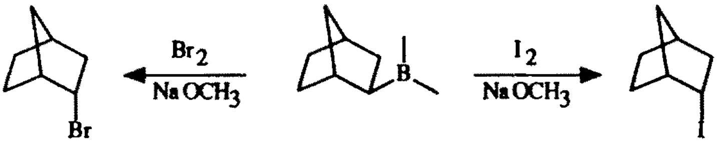
It was then considered likely that the excess iodine was causing the isomerization of the *endo*-2-iodonorbornane to the *exo*-isomer. It is well known that thermally or photolytically generated iodine atoms cause racemization of optically active alkyl iodides.[14] Such a process might account for the isomerization of the *endo*-isomer in the reaction (eq 11).



(11)

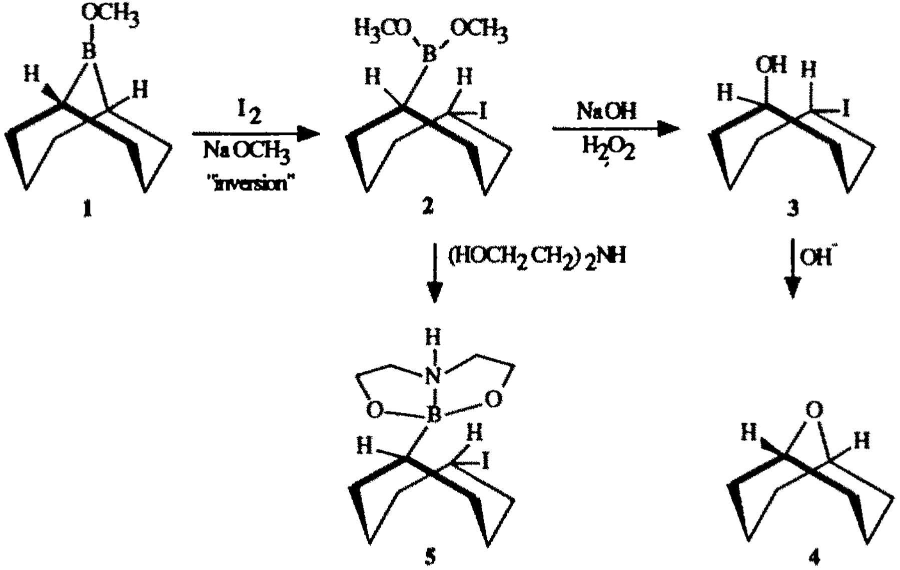
The information gained in these studies permitted for the first time a convenient synthesis of the previously unknown *endo*-2-iodonorbornane. Norbornene was quantitatively converted to essentially pure tri-*exo*-norbornylborane *via* hydroboration and, to minimize isomerization of the *endo*-isomer, the iodination reaction was conducted in the dark and run to the approximate utilization of one norbornyl group. In this fashion, 100 mmol of tri-*exo*-norbornylborane was converted into 78 mmol of 2-iodonorbornane (78% isolated yield based on one norbornyl group). Analysis by ^1H NMR revealed the compound to be 80% *endo*- and 20% *exo*-2-iodonorbornane. The small amount of *exo*-isomer could be selectively removed by solvolysis in aqueous methanol and distillation afforded pure *endo*-2-iodonorbornane.

These results, consequently, indicate that the earlier result involving sodium methoxide-induced bromination is not exceptional (eq 12).



(12)

It appeared highly desirable to further examine the novel inversion in the sodium methoxide-induced iodination reaction with other organoboranes. The iodination reaction was next studied with *B*-methoxy-9-borabicyclo[3.3.1]-nonane (*B*-methoxy-9-BBN, **1**). This organoborane possesses the special feature that reaction at one of the boron-cyclooctyl bonds allows a stereochemical determination of the reaction. Treatment of *B*-methoxy-9-BBN with iodine and sodium methoxide results in the disappearance of the iodine color in one to two hours. Following alkaline hydrogen peroxide oxidation, GC analysis reveals the formation of 9-oxabicyclo[3.3.1]nonane, 4, in 61-84% yields. Oxidation of 2 must produce the *trans*-1-iodo-5-cyclooctanol, 3, readily converted to 4 in the presence of alkali.[14] In fact, it proved possible to isolate the postulated intermediate, 2, as the crystalline derivative, 5, by treatment with diethanolamine (eq 13).



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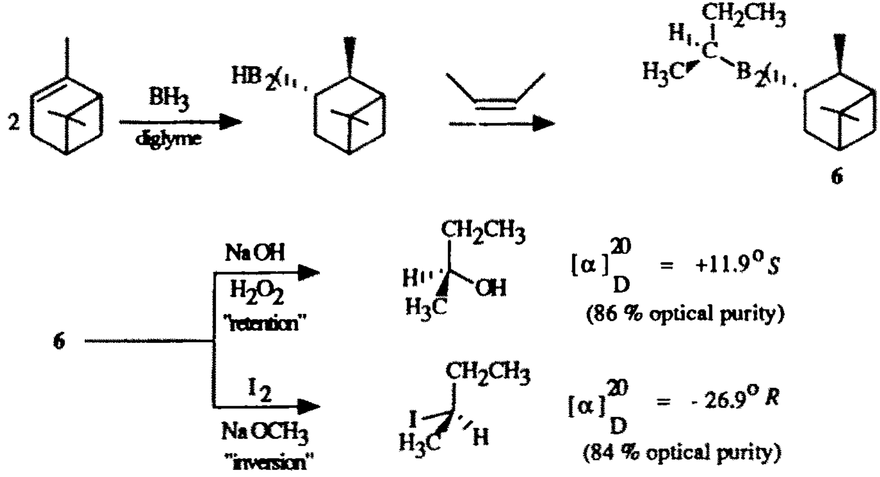
The oxidation step undoubtedly proceeds with retention. Hence, this reaction sequence provides evidence that cleavage of the boron-cyclooctyl bond of *B*-methoxy-9-BBN with iodine and sodium methoxide proceeds with inversion of configuration of the carbon center. An analogous sequence occurs in the sodium methoxide induced bromination of *B*.-methoxy-9-BBN.[1b] Thus, the novel inversion of configuration at carbon centers bound to boron in the base-induced bromination and iodination procedures is not restricted to the norbornyl system.

The final proof for the inversion of configuration in base-induced iodination is given by the formation of optically active 2-iodobutane.[15] The hydroboration of *cis*-2-butene with diisopinocampheylborane, derived from (-)-α-pinene, provides diisopinocampheyl-2-butylborane, which affords 86% optically pure [S]-2-butanol upon oxidation with alkaline hydrogen peroxide. On the other hand, treatment with iodine and sodium methoxide provides [R]-2-iodobutane in 84% optical purity (eq 14).



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Consequently, the iodination reaction, in this case, must proceed with almost 100% inversion of configuration at the carbon center attached to boron.

More recently, in the reaction of diisopinocampheyl-2-butylborane with iodine monochloride in the presence of sodium acetate, *R*-(-)-2-iodobutane was obtained in 87% optical purity,[16] supporting our earlier finding that iodination proceeds with the inversion of configuration. Significantly, the successful reaction of iodine monochloride with organoboranes has proven especially valuable in the synthesis of radioiodinated compounds. Using an *in situ* oxidation of the radioiodide anion, a wide variety of functionally substituted iodine-labeled radiopharmaceuticals have been prepared.[17]

CONCLUSIONS

The sluggishness in the reaction of organoboranes with iodine was overcome by the use of methanolic sodium hydroxide. However, only two out of three alkyl groups from a tri-*n*-alkylborane and only one of the three from a tri-*s*-alkylborane are converted to the corresponding alkyl iodide. Use of disiamylborane for hydroboration permits almost quantitative hydroiodination of terminal alkenes. Methanolic sodium methoxide provides slightly better yields and permits the presence of ester functionalities in the starting alkene. More recently, milder reaction conditions employing iodine monochloride in the presence of sodium acetate[16] or iodine in the presence of water or methanolic sodium acetate[18] have been successfully employed for the hydroiodination of various functionally substituted alkenes.

Thus, hydroboration, followed by base-induced iodination, provides a convenient route for the *anti*-Markovnikov hydroiodination of alkenes under mild conditions.

The sodium methoxide-induced iodination of organoboranes proceeds with predominant inversion of configuration at the carbon center undergoing reaction. From a synthetic viewpoint, this procedure permits the synthesis of *endo*-2-iodonorbornane (and presumably other *endo*-bicycloalkyl iodides) for the first time. A procedure has been developed which permits the conversion of olefins into alkyl iodides of excellent optical purity and highly predictable configuration.

EXPERIMENTAL

General Comments. The techniques used in handling air-sensitive materials are described elsewhere.[18] All glassware was oven-dried at 140°C for at least four hours before use, assembled hot, and cooled under a stream of prepurified nitrogen. Air- and moisture-sensitive materials were transferred using oven-dried, nitrogen-flushed hypodermic syringes fitted with stainless steel needles.

Materials. Tetrahydrofuran and diglyme were freshly distilled under nitrogen from lithium aluminum hydride. Alkenes were obtained from various commercial sources and purified, if necessary, by distillation. Iodine (Mallinckrodt Chemical Works) was used as received. The methanolic sodium methoxide solution was prepared by adding small pieces of clean sodium under a blanket of nitrogen to a flask containing absolute methanol cooled to 0°C. After stirring at room temperature for 24 h, a small amount of white material was allowed to settle, leaving a clear, colorless solution. The methanol solution of sodium methoxide was standardized by transferring 1-ml aliquots *via* syringe to a flask containing 10 ml of water and titrating with standard HCl using phenophthalein as the indicator. Tri-*n*-butylborane (Callery Chemical Corp.) was distilled before use. Tri-*sec*-butylborane was made by the hydroboration of *cis*-2-butene. Borane-methyl sulfide (Aldrich Chemical Company) was used as received. Borane-tetrahydrofuran was prepared and standardized as previously described.[19] Norbornene (Aldrich) and α-pinene (Dragoco) were used as received. *B*-methoxy-9-BBN was prepared according to the literature procedure.[19]

Analyses. GC analyses were carried out on a Hewlett-Packard 5752B chromatograph using 0.25 in OD stainless steel columns, 6 ft long, filled with 10% DC 710 on 60/80 AW-DMCS Chromosorb W. Baseline separation of *exo*- and *endo*-2-iodonorbornane was accomplished using a 24 ft x 0.25 in stainless steel column filled with 10%

Zonyl E-7 on 60/80 AW-DCMS Chromograph W. At 100°C, the *exo*-isomer is retained for a longer time than the *endo*-isomer. ^1H NMR spectra were recorded in $CDCl_3$ on a Varian T-60 (60 MHz) spectrophotometer using tetramethylsilane as an internal standard (d 0ppm) The exo:endo isomer ratios of 2-iodonorbornane were determined by integration of the C-2 methine protons at d 3.95 (*exo*-2-iodonorbornane) and d 4.20 (*endo*-2-iodonorbornane). The optical rotation measurements were made on neat materials (unless specified) in one-decimeter tubes at ambient temperature using a Carl Zeiss polarimeter.

Normal hydrocarbons (Phillips 99%) were used as internal standards. Low resolution mass spectra were obtained on an Hitachi RMU-60 and the high resolution mass spectra were taken on a CEC 21-110 instrument.

Reaction of Tri-n-butylborane with Iodine. In an oven-dried, nitrogen-flushed, 100-ml reaction flask was placed 10 mmol of tri-*n*-butylborane in 10 ml THF. The flask was maintained at 25°C and 10 mmol of iodine in THF was added, followed by the addition of a suitable base. When iodine had decolorized or after a reasonable time, the product was analyzed on GC. The results are summarized in Table 1.

Conversion of Alkenes to Alkyl Iodides. Representative Procedure. The procedure employed for the preparation of *cis*-myrtanyl iodide is representative. A dry 500-ml flask, equipped with septum inlet, thermometer well, pressure-equalizing dropping funnel, and magnetic stirrer, was flushed with nitrogen and then maintained under a static pressure of the gas. The flask was charged with 75 ml of tetrahydrofuran and 23.4 ml (150 mmol) of β-pinene and placed in a water bath at 25°C. Conversion to the trialkylborane was achieved by dropwise addition of 25.8 ml of a 2.00 *M* solution of borane (155 mmol of hydride) in tetrahydrofuran. The solution was stirred for 1h at 25°C, then 1 ml of methanol was added to destroy excess hydride. Solid iodine (28.0 g, 110 mmol) was added all at once, followed by dropwise addition of a solution of sodium hydroxide in methanol (37 ml of a 3 *M* solution, 110 mmol) over a period of 5 min. GC analysis of the reaction mixture with *n*-octane for internal standard indicated a 60% yield of *cis*-myrtanyl iodide. The reaction mixture was poured into 150 ml of water containing 3 g of sodium thiosulfate to remove excess iodine and the aqueous layer was extracted with two 100-ml portions of pentane. The combined pentane layers were dried with anhydrous sodium sulfate and distilled under vacuum. There was obtained 16.0 g (40% yield) of *cis*-myrtanyl iodide, bp 85° (0.8 mm), $n^{20}D$ 1.5467.

Iodination of Disiamylalkylboranes. The procedure is the same as described above for the reaction with other trialkylboranes, except the disiamylborane was used for the hydroboration of alkenes. The results are summarized in Table 3.

Stoichiometry and Rate Study for the Reaction of Tri-n-butyl- and Tri-*sec*-butylborane with Iodine in the Presence of Sodium Methoxide. A dry 50-ml flask equipped with septum inlet, magnetic stirrer and connecting tube was thoroughly flushed with nitrogen and maintained under a positive pressure of nitrogen through the duration of the reaction. Then, 10 mmol (2.42 ml) of tri-*n*-butylborane and 20 ml of tetrahydrofuran were added to the reaction flask. Next, 30 mmol (6.36 ml of 4.72 *M* solution in methanol) of sodium methoxide was sdded over 5 min *via* a hypodermic syringe. There was then added 10 mmol (2.11 ml) of *n*-decane as internal standard. Periodically, 1-ml aliquots of the reaction mixture were transferred to a septum-capped vial containing 1 ml of saturated aqueous sodium thiosulfate to decolorize excess iodine. Then 1 ml of pentane was added to the vial and the organic layer removed, dried over anhydrous potassium carbonate. The sample was then examined by GC to determine the extent of *n*-butyl iodide formation. A completely analogous method was followed for the reaction of tri-*sec*-butylborane. The results of this study are reported in Table 4.

General Study of the Sodium Methoxide-Induced Iodination of Trialkylboranes. In the apparatus described above were placed 20 ml of tetrahydrofuran and 30 mmol of the desired olefin. Hydroboration of the olefin was accomplished by cooling the reaction flask to 0°C, followed by the dropwise addition of 10 mmol (10.2 ml) of neat borane-methyl sulfide over 2 min. After stirring an additional 1-2 h at room temperature, 0.1 ml of absolute methanol was added to destroy residual traces of hydride. The addition of iodine, sodium methoxide, and internal standards was the same as described above. After reacting for the times indicated in Table 5, enough saturated aqueous sodium thiosulfate was added to decolorize excess iodine. The reaction mixture was extracted with 20 ml of pentane and the organic layer removed and dried over anhydrous potassium carbonate before GC analysis. The results are found in Table 5. The presence of methyl sulfide (from borane-methyl sulfide) in the reaction mixture was found not to have a deleterious effect on the reaction. Hydroboration-iodination of cyclopentene employing borane-tetrahydrofuran gave virtually the same yield (63%) of cyclopentyl iodide as the procedure employing borane-methyl sulfide (64%).

Conversion of Methyl 10-Undecenoate into Methyl 11-Iodoundecanoate via Hydroboration-Iodination. A dry 500-ml flask equipped as above was flushed with dry nitrogen and maintained under a static pressure of the gas until workup. The flask was charged with 100 ml of dry tetrahydrofuran and 150 mmol (33.7 ml) of methyl 10-undecenoate and cooled to 0°C in an ice bath. Conversion of the trialkylborane was achieved by the dropwise addition of 50 mmol (5.10 ml) of neat borane-methyl sulfide over 40 min, followed by stirring at room temperature for 1 h. Then 1 ml of absolute methanol was added to destroy traces of residual hydride. Next, 150 mmol (38.1 g) of iodine was added all at once under a blanket of nitrogen, followed by dropwise addition of 150 mmol (31.8 ml of a 4.72 *M* solution) of sodium methoxide in methanol over a peroid of 10 min. After the reaction mixture was allowed to stir 24 h, a saturated aqueous sodium thiosulfate solution was poured into the reaction mixture until the excess iodine was decolorized. The reaction mixture was extracted with 100 ml pentane and the organic layer removed and dried over anhydrous magnesium sulfate. Distillation under vacuum gave 33.1 g (68%) of methyl 11-iodoundecanoate; bp 139-141°/0.15 mm; $n^{20}D$ 1.4856. GC analysis revealed the compound was about 99% pure. The ^1H NMR spectra showed absorption at δ 3.58 (s, 3H, CH_3COO-), 3.18 (t, 2H, ICH_2-), 2.25 (t, 3H,-CH_2CO_2-) and 1.1-2.1 (broad singlet, 16H, -$(CH_2)_8$-). The low resolution mass spectra showed a weak parent ion at m/e 326. The high resolution mass spectra indicated a peak at 295.053 corresponding to *p*-OCH_3. Calcd: m/e 295.052.

Reaction of Tri-*exo*-norbornylborane with Iodine and Sodium Hydroxide. Reaction of Tri-*exo*-norbornylborane (30 mmol) was prepared exactly as described above, and after hydroboration was complete, 0.25 ml of absolute methanol was added to destroy residual traces of hydride. While flushing the reaction apparatus with nitrogen, the connecting tube was temporarily removed and 22 mmol (5.6 g) of iodine was added all at once. Then 22 mmol (7.4 ml of a 3 *M* solution in methanol) of NaOH was added dropwise over 10 min at room temperature. Enough saturated aqueous sodium thiosulfate was added to decolorize the excess iodine and *n* -decane was added as an internal standard. GC analysis indicated the formation of 9.81 mmol of 2-iodonorbornane. The product consisted of 75% *endo*- and 25% *exo*-2-iodonorbornane by GLC and ^1H NMR analysis. Product identification was established by comparison with an authentic sample of pure *exo*-2-iodonorbornane.

Preparation of *endo*-2-Iodonorbornane via Hydroboration-Iodination of Norbornene. A 1000-ml flask with septum inlet, magnetic stirrer, and connecting tube was charged with 300 mmol (28.2 g) of norbornene and flushed with nitrogen. Then, 200 ml of tetrahydrofuran was added and the reaction mixture cooled to 0°C. Hydroboration was achieved by the dropwise addition of 100 mmol (41ml of a 2.44 *M* solution in tetrahydrofuran) of borane. After stirring an additional hour at room temperature, 1 ml of absolute methanol was added to destroy residual traces of hydride (little hydrogen was evolved). The reaction apparatus was completely covered in aluminum foil and cooled to 0°C. Iodine, 220 mmol (56 g) was added all at once under a blanket of nitrogen, and 220 mmol (46.5 ml of a 4.72 *M* solution of methanol) of sodium methoxide was added dropwise over 10 min *via* syringe. Immediately, 100 ml of saturated aqueous sodium thiosulfate was added to decolorize excess iodine. The reaction mixture was then extracted with 3 x 50-ml pentane and the organic layers removed and dried over anhydrous potassium carbonate. The volatile components were removed *via* aspirator vacuum and the residual material distilled to give 17.2 g (78% based on one norbornyl group) of 2-iodonorbornane; bp 54-55° at 1.8 mm. Analysis by ^1H NMR indicated that the product consisted of 80% *endo*- and 20% *exo*-2-iodonorbornane.

To remove the small amount of *exo*-isomer, the mixture of 2-iodonorbornanes was refluxed for 3 h in 80% aqueous methanol (v/v) containing 5 g of potassium carbonate. (The *exo*-isomer, was converted to 2-methoxynorbornane.) Then 100 ml of pentane was added and the organic layer removed and dried over anhydrous potassium carbonate. Distillation gave 12.0 g of *endo*-2-iodonorbornane; bp 51.5-52.0° at 1.2 mm, $n^{20}D$ 1.5650. Analysis by ^1H NMR indicated that the material was 100% *endo*-. The compound showed resonance at δ 4.20 (1H, multiplet, C-2 methine) and 1.0-2.6 (10H, multiplet). The infrared spectra is nearly identical to the *exo*-isomer with only minor difference in the 11-13 μ region. The mass spectra shows the parent ion at m/e 222.

Reaction of B-Methoxy-9-borabicyclo[3.3.1]nonane with Iodine and Sodium Methoxide. A 100-ml flask equipped with magnetic stirrer, septum inlet, and connecting tube was flushed with nitrogen and charged with 10 ml of tetrahydrofuran and 10 mmol (1.60ml) of *B*-methoxy-9-borabicyclo[3.3.1]nonane. After cooling to 0°C, 10 mmol (2.54g) of iodine was added all at once while flushing the system with nitrogen. Then 10 mmol (2.12 ml of a 4.72 *M* solution in methanol) of sodium methoxide was added dropwise over 10 min.. After stirring an additional 2 h, the iodine color had disappeared. At this time, *n*-dodecane was added as internal standard and the mixture oxidized by addition of 10 ml of 6 *M* aqueous sodium hydroxide and dropwise addition of 4 ml of 30% hydrogen peroxide. After stirring at 40-50° for 1 h, the mixture was cooled to room temperature and the aqueous layer was saturated with potassium carbonate. The organic layer was removed, dried over anhydrous potassium carbonate, and analyzed by GC. There was formed 6.12 mmol of 9-oxabicyclo[3.3.1]nonane, 1.23 mmol of *cis*-bicyclo[3.3.0]octan-1-ol, and 0.91 mmol of *cis*-1,5-cyclooctanediol. The products were identified by coinjection on two different columns with authentic samples available from a previous study.

In a nearly identical experiment, 20 ml of water was substituted for the sodium methoxide. No decolorization of the iodine was observed in two weeks.

In a third experiment, the reaction was conducted with 10 mmol *B*-methoxy-9-borabicyclo[3.3.1]nonane, 10 mmol sodium methoxide and only 5 mmol of iodine. Following oxidation, 4.2 mmol (84%) of 9-oxabicyclo[3.3.1]nonane, 0.7 mmol *cis*-bicyclo[3.3.0]octan-1-ol, and 1.7 mmol of *cis*-1,5-cyclooctanediol were observed. In this case, iodine decolorization required 1 h.

In a final experiment, 15 mmol of *B*-methoxy-9-borabicyclo[3.3.1]nonane, 15 mmol iodine, and 15 mmol sodium methoxide were reacted for 2 h. Instead of oxidation, 30 mmol of diethanolamine was added. A white precipitate immediately formed and the material was filtered and recrystallized from tetrahydrofuran to give 3.1 g (58%) of the crystalline compound (5), mp 148-153°. The compound was reasonably air-stable, insoluble in carbon tetrachloride, chloroform, acetone, and slightly soluble in dimethyl sulfoxide and tetrahydrofuran. Addition of methanolic silver nitrate to a solution of 5 in tetrahydrofuran gave light-sensitive creamy yellow precipitate assumed to be silver iodide. The infrared spectra (incomplete) showed strong absorption at μ 3.18 (N-H), 3.5-3.55 (C-H), 6.80 (C-H), and many medium absorption from μ 7.8-13.6. The mass spectrum did not show a parent ion at m/e 352. The most intense peak was at m/e 192.

Anal. Calcd. for $C_{12}H_{23}BINO_2$: C, 41.06; H, 6.60. Found: C, 41.08; H, 6.80.

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