8 (meso), 74128-17-9; 8 (*dl*), 74219-19-5; **9**, 74128-18-0; **10**, 17940-88-4; **11**, 18163-07-0; **12**, 40965-54-6; **13**, 74128-19-1; **14**, 74128-20-4; **15**, 74128-21-5; **16**, 72610-07-2; **17**, 17680-01-2; **18**, 74128-22-6; **19**, 18182-10-0; **20** (meso), 74128-23-7; **20** (*dl*), 74143-39-8; **21** (meso), 74128-24-8; **21** (*dl*), 74128-25-9; **22**, 74128-26-0; **23**, 74128-27-1; **24**, 762-72-1; **25**, 18546-69-5; **26**, 2917-47-7; **27**, 74128-28-2; **28**, 763-13-3; **29**, 74128-29-3; **30**, 18387-24-1; **31**, 2917-40-0; **32**, 74128-30-6; $Me_3SiCH(CH_3)B(OMe)_2$, 18603-92-4; $Me_3SiCH_2CH_2B(OMe)_2$, 18551-02-5; 9-BBN, 280-64-8; BH_3·THF, 14044-65-6; *cis*-1,5-cyclooctanediol, 23418-82-8; (1-chloroethyl)trimethylsilane, 7787-87-3; $B(OMe)_3$, 121-43-7; (−)-myrtanol, 473-01-8; propanoyltrimethylsilane, 30608-90-3.

A Mild and Convenient Procedure for Conversion of Alkenes into Alkyl Iodides via Reaction of Iodine Monochloride with Organoboranes

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Alkenes are rapidly converted to alkyl iodides under mild conditions via a hydroboration–iodination sequence which utilizes iodine monochloride as the iodinating agent. The iodination proceeds with inversion of configuration. A series of functionally substituted iodides was synthesized via the new procedure.

The iodination of organoboranes in the presence of strong bases results in the regio- and stereospecific introduction of iodine in high yields.[1-3] The utility of the

$$R_3B \xrightarrow[NaOCH_3]{I_2} 3RI$$

iodination reaction is due to the variety of functionally substituted organoboranes which are available via hydroboration.[1] The reaction is also important due to the variety of iodine containing radiopharmaceuticals which have been developed in recent years.[4-6]

The iodination reaction does, however, have two potential problems. The first is the necessity of using a strong base which could either react with sensitive functional groups in complex molecules or initiate dehydrohalogenation reactions. The second is the fact that one-half of the iodine molecule is lost as iodide which is not economical when radionuclides of iodine are employed.

We report that alkenes are rapidly converted to alkyl iodides under mild conditions via a hydroboration–iodination sequence which utilizes iodine monochloride as the iodinating agent.

$$RCH{=}CH_2 \xrightarrow{BH_3} \xrightarrow{ICl} RCH_2CH_2I$$

Results and Discussion

When trialkylboranes derived from the hydroboration of terminal alkenes are treated with iodine monochloride and methanolic sodium acetate, two of the three groups on boron react instantaneously.[7] In the case of trialkylboranes derived from internal alkenes, one of the three alkyl groups on boron rapidly migrates. These results parallel those obtained when organoboranes are treated with iodine in the presence of sodium hydroxide.[8,9]

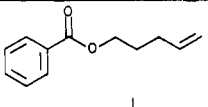
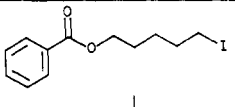
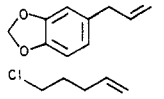
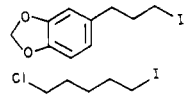
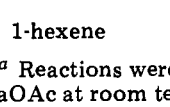
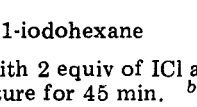
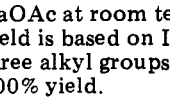
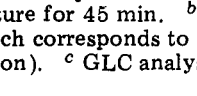
$$(RCH_2)_3B \xrightarrow[NaOAc/MeOH]{\text{excess ICl}} 2RCH_2I$$

Table I. Conversion of Trihexylborane *n*-Hexyl Iodide[a]

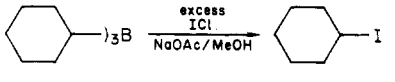
ratio of ICl/R_3B[a]	yield, %[c] 1:1 NaOAc/ R_3B[b]	2:1 NaOAc/ R_3B	3:1 $NaOAc/R_3B$
1	21	33	20[d]
2	34	58	65
3	30	59	66

[a] Reaction of trihexylborane (10 mmol) with ICl in THF (10 mL) at room temperature for 15 min. NaOAc added as 1.0 M solution in methanol. [b] Ratios refer to ratio of millimoles of reagents. [c] GLC yields. [d] In the presence of a large excess of sodium acetate, yields decrease.

Table II. Synthesis of Primary Iodides[a]

substrate	product	% yield (isolated)[b]
		88
		97
		75
		82
1-hexene	1-iodohexane	80[c]

[a] Reactions were run with 2 equiv of ICl and 3 equiv of NaOAc at room temperature for 45 min. [b] Percentage yield is based on ICl (which corresponds to two of the three alkyl groups on boron). [c] GLC analysis indicates 100% yield.



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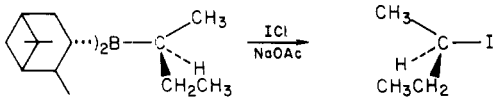
The reaction of iodine monochloride with optically active diisopinocampheyl-2-butylborane (obtained via the hydroboration of (*Z*)-2-butene with (+)-diisopinocampheylborane) produced (*R*)-2-iodobutane.[10] Thus the reaction



(92% optical purity) (87% optical purity)

proceeds via an inversion of configuration at the carbon attached to boron. This contrasts with the data gathered for the majority of organoborane reactions involving rupture of the carbon–boron bond but does coincide with the stereochemistry observed in the earlier bromination and iodination studies.[11,3]

A systematic investigation revealed that the presence of excess iodine monochloride does not result in increased yields. However, the presence of an extra equivalent of sodium acetate is advantageous. Excesses of sodium acetate greater than 1 equiv lead to diminished yields presumably due to secondary reactions of the product iodides. Representative data are presented in Table I.

We have subjected a variety of functionally substituted alkenes to the new hydroboration–iodination sequence. The results are summarized in Table II.

Experimental Section

Proton NMR spectra were recorded on a Varian Associates T-60 spectrometer. All chemical shifts are reported in parts per million downfield from Me_4Si. The optical rotations were measured with a Rudolph Instruments MP7 photoelectric polarimeter, using a sodium D lamp and a 10-mm cell.

All melting points and boiling points are uncorrected. The gas chromatography work was performed on a Varian Model 1700 dual column instrument with 6 ft × 0.25 in. 20% Carbowax C-20M on Chromsorb W and 6 ft × 0.25 in. 20% SE-30 on Chromsorb W.

Commercially available samples (Aldrich) of 1-hexene, cyclohexene, safrole, and methyl 10-undecenoate were distilled from $LiAlH_4$ or CaH_2 before use. 3-(*p*-Tolylthio)-2-methylpropene was prepared via a published procedure.[12] (−)-α-Pinene was prepared from (−)-β-pinene (Crosby Chemical Co.) by the method of Settine[13] and purified by spinning-band distillation, [α] −47.4° (92% optical purity).[13,14]

Hydroborations. General Procedure. The alkene (30 mmol) was dissolved in 5 mL of THF in a 100-mL, N_2-flushed, round-bottom flask equipped with magnetic stirrer, septum inlet, and reflux condenser. The solution was cooled to 0 °C and BH_3–THF (10 mmol, 5 mL of a 2 M solution) was added slowly via a syringe. The reaction mixture was heated to 50 °C, stirred for 1 h, and then cooled to room temperature.

Iodinations. General Procedure. Anhydrous methanol (1.0 mL) was added to the organoborane solution to destroy excess hydride. Methanolic sodium acetate (30 mL, 1.0 M) was added, followed by the dropwise addition of iodine monochloride (20 mmol, 3.2 g). The mixture was stirred for 45 min at room temperature and then poured into 100 mL of water. Sufficient aqueous sodium thiosulfate (1.0 M) was added to destroy any excess iodine monochloride and then the mixture was extracted with ether (3 × 30 mL). The combined ether layers were dried over anhydrous $MgSO_4$ and the ether was removed under reduced pressure. The products were isolated via column chromatography (alumina, mixed hexane eluant).

5-Benzoxy-1-pentene. Benzoyl chloride (0.2 mol, 23 mL) was added dropwise to a solution of 4-penten-1-ol (0.2 mol, 20 mL) in pyridine and stirred overnight at room temperature. The reaction mixture was poured into 100 mL of water and the organic layer separated. The product mixture was washed, sequentially, with dilute HCl, saturated aqueous Na_2CO_3, and water. The organic layer was dried over anhydrous Na_2CO_3 and the product distilled: bp 90–98 °C (1.0 mmHg); yield 26.9 g, (71%); NMR (neat) δ 1.5 (br m, 4, alkyl), 3.8 (t, 2, OCH_2), 4.6 (m, 2, $=CH_2$), 5.2 (m, 1, =CH), 7.3 (m, 5, Ar H).

5-Chloro-1-pentene. A solution of 4-penten-1-ol (0.15 mol, 15 mL) in 15 mL of ether and 15 mL of pyridine was added dropwise to a stirred solution of thionyl chloride (0.28 mol, 20 mL) in 15 mL of ether contained in a 100-mL flask fitted with a reflux condenser. The rate of addition was sufficient to maintain reflux. After addition of the alcohol, the ether was removed, additional thionyl chloride (0.07 mol, 5 mL) was added, and the mixture was stirred at 75 °C for 1.5 h. The cooled mixture was poured into water and the organic layer separated. The aqueous layer was extracted with ether (2 × 30 mL) and the organic layers were combined. The ether solution was dried over anhydrous Na_2CO_3, the ether was removed under reduced pressure, and the product was distilled: bp 45 °C (100 mmHg); yield 7.61 g (49%); NMR ($CDCl_3$) δ 2.1 (br m, 4, alkyl), 3.5 (t, 2, CH_2Cl), 5.0 (m, 2, $=CH_2$), 5.7 (m, 1, CH=).

1-Iodohexane. 1-Hexene (30 mmol, 2.59 g) was hydroborated with BH_3–THF (10 mmol) and then iodinated with iodine monochloride (20 mmol). The yields were determined via GLC analyses. The product exhibited spectral characteristics in accord with authentic samples.

Iodocyclohexane. Cyclohexene (3 mmol, 0.3 mL) was hydroborated with BH_3–THF (1 mmol) and then reacted with iodine monochloride (2 mmol). The yields were determined via GLC analyses. The products exhibited spectral characteristics in accord with authentic samples.

(*R*)-(−)-2-Iodobutane. A solution of diisopinocampheyl-2-butylborane (0.68 M) was prepared in diglyme according to Brown's procedure.[14,15] To 100 mL of this solution were added iodine monochloride (50 mL, 2.8 M, diglyme solvent) and methanolic sodium acetate (100 mL, 1.4 M) simultaneously over a period of 15 min. (The additions, and the subsequent manipulations, were carried out in a darkened laboratory to prevent racemization of the product.) After the additions were complete, the mixture was stirred for 1 h at 25 °C. The mixture was added to 300 mL of ice water containing 0.3 g of sodium thiosulfate. The product was extracted with pentane (6 × 50 mL); the combined pentane layers were extracted with ice water (5 × 50 mL) (to remove diglyme) and then dried over anhydrous magnesium sulfate. After removal of the solvent at 760 mmHg, fractional distillation yielded pure (*R*)-(−)-2-iodobutane: bp 45 °C (60 mmHg); $[\alpha]_D$ 27.95° (87% optical purity);[10] NMR ($CDCl_3$) δ 0.95 (t, 3, CH_3), 1.64 (q, 2, CH_2), 1.84 (d, 3, CH_3), 4.08 (sextuplet, 1, CHI).

1-Benzoxy-5-iodopentane. 5-Benzoxy-1-pentene (30 mmol, 5.7 g) was hydroborated with BH_3–THF (10 mmol) at 0 °C for 1 h. Iodine monochloride (20 mmol, 1.0 mL) was added at room temperature; after 45 min, the product was isolated via chromatography (alumina): yield 5.63 g (88% based on ICl); bp 125 °C (0.25 torr); *m/e* 318.1 (calcd 318.2); IR (neat) 1705 (C=O), 1205 (CI) cm^{-1}; NMR (neat) δ 1.7 (br envelope, 6, alkyl), 3.0 (t, 2, CH_2I), 4.2 (t, 2, CH_2O), 7.6 (m, 5, Ar H).

3-(*p*-Tolylthio)-2-methyl-1-iodopropane. 3-(*p*-Tolylthio)-2-methylpropene (30 mmol, 5.35 g) was hydroborated with 10 mmol of BH_3–THF at 0 °C. Iodination was carried out at room temperature; after 45 min, the product was isolated via chromatography: yield 5.94 g (97%); bp 110 °C (0.1 torr); *m/e* 306.2

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(15) (*Z*)-2-Butene was hydroborated with (+)-diisopinocampheylborane prepared via the hydroboration of (−)-α-pinene, $[\alpha]_D$ 47.0° (92% optical purity); see ref 13.

(calcd 306.2); IR (neat) 1195 (CI), 800 (Ar H) cm^{-1}; NMR (neat) δ 1.0 (d, 3, CH_3), 1.6 (m, 1, CH), 2.2 (s, 3, $ArCH_3$), 2.7 (d, 2, CH_2I), 3.2 (d, 2, SCH_2), 7.0 ($A'_2X'_2$, 4 Ar H).

3-(3,4-(Methylenedioxy)phenyl)-1-iodopropane. Safrole (30 mmol, 4.9 g) was hydroborated with 10 mmol of BH_3-THF at 0 °C for 1 h. Iodination was carried out at room temperature. After 45 min, the product was isolated via chromatography: yield 4.32 g (75%); bp 105 °C (0.08 torr); *m/e* 290.2 (calcd 290.1); IR (neat) 1490 (C=C), 1440 (C=C), 1250 (OAr), 1210 (CI), 1040 (CH_2-O), 940 (ArH), 800 (ArH) cm^{-1}; NMR (neat) δ 2.0 (m, 2 H, CH_2), 2.6 (t, 2, CH_2I), 3.1 (t, 2, $ArCH_2$), 5.8 (s, 2, OCH_2O), 6.6 (s, 3, Ar H).

5-Chloro-1-iodopentane. 5-Chloro-1-pentene (30 mmol, 3.1 g) was hydroborated with 10 mmol of BH_3-THF at 0 °C for 1 h. Iodination was carried out at room temperature. After 45 min, the product was isolated via chromatography: yield 3.79 g (82%); bp 30-31 °C (0.1 torr); *m/e* 232.3 (calcd 232.5); IR (neat) 1300 (CCl), 1200 (CI) cm^{-1}; NMR ($CDCl_3$) δ 1.8 (m, 6, $CH_2CH_2CH_2$), 3.2 (t, 2, CH_2I), 3.6 (t, 2, CH_2Cl).

Acknowledgment. We thank the National Institutes of Health (1-R01-GM 25817-02) for support of this research.

Registry No. Iodine monochloride, 7790-99-0; 5-benzoxy-1-pentene, 29264-40-2; benzoyl chloride, 98-88-4; 4-penten-1-ol, 821-09-0; 5-chloro-1-pentene, 928-50-7; 1-iodohexane, 638-45-9; 1-hexene, 592-41-6; iodocyclohexane, 626-62-0; cyclohexene, 110-83-8; *R*-(-)-2-iodobutane, 22156-92-9; diisopinocampheyl-2-butylborane, 26673-63-2; 1-benzoxy-5-iodopentane, 74203-20-6; 3-(*p*-tolylthio)-2-methyl-1-iodopropane, 74203-21-7; 3-(*p*-tolylthio)-2-methylpropene, 54844-24-5; 3-(3,4-(methylenedioxy)phenyl)-1-iodopropane, 74203-22-8; safrole, 94-59-7; 5-chloro-1-iodopentane, 60274-60-4; trihexylborane, 1188-92-7.

Selectivity in the Oxidation of Branched Alkenes by Thallic Salts[1]

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The effects of structure, temperature, and reaction medium on the selectivity of the oxidation of branched alkenes by thallic salts has been investigated. With increasing temperature the quantity of ketones decreases in the case of the oxidation of internal alkenes, while in the case of the oxidation of $R^1R^2C{=}CH_2$ alkenes the quantity of carbonyl compounds increases. The isoselective temperature for oxidation of internal alkenes has been found, and for $R^1R^2C{=}CH_2$ alkenes "inverse selectivity temperatures" have been determined. By use of the linear free-energy relationship, separation of the polar and steric effects has been carried out; it was found that steric effects had an influence on the ratio of ketone and aldehyde formation in the oxidation of $R^1R^2C{=}CH_2$ alkenes in an aqueous medium, while in a methanolic medium polar effects were decisive. Polar effects were also decisive in determining the ratio of carbonyl compounds and diols in the oxidation of both types of branched alkenes. The total yield of carbonyl compounds is higher for oxidation in aqueous medium.

The pyrolysis of gasoline to ethylene and propylene appears to be an attractive base process for production of carbonyl compounds. By oligomerization of its components it is possible to obtain branched alkenes and by their oxidation branched and unbranched ketones and aldehydes.

In the case of branched alkenes, their oxidation by palladium(II) salts (Wacker process) is complicated with fast isomerization of the alkene and, in addition, with formation of relatively stable π complexes of branched alkenes with palladium(II) salts.[2] The relatively high redox potential of thallic salts provides an advantage for oxidation, allowing faster product formation without isomerization of double bonds.[3]

Two characteristic products are formed by the oxidation of alkenes by thallic salts. One, invariably, was a vicinal diol, with the carbon skeleton of the starting alkene, and the other was a carbonyl compound (aldehyde and/or ketone) whose character was given by the structure of the starting alkene. By oxidation of terminal *n*-alkenes only ketones are formed[4] and in the case of internal alkenes isomeric ketones.[5] In the oxidation of $R^1R^2C{=}CH_2$ alkenes the significant difference is the fact that an aldehyde is formed as well.[6]

More recently we discovered an important effect of medium and structure on the selectivity of the oxidation of terminal *n*-alkenes.[7] In the case of branched alkenes a more complete study of the effects of experimental conditions and structure on selectivity has been lacking so far. This is the aim of this paper.

Experimental Section

Materials. The oxidation solution of thallium(III) sulfate was prepared as described previously.[8] The thallium concentration was determined by titrating the iodine liberated by reaction of Tl^{3+} with KI with a defined solution of $Na_2S_2O_3$.[9]

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