15 min. The resulting yellow solution was concentrated by distilling off part of the $CH_2Cl_2$ at 0 °C (100 torr) until finally the dioxetane distilled with the residual solvent between 0 °C (50 torr) and 20 °C (10 torr). There was obtained 2 mL of $CH_2Cl_2$ solution which contained ca. 60 mg (ca. 3%) of dioxetane **1f** in a purity of higher than 90% by NMR. Dioxetane content was estimated by iodometric titration and NMR. Attempts to isolate the compound in substance failed. When all the solvent was removed, the dioxetane decomposed vigorously even at −20 °C. The dioxetane was taken up in the appropriate solvent (toluene or benzene), and the rest of the $CH_2Cl_2$ was removed at 0 °C (10 torr) by distillation. TLC on silica gel with $CH_2Cl_2$ as eluate showed a peroxidic spot with KI in HOAC and a white spot with iodine vapor at $R_f$ 0.60. $^1H$ NMR ($CDCl_3$ at −40 °C; 400 MHz): δ 1.6 (d, $J$ = 6.3, 3 H, $CH_3$); 5.16 (dd, $J$ = 8.4, 4.5; 1 H, $H^4$), 5.30 (dd, $J$ = 7.2, 4.5; 1 H, $H^4$'), 5.84 (qdd, $J$ = 8.4, 7.2, 6.3; 1 H, $H^3$). $^{13}C$ NMR ($CDCl_3$ at −40 °C; 100 MHz): δ 20.91 (q), 78.58 (t), 79.73 (d).

**1,2-Dioxetane (1g).** A Heterogeneous mixture of 2.82 g (20.0 mmol) of bromo-2-hydroperoxyethane (**2g**) in 20 mL of $CH_2Cl_2$ and 8.00 g (143 mmol) of KOH in 20 mL of $H_2O$ was stirred vigorously for 15 min. Distillation of the $CH_2Cl_2$, at first at 0 °C (100 torr) and subsequently at 20 °C (10 torr), gave 20 mL of 0.01 M dioxetane solution (yield ca. 1% by iodometry). Attempts to concentrate the solution failed because the dioxetane was either too volatile or thermally too labile. All subsequent measurements were done with $CH_2Cl_2$ solutions of the dioxetane **1g**. TLC on silica gel with $CH_2Cl_2$ as eluate showed a peroxidic spot with KI in HOAC and a white spot with iodine vapor at $R_f$ = 0.58. $^1H$ NMR ($CD_2Cl_2$ at −40 °C; 400 MHz): δ 5.38 (s); disappeared on warmup to 40 °C within 1 h; new signal at δ 9.60 (s). $^{13}C$ NMR ($CD_2Cl_2$ at −40 °C; 100 MHz): δ 76.14; disappeared on warmup to 40 °C within 1 h.

**Chemiluminescence Measurements.**[17] The glass vial was charged with 3.0 mL of the fluorescer solution or tolune, placed into the cell compartment, and allowed to equilibrate thermally for ca. 10 min. A 10-μL aliquot of the dioxetane solution (concentration determined by weighing or iodometric titration) was introduced by means of a calibrated glass pipet. The use of Hamilton syringes must be avoided since the metallic parts cause decomposition, especially in cases of the less stable dioxetanes. The measurements for the determination of excitation yields were performed at 343 K in the case of dioxetanes **1a-e** and at 330 K for **1f** and **1g**. The chemiluminescence signal (in volts) was recorded vs. time. From the first-order decays the rate constants ($k_{obsd}$) and the initial intensities ($I_0$) were calculated by linear and nonlinear regression. The voltage signals ($A_0$) were converted into luminescence units (einstein/s·L) using the experimentally established conversion factor (7.6 ± 0.4) × $10^{-11}$ (einstein/s·L·V). The Hastings-Weber scintillation cocktail[26] served as calibration standard of the light flux. A correction of the light intensities for relative spectral response of the phototube was not necessary since the fluorescence maxima of POPOP-PPO and DBA and DPA are similar.[18a] The excitation yields were determined from these data by means of Stern-Volmer plots.[15,31] The data are collected in Table III.

For the determination of activation parameters, runs at several different temperatures were carried out by direct chemiluminescence for dioxetanes **1a** to **1f** and by DBA-enhanced chemiluminescence for **1g**. The data were processed by the isothermal kinetic method[14] from the $k_{obsd}$ values or by the "temperature jump" chemiluminescence method.[15,16]

**Chemical Titrations.** Separate stock solutions of ca. 0.3 M dioxetane and of ca. 0.1 M of BDT or of BND in benzene were prepared. By means of calibrated glass pipets, from appropriate stock solutions 50-μl aliquots of the dioxetane and 10-100-μl aliquots of the chemical titrant (BDT or BND) were transferred into a set of eight 1-mL glass ampules and when necessary diluted with benzene to a total volume of 150 μL. After sealing, the ampules were heated to 353 K in a thermostated bath for ca. 6 half-lifes of the dioxetane. For the quantitative GC analyses, to 100 μL of the above decomposed solution were added either 10 μL for singlet titration[20] or 50 μL for triplet titration[21] of a 5 × $10^{-3}$ M solution of 2-methylnaphthalene as internal standard. The excited-state yields were calculated from the GC data with the help of the Stern-Volmer plots.

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# Solvent and Counterion Effects on the Stereochemistry and the Competition between Electron-Transfer and $S_N2$ Mechanisms in the Reactions of (Trimethylstannyl)alkalies with Bromides

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**Abstract:** Reactions of (trimethylstannyl)alkalies ($Me_3SnM$, M = Li, Na, K) with bromides have been studied in solvents including tetraglyme and tetrahydrofuran, in mixtures of tetrahydrofuran with ether and with benzene, and with added crown ether, 18-C-6. Product distributions and stereochemistry have been examined. Dicyclohexylphosphine (DCPH) was used as a trap for intermediate free radicals to detect participation of an electron-transfer (ET) process which occurs in competition with the $S_N2$ mechanism. The effect of the nature of the cation on the course of the reaction depends upon the medium. The effect is not usually in simple relation to the size of the cation. The $S_N2$ mechanism competes most effectively in a good coordinating medium but is not the exclusive one with 2-bromooctane even in THF containing 18-C-6. In the poorly coordinating mixed solvents, 2-bromooctane reacts virtually exclusively by an ET process. Even the primary 1-bromooctane and 6-bromo-1-hexene show ET contributions in the mixed solvents of low cation coordinating ability. In the latter case the ET component was established both by DCPH trapping experiments and by formation of the cyclic substitution product, (cyclopentylmethyl)trimethylstannane. The mechanistic implications of these and other observations are examined.

Reactions of (triorganostannyl)alkalies with organic halides, eq 1, have attracted increasing attention in recent years. This is due in part to their usefulness in the synthesis of tetraorganostannanes. However, reaction 1 often shows unexplained

$$R_3SnM + R'X \rightarrow R_3SnR' + MX \quad (1)$$

behavior with respect to yields and stereochemistry; this has aroused curiosity concerning the mechanisms which may account for such behavior. The several mechanisms which have been considered and/or proposed fall into three general classes: direct $S_N2$ substitution,[1-6] initial electron transfer (ET) from $R_3SnM$

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Table I. Effects of Counterion and DCPH on Product Distributions from the Reaction of $Me_3SnM$ with 2-Bromooctane in THF[a]

| entry | M | [R-Br], M | addend, M | % $C_8$[b] | % 2-$Me_3SnC_8H_{17}$ | % $C_{16}H_{34}$ | % yield |
|---|---|---|---|---|---|---|---|
| 1 | Li | 0.11 | | 9.2 (±0.4) | 81 (±1.0) | 2.5 (±0.0) | 93 |
| 2 | Li | 0.11 | DCPH (0.80) | 63 (±1.0) | 23 (±1.5) | | 86 |
| 3 | Li[c] | 0.10 | | 12 (±0.0) | 81 (±1.0) | 1.5 (±0.15) | 95 |
| 4 | Li[c] | 0.10 | DCPH (1.20) | 66 (±1.0) | 29 (±1.0) | | 95 |
| 5 | Na | 0.16 | | 26 (±0.0) | 60 (±0.0) | 8.0 (±0.0) | 94 |
| 6 | Na | 0.16 | DCPH (1.0) | 85 (±1.0) | 10[d] (±0.0) | | 95 |
| 7 | Na | 0.17[e] | DCPH (1.0) | 82 (±2.0) | 11 (±0.0) | | 93 |
| 8 | K | 0.11 | | 3.7 (±0.0) | 84 (±1.5) | | 88 |
| 9 | K | 0.12 | DCPH (1.0) | 76 (±2.0) | 23 (±0.75) | | 99 |

[a] $Me_3SnM$, prepared from $Me_3SnSnMe_3$ and the metal (100% excess) added to bromooctane at 0 °C except where noted; yields based on bromooctane used. [b] $C_8$ = octane plus octenes. [c] $Me_3SnLi$ prepared from $Me_3SnSnMe_3$ and methyllithium. [d] When [DCPH] was 2.9 M 2-$Me_3SnC_8H_{17}$ was 2.9%. [e] Bromooctane added to $Me_3snNa$.

to the halide, leading to free radical intermediates,[7-13] and initial halogen–metal exchange, leading to carbanion intermediates.[14-17] Evidence for each of these mechanisms has been obtained. Our interests have been concerned with establishing the effects of reactant structures and other reaction parameters on the mechanisms and with sorting out contributions from competing mechanisms.[3,10,14,16-18] It is hopes that the results of such studies can then be used in planning approaches to examination of the individual mechanisms in detail.

As one probe for the ET mechanism we used dicyclohexylphosphine (DCPH) to trap alkyl radicals. It is a highly efficient hydrogen atom donor due to its low P–H bond dissociation energy (ca. 77 kcal/mol);[10] its p$K_a$ of 35.7 would preclude reaction with (trimethylstannyl)sodium (p$K_a$ ca. 25). This has been established by an experiment in tetrahydrofuran (THF) as the solvent.[19] These properties, with the proviso that DCPH has no significant effect on the rates of competing reactions, could lead to diversion of intermediate free radicals to reduction products (R'H) by abstraction of hydrogen atoms from the phosphine. The yield of reduction product would provide a measure of the contribution of the ET mechanism if trapping occured with unit efficiency. As an example, the reaction of $Me_3SnNa$ with 2-bromooctane in THF at 0 °C was diverted from predominant substitution (eq 1) to reduction if 1.25 M DCPH was present in the reaction mixture. We, therefore, concluded that the major reaction course involved ET and that no more than a minor fraction of the subsitution product was formed by the $S_N2$ mechanism under the conditions used.[10] In contrast, San Filippo, in a study of the stereochemistry of the same reaction found up to 100% inversion, depending upon reaction conditions.[6] This led him to conclude that the use of the phosphine introduces a substantial perturbation on the mechanism and that results such as ours could not be considered to provide a reliable indication of the mechanism(s) occurring in its absence. If this is correct, then the discrepancy between the two sets of results implies that DCPH can have a profound effect indeed in changing the mechanism from $S_N2$ to ET. This, in itself, would be worthy of examination.

Table II. Effects of Counterion and DCPH on the Stereochemistry of Trimethyl-2-octylstannane from the Reaction of $Me_3SnM$ with (+)-2-Bromooctane in THF[a,b]

| entry | M | addend, M | $[\alpha]^{22}_D$ of 2-$Me_3SnC_8H_{17}$[c] cor[d] | % ee[e] |
|---|---|---|---|---|
| 1 | Li | | −20.69° (±0.21) | 75.5 |
| 2 | Li | DCPH (1.23) | −24.29° (±0.68) | 88.6 |
| 3 | Li | DCPH (1.95) | −27.17° (±0.36) | 99.2 |
| 4 | Li[f] | | −18.30° (±0.30) | 66.8 |
| 5 | Li[f] | DCPH (1.20) | −25.87° (±0.49) | 94.4 |
| 6 | Na[g] | | −13.48° (±0.30) | 49.2 |
| 7 | Na | | −15.54° (±0.10) | 56.7 |
| 8 | Na | DCPH (1.28) | −16.18° (±0.12) | 59.1 |
| 9 | K | | −17.20° (±0.10) | 62.8 |
| 10 | K | DCPH (1.28) | −26.92° (±0.04) | 98.2 |

[a] Reaction conditions as for Table I. [b] Specific rotation $[\alpha]^{22}_D$ of (+)-2-bromooctane is in the range of 29.87–37.03°. [c] Observed specific rotation of $[\alpha]^{22}_D$ of (−)-2-$Me_3SnC_8H_{17}$ is in the range of 9.43–23.4°. [d] Based on $[\alpha]^{22}_D$ −27.40°; see Experimental Section. [e] Excess of inverted product. [f] $Me_3SnLi$ prepared from methyllithium and $Me_3SnSnMe_3$. [g] Bromooctane added to $Me_3SnNa$.

The reaction of $Me_3SnM$ with bromides in particular appears to be sensitive to certain reaction parameters, and this has led to some confusion and controversy concerning the mechanisms involved. We have focused our attention in this study on careful examination of the effects of selected parameters, specifically counterion, medium, and the presence of dicyclohexylphosphine, on the product distribution and stereochemistry of the reaction. Substrates used were 2-bromooctane, 6-bromo-1-hexene, and 1-bromooctane.

## Results

Because the reactions can be highly sensitive to variations in certain parameters, they were conducted under carefully controlled conditions; the result was good reproducibility. (Trimethylstannyl)alkalies were prepared in tetrahydrofuran (THF) by the reaction of hexamethyldistannane with the metal at 0 °C and usually used within 2 h. If solutions were stored at −10 °C for 48 h, no significant decrease in concentration was observed and the results were the same as those obtained with freshly prepared material. In order to reveal the range of experimental errors, all

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Table III. Effects of Counterion and DCPH on Product Distribution from the Reaction of $Me_3SNM$ with 2-Bromooctane in TG[a,b]

| entry | M | [R-Br], M | addend, M | % $C_8$ | % 2-$Me_3SnC_8H_{17}$ | % yield |
|---|---|---|---|---|---|---|
| 1 | Li | 0.15 | | 6.7 (±0.15) | 80 (±0.0) | 87 |
| 2 | Li | 0.17 | DCPH (1.30) | 38 (±2.0) | 49 (±1.0) | 87 |
| 3 | Na | 0.15 | | 1 (±0.0) | 90 (±0.0) | 91 |
| 4 | Na | 0.17 | DCPH (0.90) | 34 (±2.0) | 56 (±0.0) | 90 |
| 5 | K | 0.13 | | 6.0 (±1.0) | 83 (±2.0) | 89 |
| 6 | K | 0.13 | DCPH (1.30) | 36 (±2.5) | 57 (±1.0) | 93 |

[a,b] Reaction conditions as for Table I.

experiments were repeated one or more times with separate preparations of stannylalkali. Experiments with 2-bromooctane to determine product distributions (trimethyl-2-octylstannane, octane, bioctyl, and octenes) were conducted with racemic bromide, and the stereochemistry was examined using (+)-2-bromooctane. The optical rotation assumed for pure 2-bromooctane was that given in the literature,[20] and that for trimethyl-2-stannyloctane was determined by reaction of the tosylate with (trimethylstannyl)lithium in tetraglyme (2,5,8,11,1-pentaoxapentadecane) (TG). Our value was proven to lie between two previously reported values.[6b,12] In all experiments, except where noted, $Me_3SnM$ was added in 100% excess over that of the bromide in order to assure complete consumption of the latter.

In Table I are gathered results on the effect of counterion on product distribution in the absence and presence of dicyclohexylphosphine (DCPH) in THF at 0 °C. In control experiments conducted in the absence of DCPH, yields of substitution product were higher with $Me_3SnLi$ and $Me_3SnK$, both near 83%, than with $Me_3SnNa$ (60%) (entries 1, 3, 5, and 8, Table I). This was also true in the presence of DCPH (ca. 23% vs. 10%; entries 2, 9, and 6). Comparison of entry 6 with entry 7 shows no effect of the order of addition of the reactants on product distribution with $Me_3SnNa$. They also agree well with our earlier trapping experiments[10a,c] and those of San Filippo and Silverman.[6] In the experiments of entries 3 and 4, the $Me_3SnLi$ was prepared by the reaction of $(Me_3Sn)_2$ with *n*-butyllithium to test the effect of method of preparation on the behavior. It can be seen that the results agree well with those of entries of 1 and 2.

Stereochemical studies were conducted using (+)-2-bromooctane under the same conditions as those of the preceding experiments. It was first established that when excess bromide was used in the reaction with $Me_3SnNa$, the unreacted bromide showed no change in optical rotation. The results for the control experiments without added DCPH as seen in Table II are consistent with those of Table I. Higher degrees of inversion (% ee) resulted with $Me_3SnLi$ (75%) and $Me_3SnK$ (63%) than with $Me_3SnNa$ (56%): the trend is not the normal monotonic one—Li, Na, K. Reversing the order of mixing reactants (entry 6 vs. entry 7) changed % ee by about 7%, just outside the usual experimental error of ±2%. This difference is intermediate between the large[6,7,9] and negligible effects[12] of order of mixing reagents reported by others but nearer to the latter. The experiments of entries 4 and 5 were conducted with stannyllithium prepared by the $(Me_3Sn)_2$/*n*-BuLi method. Agreement with the results of entries 1 and 2 is fair, and the trends are clearly parallel.

A very probable source of the difference in behavior of $Me_3SnNa$ on the one hand and $Me_3SnLi$ and $Me_3SnK$ on the other might lie in differences in degrees of aggregation in THF. In order to test this, experiments were conducted in the better cation coordinating solvent tetraglyme (2,5,8,11,14-pentaoxapentadecane) (TG) to parallel those in THF. Results obtained on product distributions are presented in Table III and those on stereochemistry in Table IV. In the control experiments, the yields of substitution product are seen to be higher (80–90%) than in THF for all three anionoids (entries 1, 3, and 5). In the presence of DCPH, the yields for $Me_3SnLi$ fell to 49%; for $Me_3SnNa$ and $Me_3SnK$ they fell to 56% and 57%, respectively (entries 2, 4, and 6). The % ee values in Table IV show 80%, 74%, and 81%, respectively, for the counterions $Li^+$, $Na^+$, and $K^+$ in the control experiments. In the presence of DCPH the substitution product

Table IV. Effects of Counterion and DCPH on the Stereochemistry of Trimethyl-2-octylstannane from the Reaction of $Me_3SnM$ with (+)-2-Bromooctane in TG[a,b]

| entry | M | addend, M | $[\alpha]^{22}_D$ of 2-$Me_3SnC_8H_{17}$ cor[d] | % ee[e] |
|---|---|---|---|---|
| 1 | Li | | −22.04° (±0.35) | 80.4 |
| 2 | Li | DCPH (1.30) | −26.77° (±0.24) | 97.7 |
| 3 | Na | | −20.33° (±0.26) | 74.2 |
| 4 | Na | DCPH (1.23) | −26.70° (±0.46) | 97.4 |
| 5 | K | | −22.23° (±0.47) | 81.1 |
| 6 | K | DCPH (1.40) | −27.51° (±0.30) | 100.4 |

[a] Reaction conditions as for Table II. [b] Specific rotation $[\alpha]^{22}_D$ of (+)-2-bromooctane is in the range of 38.87–37.03°. [c] Observed specific rotation of (−)-2-$Me_3SnC_8H_{17}$ is in the range of 17.06–23.64°. [d] Based on $[\alpha]^{22}_D$ −27.40°; see Experimental Section. [e] Excess of inverted product.

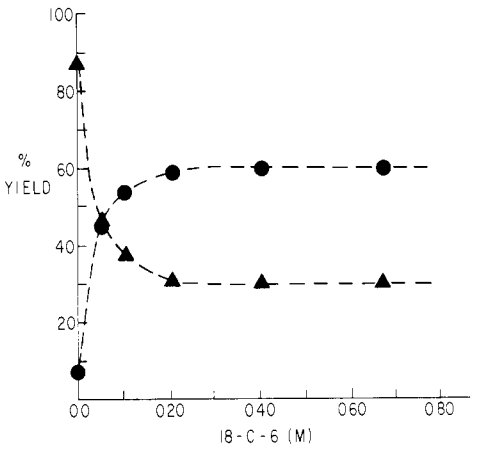


Figure 1.

was formed with essentially complete inversion with each of the three anionoids. This similarity in results would be expected if all the anionoids were present as solvent-separated ion pairs or free ions and the anions were reacting by the $S_N2$ mechanism.

To ascertain the effect of ion separation explicitly in a single solvent, the effect of the crown ether 18-C-6 (1,4,7,10,13,16-hexaoxacyclooctadecane) on the reaction of $Me_3SnNa$ with 2-bromooctane in THF was studied. The experiments were conducted with a constant concentration of DCPH (1.0 M) and varying concentrations of 18-C-6 with the results gathered in Table V (entries 1–8) and displayed graphically in Figure 1. It can be seen that the initial 87% yield of octane decreases with increasing 18-C-6 concentration and plateaus at 30% yield, with a concomitant increase in the yield of substitution product from 8.3% to a plateau at 60%. The plateaus are reached at ca. 0.20 M 18-C-6 as would be expected on the basis of the high stability constant of the complex with $Na^+$.[21] These yields are very similar to those obtained with DCPH in TG (entry 4, Table III), implying similar kinds of aggregation, presumably to solvated and "crowned" ion pairs, respectively.

A variant on these experiments was conducted with the results also gathered in Table V (entries 9–14) and plotted in Figure 2. Here the 18-C-6 concentration was maintained constant at 0.40

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**Table V.** Effects of DCPH and 18-Crown-6 on Reaction Distribution and Stereochemistry from the Reaction of $Me_3SnNa$ with 2-Bromooctane in THF[a-c]

| entry | addend,[c] M | % $C_8$[b] | % 2-$Me_3SnC_8H_{17}$ | % tot yield | % ee |
|---|---|---|---|---|---|
| 1 | 18-C-6 (0.40) | 10 | 80 | 90 | 84.0 |
| 2 | 18-C-6 (0.60) | 12 | 82 | 94 | |
| 3 | 18-C-6 (0.40) DCPH (0.10) | 19 | 75 | 94 | 89.0 |
| 4 | 18-C-6 (0.40) DCPH (0.20) | 25 | 68 | 93 | 93.0 |
| 5 | 18-C-6 (0.40) DCPH (0.50) | 30 | 65 | 95 | |
| 6 | 18-C-6 (0.40) DCPH (1.0) | 30 | 60 | 90 | |
| 7 | 18-C-6 (0.40) DCPH (1.26) | | | | 99.6 |
| 8 | 18-C-6 (0.40) DCPH (1.50) | 28 | 63 | 91 | |
| 9 | DCPH (1.0) | 87 | 8.3 | 93 | |
| 10 | DCPH (1.0) 18-C-6 (0.050) | 46 | 45 | 91 | |
| 11 | DCPH (1.0) 18-C-6 (0.10) | 37 | 54 | 91 | |
| 12 | DCPH (1.0) 18-C-6 (0.20) | 30 | 58 | 88 | |
| 13 | DCPH (1.0) 18-C-6 (0.40) | 30 | 60 | 90 | |
| 14 | DCPH (1.0) 18-C-6 (0.67) | 31 | 60 | 91 | |

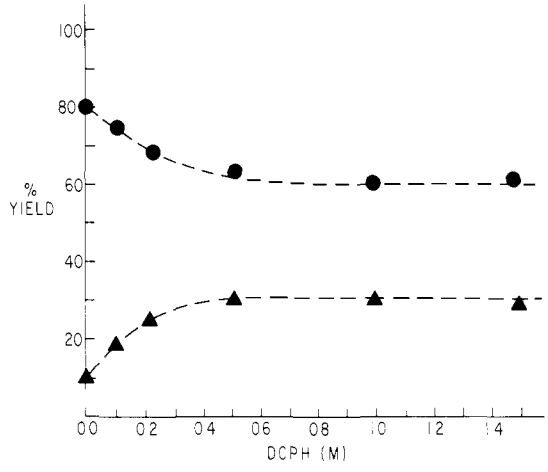



**Figure 2.**

M, well beyond the beginning of the plateau in Figure 1. This would provide the maximum ion pair separation by interaction with $Na^+$. The DCPH concentration was varied, resulting in increases in the octane yields from 10% to 28% at the expense of substitution product which decreased from 80% to 63%, each showing a plateau beyond 0.4 M DCPH. The % ee of the substitution product formed in the absence of DCPH was high (84%, entry 1) as might be expected from a substantial contribution from the $S_N2$ mechanism. At 1.26 M DCPH the ET mechanism was completely eliminated as a source of substitution product as indicated by the observation of complete inversion.

In order to probe the effect of aggregation of $Me_3SnM$, further studies were conducted in the mixed solvent 80% ether/20% THF in which ion separation should be less than in THF alone. The results in entries 1, 3, and 5 of Table VI show a substantial increase in yields of hydrocarbon products over those observed in THF to about 50% for each $Me_3SnM$. This signals a definite increase in participation by the ET mechanism. In the presence of DCPH (entries 2, 4, and 6), this becomes almost quantitative, with less than 3% of the substitution product being found in each case (entries 2, 4, and 6).

The stereochemical results in parallel experiments in the absence of DCPH are displayed in Table VII. Suprisingly the % ee with

**Table VI.** Effects of Counterion and DCPH on Product Distribution from the Reaction of $Me_3SnM$ with 2-Bromooctane in Ether/THF (80/20, v/v)[a]

| entry | M | [R-Br], M | addend, M | % $C_8$[b] | % $C_8H_{17}$-$SnMe_3$ | % R-R | % tot yield |
|---|---|---|---|---|---|---|---|
| 1 | Li | 0.10 | | 40 | 40 | 8.6 | 89 |
| 2 | Li | 0.10 | DCPH (1.20) | 88 | 2.7 | | 91 |
| 3 | Na | 0.12 | | 40 | 36 | 9.5 | 86 |
| 4 | Na | 0.10 | DCPH (1.20) | 91 | 2.8 | | 94 |
| 5 | K | 0.12 | | 38 | 31 | 13 | 82 |
| 6 | K | 0.12 | DCPH (1.20) | 88 | 2.1 | | 90 |

[a,b] As in Table I.

**Table VII.** Effects of Counterion on the Stereochemistry of Trimethyl-2-octylstannane from the Reaction of $Me_3SnM$ with (+)-2-Bromooctane in Ether/THF (80/20, v/v)

| entry | $[\alpha]^{22}_D$ | M | $[\alpha]^{22}_D$ of 2-$Me_3SnC_8H_{17}$ obsd | $[\alpha]^{22}_D$ of 2-$Me_3SnC_8H_{17}$ corr[b] | % ee |
|---|---|---|---|---|---|
| 1 | +37.03 | Li | -18.17 | -21.38 | 78 |
| 2 | +37.03 | Li | -17.50 | -20.59 | 75 |
| 3 | +37.03 | Li | -17.21 | -20.25 | 74 |
| 4 | +37.03 | Na | -3.16 | -3.72 | 14.0 |
| 5 | +37.03 | Na | -3.41 | -4.01 | 15.0 |
| 6 | +37.03 | K | -4.24 | -4.99 | 18.0 |
| 7 | +37.03 | K | -4.35 | -5.12 | 19.0 |

[a] Of 2-bromooctane used. [b] Based on +43.40° for optically pure $Me_3SnC_8H_{17}$.

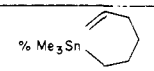
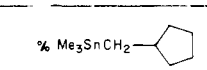
$Me_3SnLi$ was much higher (74–78%) than with the other two anionoids, both of which yielded product with less than ee 20%.

In view of the marked change in the contribution from the ET mechanism observed with the ether/THF mixed solvent, it appeared to be worthwhile to ascertain whether this effect would extent to a primary bromide to such an extent that this mechanism could be detected. 6-Bromo-1-hexene was chosen as the substrate, and the solvent was 80% benzene/20% THF. Results gathered in Table VIII provide a comparison of this solvent mixture with THF alone. The first three entries with THF show clear-cut $S_N2$ behavior in the control experiment and in the presence of either DCPH or *tert*-butylamine (TBA): only unrearranged substitution product observed. In the mixed solvent 10% of the cyclized product, cyclopentyltrimethylstannane, expected from cyclization of the 5-hexenyl radical was formed. In the presence of DCPH, this yield dropped to 1.5%, and 15% of 1-hexene was formed, confirming the intermediacy of a free radical. Interestingly, no methylcyclohexane was found. This shows that the trapping of primary free radicals under the conditions of these reactions is effective and is so fast that at 1.0 M DCPH, it intercepts the initially formed radicals before they can undergo cyclization. The results in the absence of DCPH in THF are in agreement with those of Kitching et al.[11] and Newcomb and Courtney.[13] We conducted similar experiments with 1-bromooctane as well. In the control experiments substitution product was formed in virtually quantitiative yield, and a trace of *n*-octane was observed in the benzene/THF solvent. In the presence of 1.0 M DCPH, the yield of substitution product dropped to 80%, and 12% of *n*-octane was found. These observations are in agreement with those observed with cyclopropylcarbinyl bromide. In reaction with each of the three (trimethylstannyl)alkalies, the yield of rearranged product 3-butenyltrimethylstannane was greater in 80% benzene/20% THF than in neat THF, and more 1-butene was trapped in the presence of DCPH than in its absence in each case, the amount depending on the counterion.[17b]

## Discussion

The results presented above, obtained from carefully conducted replicate experiments showing good reproducibility, permit some reliable statements to be made concerning the effects of the

Table VIII. Reactions of $Me_3SnNa$ with 6-Bromo-1-hexene at 0 °C[a-c]

| entry | addend, M | % 1-hexene | %  | %  | % tot |
|---|---|---|---|---|---|
| | | In THF | | | |
| 1 | | 0 | 98 | 0 | 98 |
| 2 | TBA (1.1) | 0 | 100 | 0 | 100 |
| 3 | DCPH (1.0) | tr | 98 | 0 | 98 |
| | | In Benzene/THF (80/20, v/v) | | | |
| 4 | | tr | 85 | 10.0 | 95 |
| 5 | DCPH (1.0) | 15 | 79 | 1.5 | 96 |

[a] Initial [R-Br], 0.10 M; initial [$Me_3SnNa$], 0.20 M. [b] Results are averages of at least two replicates with mean deviations of less than 3%.

counterion in $Me_3SnM$, the reaction medium, and the presence of DCPH on the mechanistic competition and stereochemistry of the reactions with bromides.

It is evident that the ability of species in the reaction medium to coordinate cations plays a significant role in determining the mechanistic competition between $S_N2$ and ET processes. A high degree of coordination as provided by TG as the solvent or 18-C-6 in THF, the media in which solvent-separated ion pairs must be the only significant species present, facilitates the occurrence of the $S_N2$ mechanism with 2-bromooctane. However, the ET process still competes. At the opposite extreme of a poor coordinating solvent system such as 80% ether/20% THF or 80% benzene/20% THF, ET is the predominant, if not the exclusive, pathway with the same substrate. Even primary bromides such as 6-bromohexene and 1-bromooctane, which show negligible indication of the ET process in pure THF show significant contributions from the ET process in these mixed solvents. These observations are consistent with those we made earlier with cyclopropylcarbinyl bromide.[17b]

The effects of the counterions $Li^+$, $Na^+$, and $K^+$ are not entirely straightforward in that changes in the product distributions do not necessarily follow the atomic weight sequence monotonically. This is seen in Table I in which the data show that Li and K behave similarly to each other but Na behaves differently in leading to a greater proportion of ET products in THF. This is true also in TG as the solvent, but the differences are small. In the ether/THF solvent system (Table VI), the trend, if significant, is small and monotonic. This is particularly interesting because the predominant pathway is ET. As the degree of ion pairing in this system is certainly larger than that in THF and TG, it would be expected that the ion pairs might play a significant role in determining the course of the reaction. Hence, one would expect that the counterion should have some effect, but it is small at best.

The absence of monotonic trends in the effects of the counterion is not entirely unexpected.[22] If one considers the following dissociation equilibrium in which the contact ion pair is separated by a THF molecule, one must take into account the interaction of both $Me_3Sn^-$ and THF with the counterion. It is well es-

$$Me_3Sn^-M^+ + R_2O \rightleftarrows Me_3Sn^-R_2OM^+$$

tablished that the order of energy of interaction with THF is Li > Na > K. This should favor separation of the ion pairs. On the other hand, the order of interaction of $Me_3Sn^-$ with the cations would be expected to follow the opposite order because of the large size of the orbital bearing the lone pair of electrons. In this case the order of solvation and stabilization of the contact ion pairs will follow the same order. Hence the observed order will be the result of the competition between these opposing factors. The data in Tables VI and VII are particularly striking in this context. The yields of substitution and reduction products are very similar for each of the stannylalkalies both in the control experiments and in the presence of DCPH. However, the stereochemistry with $Li^+$ shows a much greater extent of inversion than with the other counterions. Since the solvent system here is one in which contact ion pairs are expected to dominate, this suggests that the counterion may play a specific role in determining the stereochemistry without affecting the mechanistic competition between $S_N2$ and ET materially. Alternatively it might be argued that the DCPH also plays a role.

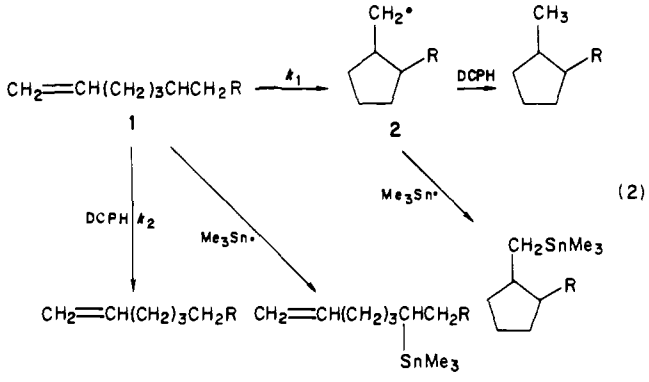
Varying counterion effects were also observed earlier in the reactions of 7-bromonorbornene with (trimethylstannyl)alkalies.[3] In THF the extent of inversion in the product followed the order Li > K > Na; in 1,2-dimethoxyethane the order was Li > Na > K.

As stated in the introduction, the use of DCPH as a free-radical trap has been questioned on the basis that its presence perturbs the mechanistic competition toward greater involvement of the ET process.[6] However, no definitive evidence for this view has been presented. In order to seek evidence, we turned to the stereochemical studies on (+)-2-bromooctane included in this report and obtained results which are subject to at least two interpretations. Consider, for example, the first two entries of Table IV. Entry 1 would normally suggest that 80% of the substitution product is formed with inversion via the $S_N2$ mechanism and the remainder by a nonspecific process involving racemizing simple free radicals. In the presence of DCPH (entry 2), only the $S_N2$ process remains as a source of substitution product as indicated by virtually complete inversion. However, the yield data of entry 2 of Table III obtained under the same conditions indicate that only 49% of the substitution product is formed by the $S_N2$ process. One interpretation for this apparent anomaly is that 80.4 (% ee, Table III) × 80 (% yield) or 64% yields of the substitution product in the control experiments of entry 1 are formed by the $S_N2$ process. From entries 2 of the tables 98 (% ee) × 49 (% yield) or 46% of racemic products is formed by this process. Thus, the DCPH decreases the $S_N2$ contribution from 64% to 46% due to an increase (ca. 18%) in the ET contribution. This interpretation fits in well with current conventional wisdom concerning free radical processes; however, independent evidence for perturbation of the mechanistic competition by DCPH is required before this can be considered to be the correct interpretation.

In an attempt to test this, we earlier examined the cyclopropylcarbinyl system which can be a very sensitive probe for free radicals because of the rapid ($k_1 = 10^8\ s^{-1}$) opening of the cyclopropylcarbinyl radical to the 3-butenyl radical. The general pattern of results was unexpected.[17b] In experiments with $Me_3SnK$ and cyclopropylcarbinyl bromide in THF, it was found that the effect of DCPH on the course of the reaction was to *increase* rather than decrease the yield of the $S_N2$ substitution product, (cyclopropylcarbinyl)trimethylstannane. With $Me_3SnLi$ and $Me_3SnNa$ no effect was observed.

5-Hexenyl systems constitute useful probes for the intermediacy of free radicals, eq 2.[2] The cyclization of **1** to **2** is normally irreversible, and the yield of cyclized product is taken as the minimum extent of free radical participation. The data of Table VII for 6-bromo-1-hexene (R = H in eq 2) in the mixed solvent 80% benzene/20% THF are pertinent in this regard. In the absence of DCPH, 10% of the cyclized substitution product was formed, indicating at least 10% of an ET component. When 1.0 M DCPH was present, 15% of the *uncyclized* trapping product, 1-hexene, was found. Thus, the trapping is more efficient than the cyclization; i.e., $k_2$ [DCPH] > $k_1$, so DCPH would be expected

(22) See: Garst, J. F. in "Solute–Solvent Interactions"; Coetzee, J. E., Ritchie, C. D., Eds.; Marcel Dekker: New York, 1969; Chapter 8.




(2)

to cause the formation of the higher yield of 1-hexene observed. Hence perturbation toward a larger ET contribution is unlikely to be the cause of the greater yield of 1-hexene in the presence of DCPH than of the cyclized substitution product in its absence.

Similar observations for a secondary bromide consistent with those described above have been reported by others since our work was initiated. Kitching reported that the reaction of $Me_3SnLi$ with 6-bromo-1-heptene in THF yielded cyclized and uncyclized substitution products (eq 2, R = Me) in a ratio of 3.8:1.[11] With the same system Ashby, using $Me_3SnNa$, also found the cyclized substitution product predominating in a ratio of at least 6:1.[12] Although the conditions used by the two groups were not identical, the results are consistent with a larger ET Component with sodium than with lithium as the counterion, in agreement with our findings for 2-bromooctane shown in Table I. Ashby also observed that the yield of reduction product was increased from 5% in the absence of DCPH to 65% when it was present in large excess. The results involving the use of stereochemistry and free radical cyclization as probes led to the conclusion that reactions of $Me_3SnM$ with simple secondary bromides in THF proceed largely by the electron-transfer mechanism. In addition our results show how the extent of its contribution can be changed by addends, solvents, and the counterion which can change the equilibrium constants for dissociation.

If DCPH has a perturbing effect on the mechanistic competition by facilitating the ET mechanism, one might expect that the effect would increase monotonically with DCPH concentration until this was the only process occurring. This is not observed in the data plotted in Figure 2. There is a plateau in the plot beginning around 0.5 M DCPH for this particular system which contained 0.4 M 18-C-6 in THF. Similar behavior was observed earlier with 2-bromobutane in THF.[10a,b] In that report it was also shown that similar plots with 1-bromoadamantane and bromocyclohexane did approach 100% hydrocarbon with increasing DCPH concentration from which is was concluded that these substrates reacted entirely by an ET process.[8,9] The results for bromocyclohexane are in accord with stereochemical results obtained with 4-alkyl analogues. If DCPH does indeed perturb the reaction, the kind of effect seen in Figure 2 must be due to some kind of saturation phenomenon which would suggest that it does not function as a catalyst.

In control experiments it was shown that DCPH does not consume either 2-bromooctane or $Me_3SnNa$ under conditions of the experiments in THF. When $Me_3SnNa$ was added to a solution containing excess bromide and DCPH, the amount of bromide consumed was equal to that of the $Me_3SnNa$. On the other hand, when trimethylstannane was used in place of DCPH, 94% of *n*-octane and 2.5% of 2-(trimethylstannyl)octane were formed from the bromide within a few minutes. Under these conditions only 9% reduction of the bromide occurred in a reaction between the bromide and stannane alone. Thus, the ET reaction of $Me_3SnNa$ served as a catalyst for reduction of the bromide by stannane through rapid generation of radicals for initiation of the radical chain reduction process, but this does not occur with DCPH.

None of the observations just discussed provides support for the simple perturbation interpretation, and some can be taken as evidence against it. An alternative interpretation merits consideration.[23]

**Table IX.** Stereochemistry in Diversion of Reactions of 2-Bromooctane with $Me_3SnM$ to Octane Formation by DCPH[a]

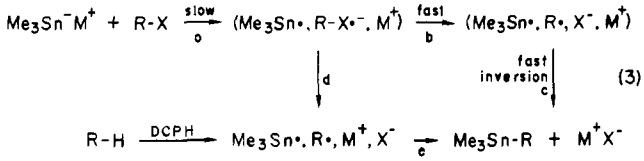
| | $Me_3SnLi$ in | | $Me_3SnNa$ in | | $Me_3SnK$ in | |
|---|---|---|---|---|---|---|
| | THF | TG | THF | TG | THF | TG |
| % diverted | 58 | 31 | 50 | 34 | 61 | 26 |
| % ee diverted | 66 | 51 | 56 | 37 | 49 | 42 |

[a] Estimated from (% yield in control) × (% ee in control) = (% yield untrapped) × (% ee untrapped) + (% diverted) × (% ee diverted); values of % yield and % ee taken from Tables I–IV; % ee untrapped taken as 59% and 97% for $Me_3SnNa$ in THF and TG, respectively, and 99% for $Me_3SnLi$ and $Me_3SnK$ in both solvents.

According to this view the exemplary data of entries 1 and 2 of Tables III and VI are analyzed as follows. The 49% yield of substitution product in the presence of DCPH is taken as a measure of the $S_N2$ contribution in the control experiment as well. Therefore, this also contributes 49% to the ee in the control experiment of entry 1. Now, 80–49 = 31% of the substitution product is formed via ET and it must be formed with excess inversion to account for observation of the ee 80.4% in the control, which would be only about 48% if the ET process occurred with complete racemization of radical intermediate(s). From the yields and % ee given in Tables I–IV one can use the above assumptions and estimate the % ee for the product that was diverted by DCPH to hydrocarbon. This example yields a ee 56% for the ET product. Data for the other experiments are gathered in Table IX. These values are fairly sensitive to the yield data and should not be taken to be of high precision; the apparent trends may have little significance.

Perhaps the strongest support for this interpretation comes from the data for $Me_3SnNa$ in THF. From entries 5 and 6 in Table I, the yield of substitution product drops from 60% in the control to 10% in the presence of 1.0 M DCPH. Yet the % ee of the product shows little change (from 57% to 59% in entries 7 and 8 of Table II). This clearly means that those intermediates which were diverted to forming the reduction product would have provided a substitution product with ca. ee 58%.

The major problem with this interpretation lies in specification of the nature of the intermediate(s). In the absence of the stereochemical information, we first assumed simple alkyl free radicals.[10] The formation of product with substantial % ee requires a different type of intermediate.[17c] It must have free radical character because it can be trapped, and it must have a lifetime of the order of $10^{-5}$ s if it is to be capable of cyclization in competition with trapping, as is the case with the 5-hexenyl radical and the 1-methyl-5-hexenyl radical.[12] Ashby has suggested that this can be accounted for by assuming reaction in a solvent cage as shown below in eq 3a–c. Radicals escaping from the cage in




(3)

step d would racemize and would form a racemic substitution product in step e or they could be trapped by DCPH in step f. This scheme does not appear to account for our combined stereochemical and trapping data. Consider again entry 1 of Table IV. According to the scheme of eq 3a–c the ee 80% is the result of combined $S_N2$ and geminate ET processes, and the remaining 20% of substitution product is formed by way of kinetically free 2-octyl radicals which have separated and racemized before coupling with trimethylstannyl radicals. However, from entry 2 of Table III, one sees that in the presence of DCPH, only 49% of product with ee 98% is formed. This means that 31% of the product which should have been formed via the geminate process

(23) Wilt, J. W In "Free Radicals"; Kochi, J., Ed.; Wiley: New York, 1973; Vol. 1, Chapter 8.

has been trapped by DCPH to form the $C_8$ hydrocarbon. According to the accepted concept of the solvent cage, such trapping cannot occur. If the double bonds in the hexenyl and heptenyl substrates do not change the mechanism, what is required is an intermediate with free radical behavior, a lifetime of about $10^{-5}$ s, which can be trapped with DCPH and which can provide a substitution product with partial inversion in configuration. These requirements could be met if the components of the first geminate cluster were held together as a complex of suitable stability, reactivity, and stereochemical integrity. Comments concerning a likely structure would be speculative and are best deferred pending acquisition of appropriate experimental data.

The literature on the reactions of (trialkylstannyl)alkalies with 2-halooctanes in particular contains some results which show considerable variance although conducted under ostensibly identical conditions. Workers in the field are aware that a variety of parameters can affect the course of these reactions; these have been pointed out by San Filippo.[6,9] Our study was not designed to sort out all or many of these effects, but rather to focus on certain parameters in carefully conducted and replicated experiments. Even so, the apparent discrepancies in the literature are quantitative and such that they do not affect the differing major conclusions or interpretations which can be reached from the current state of knowledge of this area.

In summary, the effects of counterion solvation on the mechanistic competition between the $S_N2$ and ET mechanisms of bromides with $Me_3Sn^-M^+$ have been examined. The secondary alkyl bromide reacts by competition between these mechanisms in THF and TG or THF with crown ether, the cation solvating agents enhancing the $S_N2$ contribution. Primary bromides show little or no ET reaction in these solvents. In 80 ether/20% THF or 80% benzene/20% THF, the ET process is virtually the excluive process with secondary bromides. Even primary bromides show a modest ET contribution in these poorly coordinating solvent systems. Most of the sterochemical and yield data with 2-bromooctane can be interpreted as involving perturbation of the mechanistic competition toward ET by DCPH used as a radical trap. However, none of the other data acquired to date require this interpretation. An alternative interpretation assuming no perturbation is consistent with all the data. It requires a free radical intermediate which can lead to a substitution product with partial inversion in configuration, a requirement for which we know of no simple precedent.

## Experimental Section

**General.** Proton magnetic resonance spectra were obtained at 60 MHz by using a Varian EM360A instrument. Chemical shifts are reported in parts per million downfield from internal tetramethylsilane followed in parentheses by multiplicity, coupling constants, number of protons, and assignment. $^1H$–$^{119}Sn$ coupling constants are reported as $J(Sn-H)$, with the superscript denoting the number of bonds intervening between the nuclei. Analytical gas chromatographic analyses were performed with a Hewlett-Packard 5750 instrument with a thermal conductivity detector. Unless otherwise specified a stainless steel column, 16 ft. × 0.25 in. with 15% UCW 98 on Chromosorb W, AW-DMCS, was used. Yields were determined by internal standard techniques from areas obtabine by digital integration by using a Columbia Scientific Industries Model Supergrator-1. Optical rotations were measured in pentane using a Pepol Model 60 electronic polarimeter at 589 nm. Precision was 0.001°.

Tetrahydrofuran (THF) was dried by distillation from molten potassium. Tetraglyme (TG) was distilled from molten sodium at ca. 0.01 torr. Chlorotrimethylstannane and hexamethyldistannane were prepared as previously described.[10]

**2-Bromooctane.** A modification of the procedure of Wiley[24] was used. A flame-dried flask was charged with 400 mL of spectro-grade methylene chloride and 52.4 g (0.20 mol) of triphenylphosphine under argon. The mixture was cooled to 0 °C and 32 g (0.20 mol) of bromine added with stirring.

To the resulting yellow slurry of bromotriphenylphosphonium bromide was added 2-octanol (20.5 g, 0.16 mol) in 20 mL of $CH_2Cl_2$ over 0 min; stirring was continued overnight at room temperature. The solvent was removed in a rotary evaporator and triturated repeatedly with pentane and the extracts were combined, washed with aqueous $NaHCO_3$, dried over $Na_2SO_4$, concentrated, and distilled, yielding 21.4 g (69%) of 2-bromooctane, bp 80–81 °C/16 torr (lit.[20] bp 66–67 °C/9 torr). $^1H$ NMR ($CCl_4$) $\delta$ 0.9–1.33 (13 H, m), 1.67 (3 H, d), 3.93 (1 H, m).

**(+)-2-Bromooctane.** The above procedure was followed using (−)-2-octanol,[25] $[\alpha]^{22}_D$ −9.43°. The bromide had $[\alpha]^{22}_D$ +37.03°; optical purity was 85% based on the literature value of +43.40°.[20]

**(−)-2-Octyl Tosylate.** A modification of a previously described procedure was used.[26,27] To a stirred solution of purified *p*-toluenesulfonyl chloride (15.0 g, 70 mmol) in 120 mL of dry pyridine cooled in a salt–ice bath was added 2.5 g (19 mmol) of (−)-2-octanol ($[\alpha]^{22}_D$ −9.43° in pentane) over 10 min. After standing for 3 days at 0 °C, the mixture was poured into 250 mL of cold 10% HCl. The solution was extracted with pentane (3 × 100 mL) and the extracts were combined, dried over $MgSO_4$, and concentrated to yield 4.34 g (79%) of the tosylate as an oil which was used without further treatment.

**(+)-Trimethyl-2-octylstannane.** To the tosylate described above (1.0 g, 3.52 mmol in 10 mL of dry TG) under argon at 0 °C was added 14 mL of 0.5 M (trimethylstannyl)lithium (7.0 mmol) in TG via syringe. After 1 h the mixture was quenched with a large excess (60 mL) of 30% $H_2O_2$ and then extracted with pentane (2 × 150 mL). The combined extracts were washed with water and dried over $Na_2SO_4$, and the trimethyl-2-octylstannane was collected by GLPC; $[\alpha]^{22}_D$ +26.03° (pentane). As the alcohol used was 95% optically pure,[25] the rotation of optically pure trimethyl-2-octylstannane is calculated to be +27.40° (lit.[6b,12] $[\alpha]^{25}_D$ 26.1°; $[\alpha]^{25}_D$ 28.4°). GLPC showed the product to contain less than 1% impurity: NMR ($CCl_4$) $\delta$ 0.00 (9, s, $^2J(^{119}Sn-^1H)$ = 50.0 Hz), 0.87–1.23 (17, m).

**(Trimethylstannyl)sodium and (Trimethylstannyl)potassium.** In a typical reaction, 3.05 g (9.30 mmol) of hexamethyldistannane was added to 25 mL of dry THF or TG in a three-neck flame-dried flask under argon. Finely cut metal (26 mmol) was added and the mixture stirred rapidly at 0 °C for 6–8 h. The black precipitate which appeared was allowed to settle; the supernatant was removed and centrifuged to provide clear yellow–green solution. The concentration of stannylalkali was determined as follows. An aliquot was treated with excess 1-bromobutane. The yield of butyltrimethylstannane was then obtained by GLPC using a 15% SE-30 on Chromosorb W column (16 ft × 0.25 in.).

**(Trimethylstannyl)lithium** was prepared as above except that the metal was rinsed with methanol to remove the black coating and then with petroleum ether before use. All operations involving (trimethylstannyl)alkalies were conducted under argon.

**Reactions of (Trimethylstannyl)alkalies with (+)-2-Bromooctane.** In a typical reaction, 0.50 g (2.6 mmol) of (+)-2-bromooctane was added to 10 mL of solvent in a flame-dried flask under argon. After the solution was cooled at 0 °C for 15 min, (trimethylstannyl)alkali solution (0.4 = 0.6 M) was added in 100% excess via syringe. After 1 h the mixture was carefully quenched with 30% $H_2O_2$ and extracted with pentane.[28] The trimethyl-2-octylstannane was collected by GLPC using the SE-30 column, and its optical rotation was measured. When the effect of dicyclohexylphosphine was under study, it was added to the solution of bromooctane before addition of the (trimethylstannyl)alkali. When the effect of 18-C-6 was under study, a stock solution was added to the (trimethylstannyl)alkali solution. The resulting solution was then added to the 2-bromooctane solution to initiate the reaction.

**Product Yields in the Reactions of (Trimethylstannyl)alkalies with 2-Bromooctane.** The yields were determined in separate experiments conducted under the same conditions but on a smaller (0.14–0.35 mmol bromooctane) scale. It was observed that the same results were obtained whether the reaction product mixture was analyzed directly or if it was quenched, extracted, and then analyzed.

**Control Experiments. (a) Optical Stability of 2-Bromooctane under the Reaction Conditions.** (+)-2-Bromooctane (0.97 g, 5 mmol) with $[\alpha]^{22}_D$ +33.49° dissolved in 20 mL of THF was transferred into a flame-dried flask under argon. After the solution was cooled to 0 °C, 5 mL of 0.5 M (2.5 mmol) of (trimethylstannyl)sodium was added. The reaction product mixture was quenched with water and extracted with pentane, and the extract was concentrated after drying with $Na_2SO_4$. Unreacted 2-bromooctane was collected by GLPC and its optical rotation measured: $[\alpha]^{22}_D$ +33.30°, indicating no significant isomerization.

**(b) Reaction of $Me_3SnNa$ with DCPH.** (Trimethylstannyl)sodium (1 mL of a 0.60 M solution in THF) was added to 1 mL of 3.0 M DCPH (3.0 mmol) at 0 °C. After 1 h *n*-butyl bromide (1.20 mmol) was added

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(28) The reaction between DCPH and $H_2O_2$ is highly exothermic!

via syringe and the resulting *n*-butyltrimethylstannane determined quantitatively by GLPC; the calculated concentration of $Me_3SnNa$ was 0.59 M, indicating no significant reaction with DCPH.

**(c) Reaction of DCPH with 2-Bromooctane.** To 3 mmol of DCPH under argon was added 0.4 mmol of 2-bromooctane in 1 mL of THF at ice-water temperature. After 15 min 1.4 mL of 0.60 M (0.8 mmol) (trimethylstannyl)sodium was added, and the yields of trimethyl-2-octylstannane and $C_8$ hydrocarbons were determined. In a number of experiments, the combined yields of stannane and $C_8$ were the same within ±2% as those obtained in the absence of DCPH.

**(d) Reaction of Dicyclohexylphosphine with 2-Bromooctane in the Presence of (Trimethylstannyl)sodium.** (Trimethylstannyl)sodium (0.021 mmol) was added under argon to a solution of 0.140 mmol of 2-bromooctane and 1.70 mmol of dicyclohexylphosphine at 0 °C. After 4 h the mixture was analyzed by GLC and found to contain 0.019 mmol of octane.

In a similar experiment (trimethylstannyl)sodium (0.063 mmol) was added to 0.0160 g (0.125 mmol) of nonane (internal standard), 0.0272 g (0.141 mmol) of 2-bromooctane, and 0.337 g (1.70 mmol) of dicyclohexylphosphine in 1.5 mL of dry THF under argon. After 4 h at 0 °C the mixture was analyzed by GLC and found to contain 0.060 mmol of octane.

**(e) (Trimethylstannyl)sodium as Initiator in the Reaction of 2-Bromooctane with Trimethylstannane. Reaction of Trimethylstannane with 2-Bromooctane.** Trimethylstannane (0.20 g; 1.21 mmol) was added to 0.0313 g (0.244 mmol) of nonane (internal standard) and 0.0913 g (0.473 mmol) of 2-bromooctane in 3.0 mL of dry THF under argon. The vial was cooled to 0 °C for 40 min. GLC analysis indicated reaction of 0.043 mmol of bromide and the formation of 0.042 mmol of octane.

**Reaction of Trimethylstannane with 2-Bromooctane in the Presence of (Trimethylstannyl)sodium.** To a solution of 0.50 mmol of 2-bromooctane and 1.20 mmol of trimethylstannane at 0 °C was added under argon 0.05 mmol of (trimethylstannyl)sodium in THF. After 40 min the mixture was analyzed by GLC and found to contain 0.34 mmol of octane and less than 1% trimethyl-2-octylstannane; 0.35 mmol of 2-bromooctane had reacted.

A similar experiment to the above in which 100% excess (1.0 mmol) of (trimethylstannyl)sodium was added to a solution of 2-bromooctane (0.50 mmol) and trimethylstannane (1.0 M) resulted in the immediate consumption of 2-bromooctane and the formation of 94% octane and 2.5% trimethyl-2-octylstannane.

**(Trimethylstannyl)alkalies in Mixed Solvents.** Preparations in 80% benzene/20% THF have been described previously.[17b] Solutions in 80% ethyl ether/20% THF were prepared by adding 5.0 g (15 mmol) of $(Me_3Sn)_2$ and 40 mmol of the metal to 20 mL of a 50/50 (v/v) mixture of ether/THF in a flame-dried flask in an argon atmosphere. The mixture was stirred vigorously for 6-8 h at 0 °C and diluted with 30 mL of ether. The resultant slurry was centrifuged. The supernatant of $Me_3SnLi$ was clear with a slight brownish cast; those from $Me_3SnNa$ and $Me_3SnK$ were deeper in color. Reactions of aliquants with 1-bromobutane followed by GLPC determination of the 1-butyltrimethylstannane formed indicated yields of 70-85%.

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# Absolute Stereochemistry of (+)-1,8a-Dihydro-3,8-dimethylazulene, a Labile Biosynthetic Intermediate for 1,4-Dimethylazulene. Determination by Theoretical Calculation of CD Spectra and Verification by Synthesis of Model Compounds

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**Abstract:** The absolute stereochemistry of (+)-1,8a-dihydro-3,8-dimethylazulene (**1**), a labile trinorsesquiterpenoid biosynthetic intermediate for 1,4-dimethylazulene (**2**), isolated from the liverwort *Calypogeia granulata* Inoue, was determined to be 8a*S* by theoretical calculation of CD spectra; the labile biosynthetic intermediate **1** with a unique 1,8a-dihydroazulene skeleton shows very intense optical rotation, $[\alpha]_D$ +1165°, and CD Cotton effects, $\lambda_{ext}$ 314.0 nm, $\Delta\epsilon$ +19.7 and $\lambda_{ext}$ 235.2 nm, $\Delta\epsilon$ −47.4, suggesting a strongly distorted conjugated tetraene system. On the basis of the $\pi$-electron framework approximation, the CD curve of (8a*R*)-1,8a-dihydroazulene (**5**) was calculated by the SCF-CI-dipole velocity MO method. The resultant calculated CD Cotton effects, $\lambda_{ext}$ 313 nm, $\Delta\epsilon$ −13.9 and $\lambda_{ext}$ 219 nm, $\Delta\epsilon$ +46.2, were opposite in sign to those of the natural product **1**. Accordingly, the absolute stereochemistry of the labile biosynthetic intermediate (+)-**1** was theoretically determined to be 8a*S*. The conclusion was experimentally proved by the synthesis of model compounds (1*S*,8a*S*)-(+)-1,8a-dihydro-1-methoxy-8a-methylazulene (**7**) and (1*S*,8a*S*)-(+)-1,8a-dihydro-1-methoxy-6,8a-dimethylazulene (**8**) as follows. Compounds **7** and **8** were synthesized starting from optically pure Wieland-Miescher ketone (*S*)-(+)-(**9**), $[\alpha]_D$ +98.5°, via reactions of 15 steps, respectively. The product **7**, bp 35-45 °C (0.067 kPa) and $[\alpha]_D$ +393.3°, shows CD Cotton effects, $\lambda_{ext}$ 321.0 nm, $\Delta\epsilon$ +5.7 and $\lambda_{ext}$ 221.3 nm, $\Delta\epsilon$ −24.5, which are similar, in both sign and shape, to those of the natural product **1**. Similarly, compound **8**, bp 60-70 °C (0.029 kPa) and $[\alpha]_D$ +323.8°, exhibits CD Cotton effects, $\lambda_{ext}$ 318.6 nm, $\Delta\epsilon$ +4.3 and $\lambda_{ext}$ 220.7 nm, $\Delta\epsilon$ −18.1. Therefore, by comparison of the CD spectrum of **1** with those of the model compounds, it was experimentally proved that the natural dextrorotatory 1,8a-dihydro-3,8-dimethylazulene (**1**) had 8a*S* absolute configuration.

Recently much attention has been focused on the chemistry of trinorsesquiterpenes with a 1,4-dimethylazulene skeleton, isolated from the sources of marine soft corals or liverworts.[2-7] One of us first isolated chiroptically active 1,8a-dihydro-3,8-di-

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