# Nucleophilic Aromatic Substitution by Organostannylsodiums. A Second-Order Reaction Displaying a Solvent Cage Effect

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**Abstract:** Results of a study of mechanistic aspects of the reaction of triorganostannylsodiums with halobenzenes are reported. The reaction in tetraglyme, which is first order in each reactant, is unusually fast for an unactivated nucleophilic aromatic substitution, and provides high yields of arylstannanes, $R_3SnAr$. Minor amounts of $R_2SnAr_2$ and $R_4Sn$ are also formed by a mechanism which is presumed to involve initial dissociation of $R_3SnNa$ into $(R_2Sn)$ and RNa. Reduction product, ArH, is formed when effective proton donors are present in the reaction mixture. ArD is formed when 2-propanol-*d* is present, indicating that aryl anions are intermediates. The initial step in the proposed mechanism of the reaction between the aryl halide and organostannylsodium results in the formation of caged species, which may react in the cage to form substitution product, $ArSnR_3$, or diffuse from the cage as ArNa and $R_3SnX$, which may react with each other to form more substitution product or with other species present in the bulk of the solvent. This concept of the mechanism is based on the results of proton trapping, which shows a saturation effect, and on the effect of solvent viscosity on the fractions of ArH and $ArSnR_3$ formed in the presence of *tert*-butyl alcohol. Study of the course of reactions of trimethylstannylsodium with aryl bromides bearing intramolecular traps such as ketone carbonyls and hydroxyl groups provides support for the mechanism proposed. The order of reactivities of aryl halides is ArI > ArBr > ArCl > ArF.

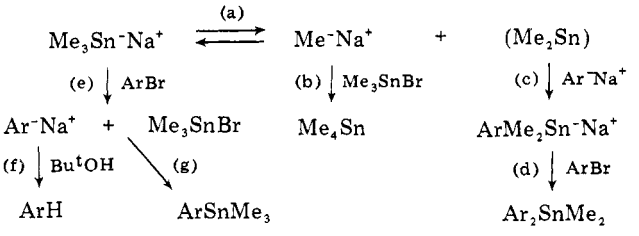
The first preparation of an arylstannane by the reaction of an organostannylalkali and an aryl halide was reported by Kraus and Sessions[1] in 1922. They treated trimethylstannylsodium and *p*-dichlorobenzene in liquid ammonia and obtained an unspecified yield of *p*-bis(trimethylstannyl)benzene. Bromobenzene and trimethylstannylsodium reacted to form 14% of trimethylphenylstannane, along with benzene under similar conditions.[2] The reaction of triphenylstannyllithium with iodobenzene in ether,[3] with bromobenzene in tetrahydrofuran,[4] and with substituted iodobenzenes[5,6] and bromobenzenes[5] in ether have also been examined. These reactions appear to be quite facile as exemplified by the observation that the reaction between triphenylstannyllithium and bromobenzene was exothermic, which is remarkable because the substrate in this nucleophilic aromatic substitution carried no activating substituents. This fact, the highly variable yields obtained in the reactions, the observation of benzene as a product, and the evidence for halogen–metal exchange[5] led us to embark upon a mechanistic study of the reaction[7] as a part of a broad investigation into the chemistry of organostannylalkalis.

**Course of the Reaction.** We chose to use trimethylstannylsodium as the nucleophile in this study because the products formed would be volatile enough for GLC analysis, and the presence of the methyl groups facilitated NMR characterization and analysis. Tetraglyme was the solvent chosen because it was expected that solvent-separated or free trimethylstannyl ions would be the predominant species present. We have reported on the synthetic utility and limitations of the reaction with aryl bromides.[8,9] Products of the reaction using the aryl halide in about 100% excess with chloro-, bromo-, and iodobenzenes are shown by the data in Table I, and indicated in eq 1.

$$Me_3Sn^-Na^+ + PhX \rightarrow Me_3SnPh + PhH + Me_4Sn + Me_2SnPh_2 \quad (1)$$

Small but significant amounts of tetramethylstannane and dimethyldiphenylstannane were formed from each of the halides. However, the presence of *tert*-butyl alcohol in the reaction with bromobenzene (item 6) virtually eliminated the formation of the latter as a product and decreased the yield of trimethylphenylstannane; and the yield of benzene was correspondingly increased. Comparison of the results of items 4 and 5 shows that neither dimethyldiphenylstannane nor tetramethylstannane is formed from trimethylphenylstannane. A rationale for the formation of all of the products is shown in Scheme I. The key step in the formation of the organotin by-products is the dissociation of trimethylstannylsodium to form methylsodium and dimethyltin, step (a). The former reacts with bromotrimethylstannane to form tetramethylstannane, step (b); the latter first reacts with arylsodium to form aryldimethylstannylsodium, step (c); which then reacts with aryl bromide to form diaryldimethylstannane in step (d). Evidence for step (a) came from the observation that, when freshly prepared trimethylstannylsodium in tetraglyme (TG) containing piperidine (as a proton source) was allowed to stand for 2 days, about 6% of a gas was evolved. This showed the highly characteristic IR spectrum of methane with vibration–rotation bands centered at 3020 and 1306 $cm^{-1}$.[10] The formation of arylsodium, step (e), was verified by the increased formation of benzene in the presence of *tert*-butyl alcohol. This trapping reaction virtually eliminates the (c)–(d) sequence, but still permits the formation of a substantial yield of aryltrimethylstannane, step (g).[11] A rationale for this is given later.

Scheme I




In synthetic experiments it was shown that *o*-dibromobenzene reacted with 2 molar equiv of trimethylstannylsodium to provide 42% isolated yields of *o*-bis(trimethylstannyl)benzene.[8,9] If the aryl anion is an intermediate one might expect that benzyne could be formed by loss of bromide from *o*-bromophenylsodium. Indeed, when the reaction was conducted in solvent containing 30% furan the Diels–Alder adduct with benzyne, product 7 in Scheme II, was found in yield comparable to that of the disubstitution product.[8,9] In order to gain further information concerning possible intermediates reac-

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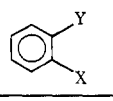
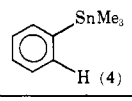
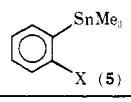
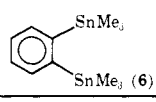
**Table I.** Reaction Products of Halobenzenes with Trimethylstannylsodium[a]

| Item | Halide | % Ph as $Me_3SnPh$ | % Sn as $Me_3SnPh$ | % Ph as $Me_2SnPh_2$ | % Sn as $Me_2SnPh_2$ | % Ph as PhH | % Sn as $Me_4Sn$ | % Ph found | % Sn found |
|---|---|---|---|---|---|---|---|---|---|
| 1 | PhCl[b] | 76 | 64 | 1.3 | 0.5 | 4.2 | 19 | 82 | 84 |
| 2 | PhBr[c] | 93 | 87 | 2.0 | 1.0 | 4.0 | 4.0 | 99 | 92 |
| 3 | PhI[c] | 78 | 76 | 13 | 7 | 7 | 10 | 98 | 93 |
| 4 | PhBr[d] | 92 | 84 (93)[e] | (4)[e] | | | (3)[e] | | |
| 5 | PhBr | + $Me_3SnPh$[f] | (90)[e,f] | (5)[e,f] | | | (5)[e,f] | | |
| 6 | PhBr | + *t*-BuOH[g] 68 | 60 | ≪1 | ≪1 | 33 | 6 | 101 | 66 |

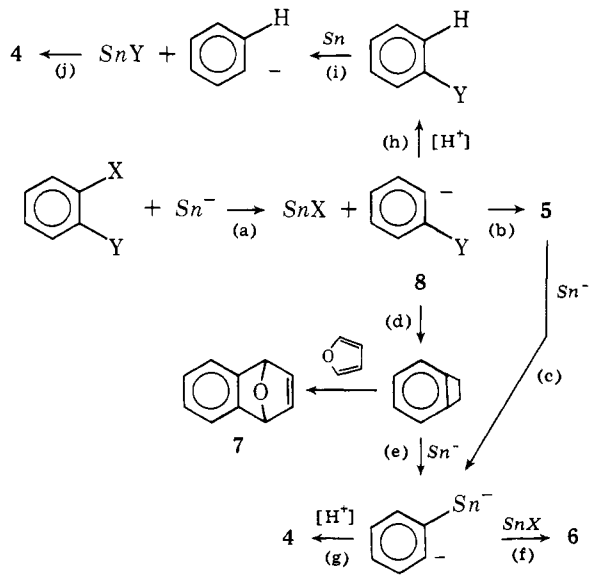
[a] In TG at 0 °C. [b] Two determinations with 5% deviation. [c] Three determinations with 5% deviations. [d] One milliliter of 0.5 M $Me_3SnNa$ added to 1 mL of 0.977 M PhBr consumed 0.459 mmol of PhBr to give 0.420 mmol of $Me_3SnPh$. [e] Relative yields of volatile tin products calculated from areas of GLC traces. [f] As under *d* with 1.21 mmol of $Me_3SnPh$ added. Yield of $Me_3SnPh$ based on 92% of 0.462 mmol of PhBr consumed. [g] To 1 mL of 0.444 M PhBr + 0.125 M *t*-BuOH was added 2 mL of 0.1 M $Me_3SnNa$ in TG.

**Table II.** Course of Reaction of *o*-Haloaryl Halides with Trimethylstannylsodium in TG[a]

| Item | Aryl halide | Product distribution, % | | |
|---|---|---|---|---|
| |  |  |  |  |
| | | H (4) | X (5) | $SnMe_3$ (6) |
| 1 | X = Y = Br[b] (**1**) | 6 (4)[c] | 19 (13)[c] | 75 (53)[c] |
| 2 | **1**[d] | 7 | 15 | 78 |
| 3 | **1** + *t*-BuOH[e] | 38 | 35 | 27 |
| 4 | X = Cl; Y = Br (**2**) | | 93 (72)[f] | 7 (5.4)[f] |
| 5 | X = Y = Cl (**3**)[g] | 13 | 65 | 22 |

[a] Initial [$Me_3SnNa$], 0.3–0.5 M; *T*, 0 °C. [b] Reaction carried out to 20% halide consumption; 0.46 mmol of $Me_3SnNa$ consumed 0.22 mmol of *o*-dibromobenzene. [c] Yields based on halide consumed. [d] Average of two experiments; 0.5 mmol of $Me_3SnNa$ added to 1 mmol of *o*-dibromobenzene. [e] Ratio of *t*-BuOH:*o*-dibromobenzene:$Me_3SnNa$ = 3:1:0:5. [f] Absolute yield based on tin added. *o*-Chlorobromobenzene:$Me_3SnNa$ = 2:07. [g] *o*-Dichlorobenzene:$Me_3SnNa$ = 5:1; reaction time 4 h.

Scheme II[a]



[a] $Na^+$ omitted; *Sn* = $SnMe_3$; structures of 4–6 shown in Table II.

tions involving excess *o*-dihalobenzenes were conducted, items 2–5 in Table II. As expected, the presence of *tert*-butyl alcohol caused a decrease in the proportion of **6** and an increase in **4** and **5.** The appearance of **5** in all of the experiments summarized in Table II indicates that benzyne is not the sole precursor of **6.** Scheme II outlines possible pathways to the products observed. Formation of **6** by way of benzyne involves steps (a), (d), (e), and (f). Steps (a) and (b) lead to **5,** which can also be converted to **6** by steps (c) and (f). Two pathways to **4** are possible: steps (a), (h), (i), and (j), or (a), (d), (e), and (g). In steps (g) and (h) the proton source may be the solvent or, as in item 3, *tert*-butyl alcohol.

Items 4 and 5 in Table II require comment because both substrates should form *o*-chlorophenylsodium in step (a), and yet the product distributions are significantly different, with **2** yielding more of **5** and less of **6** than **3.** The abstraction of chlorine from **3** is much slower than the abstraction of bromine from **2.** Thus, the concentrations of the intermediate **8** (Y = Cl) and of chlorotrimethylstannane are always low. Their reaction with each other, step (b), does not compete effectively with loss of chloride ion in step (d), nor with proton abstraction from solvent in step (h). When X is Br the rate of step (a) is much faster by a factor of about 1000 (see below) so that bromotrimethylstannane and **8** attain much higher concentrations so that their reaction with each other can compete effectively with steps (d) and (h).

In order to ascertain whether the conventional benzyne mechanism occurs with monohaloarenes the product distributions from reactions of *p*-tolylhalides with trimethylstannylsodium in TG were examined with the results displayed in Table III. The *p*-methyl substituent was used because the intermediate benzyne is more likely than others to yield a mixture of meta- and para-substitution products. For example, Pereyre and co-workers report that the reaction of tri-*n*-butylstannyllithium with *p*-fluorotoluene provided a mixture of *p*- and *m*-tolyltri-*n*-butylstannanes in a ratio of 0.75.[12] The first three items in Table III indicate that direct substitution is the only course followed under our reaction conditions. However, item 4 shows a para/meta ratio of 2.33, indicating incursion of the arynic intermediate. The time allowed for this very slow reaction was more than five times that in the experiment of item 3. This time factor suggests that methylsodium formed by the dissociation of trimethylstannylsodium may be responsible for generating the aryne. Further study on this question is needed.

**Kinetics of the Reaction.** The kinetics of the reaction of chlorobenzene with trimethylstannylsodium in TG were examined. Clean second-order kinetics were observed, and the results obtained follow: at 0.05 °C $k_2 = 2.10 \times 10^{-5} \pm 0.04$

**Table III.** Product Distributions in the Reaction of *p*-Tolyl Halides with Trimethylstannylsodium in TG

| Item | X | M | Reaction time, h | % para[a] | % meta[a] | *p*-/*m*- |
|---|---|---|---|---|---|---|
| 1 | Br | Na | <1 | 99 | ND[d] | >100 |
| 2 | Cl | Na | 61 | 97 | <1 | >100 |
| 3 | F | Na | 26 | ~100[b] | ND[d] | >100 |
| 4 | F | Na | 166 | 70[b,c] | 30[b,c] | 2.33 |

[a] Unless otherwise noted, percent yields are based on substitution product found divided by halide consumed. [b] Relative yields of substitution products. [c] Yield of $Me_3SnAr$ = 5.4%. [d] ND = not detected.

**Table IV.** Effect of *tert*-Butyl Alcohol Concentration on the Course of Reaction of Trimethylstannylsodium with Bromobenzene[a]

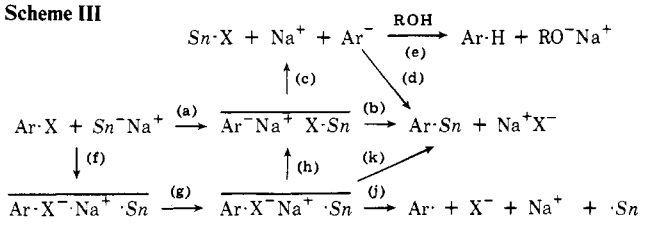
| [*t*-BuOH]/[*Sn*$^-$] | PhBr,[b] mmol | $Me_3SnPh$, mmol | OH, mmol | $Me_3SnPh$,[c] % | PhH,[c] % | % Ph found |
|---|---|---|---|---|---|---|
| 0.00 | 0.395 | 0.343 | 0.004 | 89 | 1 | 90 + 10[d] |
| 1.23 | 0.357 | 0.235 | 0.138 | 66 | 39 | 105 |
| 2.51 | 0.382 | 0.213 | 0.159 | 56 | 42 | 98 |
| 3.09 | 0.380 | 0.215 | 0.163 | 57 | 43 | 100 |
| 3.73 | 0.380 | 0.210 | 0.179 | 55 | 47 | 102 |
| 4.37 | 0.375 | 0.205 | 0.175 | 55 | 47 | 102 |
| 6.27 | 0.368 | 0.195 | 0.184 | 53 | 50 | 103 |

[a] One milliliter of 0.375 M $Me_3SnNa$ in TG added to 1 mL of TG solutions containing 0.976 M PhBr and *tert*-butyl alcohol at 0 °C. [b] mmol of PhBr consumed. [c] Based on PhBr reacted. [d] Approximately 5% $Me_2SnPh_2$ was formed.

$M^{-1}\,s^{-1}$; at 29.13 °C $k_2 = 28.0 \times 10^{-5} \pm 0.25\ M^{-1}\,s^{-1}$ from which $\Delta H^{\ddagger}$ = 14 kcal/mol and $\Delta S^{\ddagger}$ = −28 eu. The most nearly comparable system for which data appear to be available is the reaction between phenyllithium and *p*-bromotoluene for which the activation parameters are $\Delta H^{\ddagger}$ = 16 kcal/mol and $\Delta S^{\ddagger}$ = −23.6 eu.[13] However, the significance of the similarities in these data is limited in view of the differences in the parameters of the two reacting systems. Bromo- and iodoarenes are so reactive with trimethylstannylsodium that study of their kinetics will require development of appropriate fast reaction techniques.

**Intermolecular Trapping and the Viscosity Effect.** As indicated by the data in item 6 of Table I phenylsodium can be intercepted by adding *tert*-butyl alcohol to the reaction mixture. In order to ascertain how effective such trapping can be a series of experiments with increasing concentrations of *tert*-butyl alcohol were conducted using bromobenzene as the substrate. The results are gathered in Table IV. Inspection of the column showing the amounts of bromobenzene consumed shows that, even at the highest concentration of alcohol, virtually all of the trimethylstannylsodium was consumed in reacting with the halide rather than with the alcohol. This indicates a strong preference for attack at the "soft" bromine over the "hard" proton. The yields of substitution product and of benzene change very rapidly when small amounts of alcohol are present, but nearly reach a plateau when the ratio of alcohol to initial stannylsodium is above three. When 2-propanol-*O*-*d* with 98% *O*-*d* was used in place of *tert*-butyl alcohol the arene formed contained 96% of one atom of deuterium per molecule, confirming the assumption that proton abstraction is the source of the hydrogen in the reduction product. A free radical would be expected to abstract the hydrogen atom attached to the hydroxyl-bearing carbon. This suggests that the mechanism becomes dichotomous at some point along the overall reaction coordinate. One possibility is that this occurs in the initial step with one transition state leading to the products of halogen–metal exchange as depicted in Scheme I, and the other is a direct nucleophilic attack on the halogen-bearing carbon of the benzene ring. The saturation in the amount of trapping possible also suggests a cage effect such as occurs in free-radical decomposition reactions. In the present case the initial reaction could be the halogen–metal exchange resulting in the formation of the elements of arylsodium and halotrimethylstannane in a solvent cage, step (a) in Scheme III. A certain fraction of these react within the cage, step (b), and the remainder diffuse apart, step (c).

**Scheme III**




If no efficient proton donor or other electrophile is present in the medium the diffused species can also react to form the substitution product, step (d). If an alcohol, for example, is present the arylsodium reacts with it efficiently to form arene at the expense of substitution product, step (e).

A distinction between the two can be made by a study of the effect of viscosity on the product distribution. No effect would be observed in the first case which involves competition between attack on bromine and carbon in the initial, rate-determining step of the reaction, whereas the relative rates of coupling within the cage and diffusion from the cage would be viscosity dependent. Results of experiments with *p*-bromotoluene in mixtures of TG and dimethoxyethane (DME) containing 0.5 M *tert*-butyl alcohol which should trap the maximum amount of arylsodium are gathered in Table V. The ratio of toluene to *p*-tolyltrimethylstannane clearly increases with a decrease in the viscosity of the medium. Thus, on the reasonable assumption that TG and DME mixtures are very similar in their specific solvating characteristics the viscosity effect qualitatively supports the cage mechanism.

For free radicals formed in a solvent cage Koenig[14a] has used a simple diffusive model to develop a quantitative relationship between the yield of cage combination product and viscosity shown in the equation

$$1/\phi - 1 = a + b(\eta)^{-1/2} = [\mathrm{ArH}]/[\mathrm{ArSnMe_3}] \quad (2a)$$

where $\phi$ is the yield of product formed in the cage. This treatment ignores any direct intermolecular force effects between the diffusing particles. It describes the viscosity dependence reasonably well for several systems in which the diffusing radicals are dipoles.[15] If the species diffusing from the cage are

**Table V.** Effect of Solvent Viscosity on the Product Distribution[a]

| DME/TG, % v/v | PhMe, % | PhMe/ArSn[b] | $\eta$,[c] cP | $\eta^{-1/2}$ | $\epsilon$[c] | $(\epsilon\eta)^{-1/3}$ |
|---|---|---|---|---|---|---|
| 0 | 49 | 0.96 | 2.93 | 0.58 | 7.55 | 0.356 |
| 20 | 55 | 1.22 | 1.80 | 0.74 | 7.35 | 0.423 |
| 40 | 60 | 1.50 | 1.21 | 0.91 | 7.23 | 0.485 |
| 60 | 64 | 1.78 | 0.87 | 1.07 | 7.05 | 0.546 |
| 80 | 69 | 2.23 | 0.60 | 1.29 | 6.87 | 0.623 |

[a] Reactant concentrations: ArBr, 0.20 M; $Me_3SnNa$, 0.10 M; *t*-BuOH/$Me_3SnNa$, 5.0; 1, 25 °C. [b] *p*-$MePhSnMe_3$. [c] Solutions were 0.5 M in *t*-BuOH, 0.2 M in ArBr, and 0.06 M in decane in order to approximate reaction medium at start of reaction.

charged or highly polar other behavior might be expected. In fact, if one assumes that the field between the particles is very strong compared with thermal fluctuation forces leading to diffusion a different relationship would apply.[16] As shown in eq 2 the dependence of the yield function is on the reciprocal of the cube root of the product of viscosity and dielectric constant. A test of the relationships 2a and

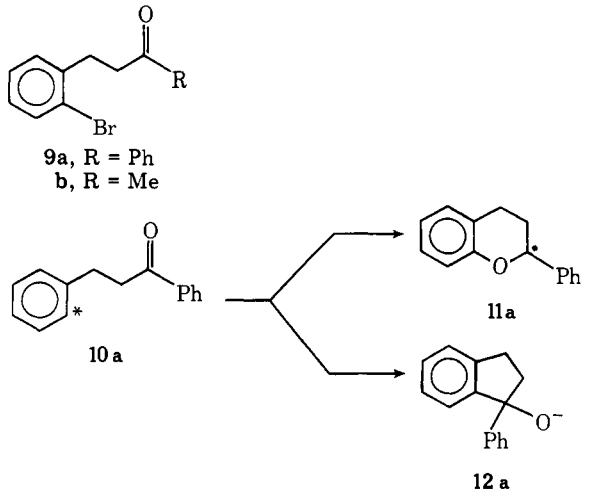
$$1/\phi - 1 = 3\,(a'/\epsilon\eta)^{1/2} + b' = [\mathrm{PhMe}]/[\mathrm{PhSnMe_3}] \quad (2b)$$

plotted in Figure 1 from the data in Table V shows that the first accurately describes the yield ratio, whereas the second does not, for its plot clearly is not linear. This implies that if the initial reaction in the mechanism is step (a) of Scheme III the forces between the arylsodium and halostannane dipoles fall into the weak field region under our experimental conditions. An alternative possibility is that a different mechanism, represented by steps (f), (g), and (j) as primary processes, is involved. In this scheme coupling can occur at the free-radical stage in step (k), and diffusion can also occur at this stage in step (j). Arylsodium is then formed by reduction of aryl radicals by electron transfer from stannyl radicals or from stannyl anion. However, if nearly 50% of the reaction (Table IV) occurs by this pathway one might expect to find significant amounts of biaryl in the reaction product mixtures. None was detected, and the material balances for aryl groups were quantitative within experimental error. Furthermore, aryl radicals might be expected to react with stannyl anions, not by electron transfer, eq 3, but by simple coupling, eq 4, as occurs in the $S_{RN}1$ mechanism with nucleophiles as diverse as the amide ion,[17a,b] arenethiolate anions,[18] and delocalized carbanions,[19] among others.

$$\mathrm{Ar}\cdot + {}^{-}Sn \rightarrow \mathrm{Ar}^{-} + \cdot Sn \quad (3)$$

$$\mathrm{Ar}\cdot + -\mathrm{Sn} \rightarrow \mathrm{Ar} - Sn^{-}\cdot \quad (4)$$

**Intramolecular Trapping.** One approach designed for intramolecular trapping of intermediates in the reaction involved synthesis of compounds **9.** Upon reaction with trimethylstannylsodium **9a** would form **10a.** If **10a** is a radical it might



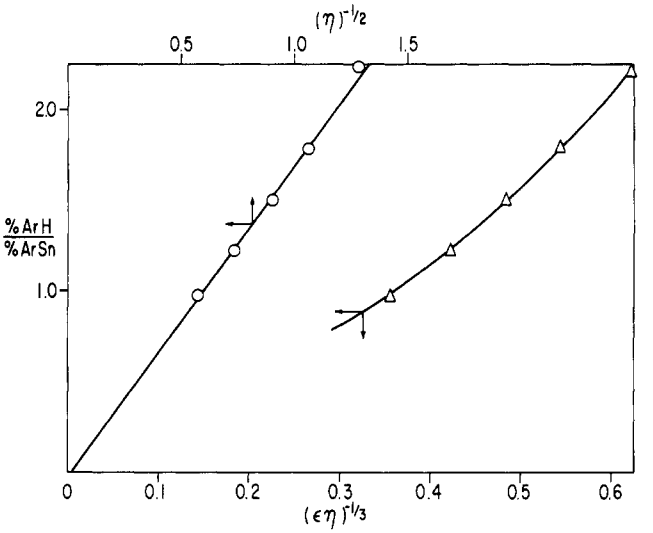
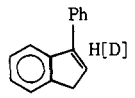
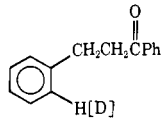
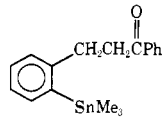
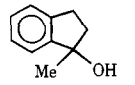
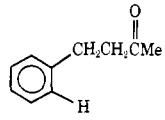
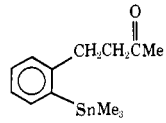




**Figure 1.** Ratio of yields of reduction to substitution products as functions of reciprocal square root of viscosity and reciprocal cube root of the product of viscosity and dielectric constant in TG/DME at 25 °C.

undergo cyclization to form the benzotetrahydropranyl radical **11a,** which is both an $\alpha$-oxy and a benzylic radical when R = phenyl.[20] If **10a** is an anion it would be expected to attack the carbon atom of the carbonyl group to form the indanyloxy anion, **12a.** Results obtained from the reaction of **9a** with trimethylstannylsodium are gathered as the first three entries of Table VI. The volatile products detected were 1-phenylindene (from dehydration of 1-phenylindanol in the course of workup), 3-(*o*-trimethylstannylphenyl)propiophenone, and 3-phenylpropiophenone. No indication of the presence of the tetrahydropyran expected from hydrogen transfer from the solvent to **11a** was observed. When the methylene hydrogens $\alpha$ to the carbonyl group were replaced by deuteriums the yields of the first two products increased at the expense of the third. Examination of the mass spectrum of the reduction product showed the presence of 0.75 atoms of deuterium per benzene ring in the $C_7H_7$ fragment, indicating that most of the hydrogen at the site of reduction came from the methylene protons $\alpha$ to the carbonyl group. A primary kinetic isotope effect in this process is indicated by the decrease in the yield of reduction product relative to yields of the other two. Comparison of the results of experiments 1-4 shows that dilution has no significant effect on the product distribution, thus revealing that the proton transfer in the reduction is an intramolecular process. A corollary is that the phenyl anion shows a distinct preference for proton abstraction over attack at the carbonyl carbon in this system. The last three items in the table show that the acetyl group competes more effectively than the benzoyl group for reaction at the carbonyl carbon relative to methylene proton abstraction, and in formation of the substitution product. This behavior is to be expected because of the absence of conjugation of the carbonyl with a $\pi$ electron releasing system. All of these observations are consistent with

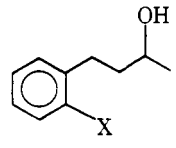
**Table VI.** Product Distribution from Intramolecular Ketone Trapping Experiments

| Substrate | Products | % Experiment 1[b] | [1][b,c] | 2[b] | 3[b] | 4[b] |
|---|---|---|---|---|---|---|
| **9a** |  | 7 | [12.5] | 6 | 7 | 11 |
| |  | 66 | [50] | 64 | 63 | 65 |
| |  | 26 | [37.5] | 30 | 30 | 24 |
| **9b** |  | 16[d] | | | | |
| |  | 22[d,e] | | | | |
| |  | 22[d,e] | | | | |

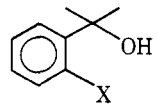
[a] From the relative areas of VPC traces. [b] Concentrations of ArBr for experiments 1, [1], 2, 3, and 4 were 0.210, 0.228, 0.015, 0.023, and 0.048 M, respectively. [c] Values in brackets are for the deuterated compound: $\sim CD_2C{=}O$. [d] Isolated yield. [e] Isolated as a 50:50 mixture.

step (a) of Scheme III as the initial transformation in the mechanism. However, they do not rule out the alternative free-radical process: both the hydrogen transfer and the cyclization processes could occur by way of the aryl free radical.

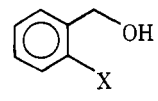
A further examination of intramolecular trapping using the hydroxylic proton as the electrophile was made with com-



**13a**, X = Br
**b**, X = H
**c**, X = $SnMe_3$



**14a**, X = Br
**b**, X = H
**c**, X = $SnMe_3$



**15a**, X = Br
**b**, X = H
**c**, X = $SnMe_3$

pounds **13a, 14a,** and **15a** as substrates. Upon reaction with trimethylstannylsodium in TG **13a** yielded 45% of the reduction product, **13b,** and 26% of the substitution product, **13c.** The benzylic alcohols **14a** and **15a** yielded the corresponding reduction products **14b** and **15b,** but none of the substitution products **14c** or **15c,** respectively. However, trimethylstannane was also formed in each case indicating competition between hydroxyl and bromo groups for reaction with the stannylsodium. Therefore, reactions were conducted using excess bromo alcohol to ensure that reaction at bromine would occur with the alcohol rather than with the corresponding alkoxide. One would expect that the negatively charged stannyl anion would react more slowly at the bromine of the negatively charged alkoxide than of the uncharged alcohol. Thus the products formed by replacement of bromine should arise from the alcohol. Only reduction products **14b** and **15b** were observed even though as little as 0.1% of substitution products could have been detected. The substitution product **14c,** which was synthesized independently, was found to be extremely sensitive

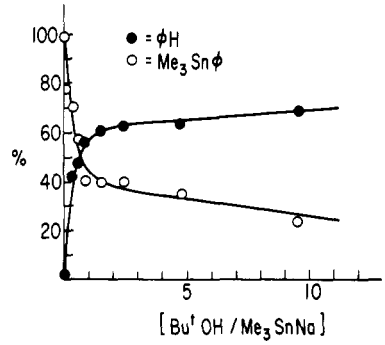



**Figure 2.** Effect of *tert*-butyl alcohol concentration on the yield of benzene formed in the reaction of iodobenzene and trimethylstannylsodium in TG at 25 °C.

to protodestannylation, and would not have survived under the conditions of analysis. Authentic **15c** was found to be stable under these conditions, so that it can be concluded that none was formed in the reaction. Proton abstraction from an $\alpha$-hydroxy group by the ortho anionic center could compete effectively within the initial solvent cage with nucleophilic attack at the tin of bromotrimethylstannane. If a free-radical intermediate were involved, coupling of aryl and stannyl radicals to form substitution product should occur within the cage in preference to hydrogen atom transfer from oxygen to the aryl carbon.

**Effects of Halogen Variation.** The effects of *tert*-butyl alcohol concentration on the product distribution when iodobenzene and trimethylstannylsodium were allowed to react in TG are shown in Figure 2. The result is qualitatively similar to that observed with bromobenzene. The degree of trapping is somewhat greater for a given concentration of alcohol, and the curves do not appear to level off as much. This latter effect

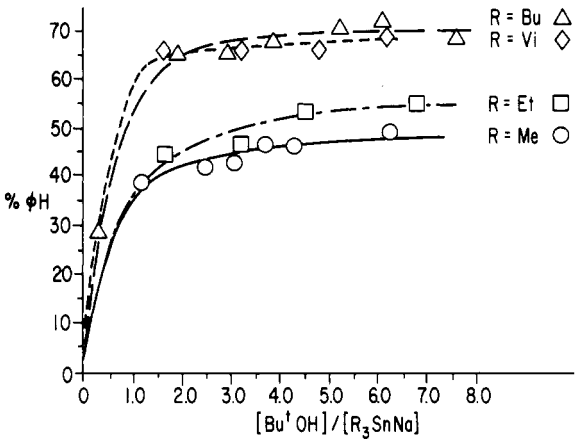



**Figure 3.** Effect of *tert*-butyl alcohol concentration on the yield of benzene formed in the reaction of bromobenzene with $R_3SnNa$ in TG at 25 °C.

is probably due to the decreased viscosity when more alcohol is present in the reaction medium. The lower proportion of cage product can be attributed to a lower reactivity of iodotrimethylstannane as compared with the bromo analogue. Similar experiments could not be conducted with chlorobenzene because its rate of reaction with trimethylstannylsodium was much slower than that of *tert*-butyl alcohol.

Although more detailed kinetic studies remain to be made, a comparison of the relative reactivities of the halobenzenes was made by conventional competition experiments. The results indicated that bromobenzene is about $10^5$ times as reactive as chlorobenzene, and iodobenzene about ten times as reactive as bromobenzene. This latter number is almost certainly too low for the rates of reaction of bromo- and iodobenzenes with trimethylstannylsodium are so fast that complete mixing of the reagents was not achieved before substantial reaction had occurred, thus yielding smaller differences in relative reactivities than the actual values.

**Effect of Substituents on Tin.** The effects of modest changes in the steric bulk at the tin atom were estimated by examining the reactions of triethyl- and tri-*n*-butylstannylsodium with bromobenzene with respect to the proportion of cage and noncage products formed as a function of the concentration of *tert*-butyl alcohol. Results are depicted in Figure 3 along with those for trimethylstannylsodium and trivinylstannylsodium. There is an increase in the proportion of benzene as the bulk of the alkyl group increases consistent with a decrease in the rate of reaction in the cage between arylsodium and halotrialkylstannane relative to the rates of diffusion.

Comparison of the results obtained with triethylstannylsodium and trivinylstannylsodium[21] should provide some information about the electronic effect on the cage reaction because the steric effects should be similar. Unexpectedly, the vinyl analogue, which would form bromotrivinylstannane with the more electrophilic tin in the cage, undergoes diffusion relative to cage reaction faster than the ethyl analogue. An explanation with the information at hand would be speculative.

**On the $S_{RN}1$ Mechanism.** This mechanism, which leads to very facile reaction of unactivated aryl halides with nucleophiles,[17a,b] must be explicitly examined as a possibility for the reaction under consideration. If the proposed cage effect is indeed real then the free-radical $S_{RN}1$ chain process cannot be involved in that part of the overall reaction. If it is involved in the noncage part of the reaction it is necessary to account for the formation of the reduction product in the presence of alcohol. A scheme which might account for this has been suggested.[17c] This is shown in eq 5–12. The first three of these represent the normal $S_{RN}1$ process.

$$Ar\cdot + Me_3Sn^- \rightarrow Ar\text{-}SnMe_3^-\cdot \quad (5)$$

$$Ar\text{-}SnMe_3^-\cdot + ArBr \rightarrow ArBr^-\cdot + ArSnMe_3 \quad (6)$$

$$ArBr^-\cdot \rightarrow Ar\cdot + Br^- \quad (7)$$

$$Me_3Sn^- + ROH \rightarrow RO^- + Me_3SnH \quad (8)$$

$$Me_3SnH + Ar\cdot \rightarrow Me_3Sn\cdot + ArH \quad (9)$$

$$Me_3Sn\cdot + ArBr \rightarrow Me_3SnBr + Ar\cdot \quad (10)$$

$$2Me_3Sn\cdot \rightarrow Me_3Sn\text{-}SnMe_3 \quad (11)$$

$$Me_3Sn\cdot + Ar\cdot \rightarrow Me_3SnAr \quad (12)$$

Trimethylstannane is formed in eq 8 by proton transfer from alcohol to stannyl anion when the former is present. Diversion from the normal $S_{RN}1$ process then occurs in eq 9 resulting in a trimethylstannyl radical and the reduction product. The radical may then react further as in eq 10, 11, or 12. A key step in formation of the reduction product is eq 8, a bimolecular reaction which occurs *in competion with* step (a) of Scheme III. If this were the case an increase in alcohol concentration should lead to a monotonic increase in the yield of reduction product, and the cage process should diminish in importance concomitantly—the leveling off in distributions of reduction and substitution products should not be observed. Experiments were conducted which verified the relative slowness of the reaction between trimethylstannylsodium and *tert*-butyl alcohol as compared with the virtually instantaneous reaction with bromobenzene. The stannylsodium was allowed to stand with a fivefold excess of the alcohol in TG for 90 and 120 min in separate experiments. Addition of *n*-butyl bromide resulted in the formation of 39 and 20% of *n*-butyltrimethylstannane, respectively, in the two experiments. The validity of this procedure was ascertained by the observations that when *n*-butyl bromide alone or in the presence of *tert*-butyl alcohol was treated with trimethylstannylsodium quantitative yields of *n*-butyltrimethylstannane were formed.

Trimethylstannylsodium can be prepared in liquid ammonia[1] and shows no signs of reacting with the solvent to form trimethylstannane. Yet when bromobenzene was added to such a preparation 96% of the aryl groups appeared as benzene and 4% as trimethylphenylstannane. Although the conditions of this experiment were quite different from those used in the major portion of this study, the result confirms the conclusion that the $S_{RN}1$ process is not involved. In yet another experiment trimethylstannylsodium was added to a solution of bromobenzene and trimethylstannane in TG. Analysis after 15 min revealed the formation of 98.7% of trimethylphenylstannane and no detectable benzene.

The results of the above-described experiments demonstrate in compelling fashion that the $S_{RN}1$ mechanism plays no detectable role in the reactions of aryl bromides with trimethylstannylsodium discussed in this paper.

## Conclusions

All of the results presented above are consistent with a mechanism in which trialkylstannylsodium reacts with aryl halide by nucleophilic displacement on halogen (halogen–metal exchange) in an initial step. The resulting halotrialkylstannane and arylsodium can react within the solvent cage in which they are formed, or they may diffuse out of the cage to react later with each other, or with other species present in the bulk of the medium. The $S_{RN}1$ mechanism does not participate in the systems studied. A more complex mechanism involving initial electron transfer from the stannyl anion to the aryl halide is not required by the data, nor is it rigorously excluded. Perhaps the major contribution of this work is the observation of the role played by the cage effect, the recognition of which offers the possibility of controlling the distribution of reaction

products by altering the viscosity of the reaction medium. It suggests that such control may be possible in a variety of other reactions in which reactive intermediates are formed in the initial step of a multistep mechanism.

## Experimental Section

**General.** Melting points and boiling points are uncorrected. Carbon-hydrogen analyses were done by Instranal of Rensselaer, N.Y. Infrared spectra were recorded on a Beckman IR-8 or IR-10 instrument. Infrared data are reported in units of $cm^{-1}$.

Unless otherwise noted, proton nuclear resonance spectra were obtained at 60 MHz using a Varian A-60A instrument. Samples requiring higher resolution or greater sensitivity were obtained at 100 MHz using a Varian HA-100D NMR spectrometer which was interfaced with a Digilab FTS/NMR-3 pulse and data system. Spectra were obtained in either the continuous wave frequency sweep mode with internal homonuclear lock or in the Fourier transform mode with heteronuclear fluorine lock. Hexafluorobenzene contained in an insert provided the fluorine resonance for locking. Chemical shifts ($\delta$) are reported in parts per million downfield from internal tetramethylsilane followed in parentheses by the multiplicity, coupling constant, number of protons, and assignment. Proton-tin-119 coupling constants are reported as $^{x}J$(Sn-H) with the superscript denoting the number of bonds intervening between the coupled nuclei.

Analytical gas chromatographic analyses were performed on an F & M Hewlett-Packard Model 5750 instrument equipped with flame ionization and thermal conductivity detectors. Peak areas in the chromatogram were determined either by disc integration or by digital integration with a Columbia Scientific Industries, Automatic Digital Integrator, Model CRS-208, equipped with an angular baseline corrector and a digital printer.

High-pressure liquid chromatography (HPLC) was performed on a Waters Associates ALC 200 series chromatograph equipped with a Model 6000A solvent delivery system, a U6K universal injector, and a refractive index detector.

All reactions with trimethylstannylsodium were conducted under an inert atmosphere of high-purity nitrogen (99.996%) which was passed through a column of Drierite. Tetraglyme (Ansul Corp.) was dried by high-vacuum distillation from molten sodium. All other chemicals were used without further purification. Tetramethylstannane was a gift from M & T Chemical Co.

**Trimethylstannylsodium** was prepared as previously described[9] from hexamethyldistannane and metallic sodium or sodium naphthalene. In the latter case sodium naphthalene was prepared by stirring 3.55 g (28 mmol) of naphthalene with 0.9 g (39 mmol) of sodium in 100 mL of TG dried by distillation from sodium at reduced pressure followed by elution from a column of activated alumina. Sufficient sodium naphthalene (ca. 50 mL) was added to 2.09 g (6.38 mmol) of hexamethyldistannane in 2 mL of TG to cause a color change from red to dark green. After standing for a few minutes the solution again became red. Concentrations of trimethylstannylsodium were determined by reaction of 1 mL of the solution with excess bromobenzene. Trimethylphenylstannane and benzene, when present, were determined by GLC with octane as an internal standard (6 ft × 0.125 in. stainless steel (ss) column, 15% polyphenyl ether (6r) on 80–100 Chromosorb W, temperature program 50–250 °C at 10 °C/min). Components eluted in the following order: PhH, $C_8H_{18}$, PhBr, $Me_3SnPh$, Naph, and TG.

**Trivinylstannylsodium.** Hexavinyldistannane was prepared by the reduction of chlorotrivinylstannane with sodium in liquid ammonia.[22] It was then converted into trivinylstannylsodium by reaction with sodium naphthalene in TG as described above for trimethylstannylsodium.

Triethylstannylsodium and tri-*n*-butylstannylsodium were prepared from the corresponding distannanes by the same procedure.

**Reaction of Bromobenzenes with Trimethylstannylsodium.** In a typical reaction, 5.0 mL (ca. 0.5 mmol) of trimethylstannylsodium was added by syringe to 161.7 mg (1.030 mmol) of bromobenzene and 69.0 mg (0.514 mmol) of *tert*-butylbenzene. Reactions were carried out under an atmosphere of nitrogen at 0 °C in 5-mol vials equipped with rubber septa and glass-enclosed magnetic stirring bars made by sealing 0.5-in. sections of paper clips in capillary tubing. The trimethylstannylsodium solution contained dodecane as an internal standard. GLC analysis of the crude reaction mixture (10 ft × 0.125 in. ss column, 10% UCW98 on 80–100 Chromosorb W, temperature program 35–200 °C at 6 °C/min, disc integration) gave, in order of elution, compound (mmol) $Me_4Sn$ (0.0163), PhH (0.0066), PhBr (0.526), *t*-BuPh (0.514), $Me_3SnPh$ (0.471), $C_{12}$ (0.492), TG, and $Me_2SnPh_2$ (0.0066).

**Dimethyldiphenylstannane.**[23] To phenylmagnesium bromide, prepared from 6.28 g (40 mmol) of bromobenzene and 0.97 g (41 mmol) of magnesium turnings, was added a saturated solution of 4.44 g (20 mmol) of dimethyldichlorostannane in diethyl ether. After refluxing for 1 h, the reaction mixture was decomposed with water, extracted with ether, dried ($MgSO_4$), and concentrated. Fractional distillation yielded 2.2 g (36%) of pure dimethyldiphenylstannane: bp 110 °C (0.25 Torr) [lit.[20] 127–140 °C (3 Torr)]; NMR (neat) $\delta$ 0.47 (s, $^{2}J$(SnCH) = 56 Hz, 6, $(CH_3)_2Sn$) and 7.1–7.5 (m, 10, ArH).

**Isolation of Dimethyldiphenylstannane from the Reaction of Bromobenzene with Trimethylstannylsodium.** Excess bromobenzene was added to 5 mL (3.5 mmol) of trimethylstannylsodium in TG. After 0.5 h, the reaction mixture was decomposed with 20 mL of water, extracted with 20 mL of petroleum ether, and washed repeatedly with water. Injection of the crude products with dimethyldiphenylstannane showed an identical retention time with the compound eluting after TG. GLC conditions: 15 ft × 0.125 in. ss column, 10% Apiezon L on 90–100 Anakrom ABS,[24] isothermal at 260 °C. Approximately 1 mg of the eluant tentatively assigned as dimethyldiphenylstannane was isolated by preparative GLC: 6 ft × 0.25 in. ss column, 15% Apiezon L on 60–80 Chromosorb W, isothermal at 255 °C; 100-MHz proton Fourier transform (pFT) NMR ($CCl_4$) $\delta$ 0.48 (s, $^{2}J$(SnCH) = 55 Hz, $(CH_3)_2Sn$) and 7.15–7.45 (m, ArH).

**Methane Evolution from Trimethylstannylsodium and Piperidine.** Sufficient 1 M sodium naphthalene (ca. 14 mL) in TG was added to 2.036 g (6.22 mmol) of hexamethyldistannane in 1 mL of TG to cause a color change from red to dark green. The dark green color due to excess sodium naphthalene soon disappeared. The reaction vessel was then connected to a gas buret and 2.46 mL (ca. 25 mmol) of dry piperidine was added. After 43 h, 15 mL of gas had evolved. Its IR spectrum was recorded: 3020 and 1306 $cm^{-1}$. These absorptions were flanked by equispaced decaying absorptions characteristic of the rotational-vibrational spectrum of methane.[25] An authentic sample of methane gave an identical spectrum.

**Intermolecular Trapping with *tert*-Butyl Alcohol.** A 0.375 M solution of trimethylstannylsodium in TG was prepared from hexamethyldistannane and sodium. One-milliliter aliquots of the anion solution were then added with stirring at 0 °C 1 to mL of TG solutions containing 0.976 M bromobenzene, 0.322 M octane, and varying concentrations of *tert*-butyl alcohol: 0.1, 0.23, 0.47, 0.50, 0.70, 0.82, and 1.17 M. After stirring for 5 min the sample vessels were then fitted with glass stoppers and were placed in the refrigerator until analysis. GLC analysis (6 ft × 0.25 in. glass column, 5% Apiezon L on 60–80 Chromosorb G, temperature program 50–250 °C at 10 °C/min, digital integration) showed the following compounds in order of elution: *t*-BuOH, $Me_4Sn$, PhH, $C_8H_{18}$, PhBr,$PhSnMe_3$, and TG.

**Reaction of Tributylstannylsodium with Bromobenzene in the Presence of *tert*-Butyl Alcohol.** In a typical reaction 1 mL of a 0.21 M solution of tributylstannylsodium was added with stirring at 25 °C to 2 mL of a TG solution of 0.412 M octadecane, 0.243 M bromobenzene, 0.079 M octane, and $X$ M *tert*-butyl alcohol ($X$ = 0.1, 0.03, 0.20, 0.41, 0.54, 0.60, and 0.80 M). Approximately 15 min after reaction, 1 mL of the reaction mixture was added to 2 mL of water and extracted with 1 mL of pentane. GLC analysis (10 ft × 0.125 in. ss column, 10% UCW98 on 80–100 Chromosorb W, temperature program 50–280 °C at 10 °C/min, digital integration) gave the following compounds in order of elution: PhH, $C_8H_{18}$, PhBr, Naph, TG, $C_{18}H_{40}$, and $Bu_3SnPh$.

The same procedure was used in the other series of trapping experiments. With triethylstannylsodium it was necessary to separate the products by extraction with pentane and water, followed by GLC analysis of the pentane layers. This was due to the simultaneous elution of triethylphenylstannane and TG. Small amounts of tetraethylstannane and hexaethyldistannane were indicated by coinjection of authentic samples. Toluene and hexadecane were used as internal standards.

With trivinylstannylsodium toluene and hexadecane were used as internal standards. Substantial amounts of diphenyldivinylstannane and tetravinylstannane were observed in the experiment without alcohol, but were absent in the others. Relative amounts of benzene, toluene, and bromobenzene could be determined directly on the reaction product mixtures. The amounts of phenyltrivinylstannane and

dodecane were determined on the pentane extracts after application of the extraction procedure described above.

**Reaction of Trimethylstannylsodium with *p*-Bromotoluene Containing 2-Propanol-*d*.** To 0.5 mL (ca. 4 mmol) of *p*-bromotoluene in 4 mL of dry TG was added 4 mL (3.66 mmol) of a 0.92 M solution of trimethylstannylsodium in TG. GLC analysis of the reaction mixture indicated the presence of ca. 2% toluene.

The above reaction was repeated in the presence of 2-propanol-*d* (Aldrich, 98% D) by adding 20 mL (18.4 mmol) of trimethylstannylsodium at 0 °C to 3.087 g (18.1 mmol) of *p*-bromotoluene and 7.78 mL (ca. 100 mmol) of 2-propanol-*d* in 10 mL of TG. The volatile products were then vacuum distilled (30 °C, 0.025 Torr) to a liquid nitrogen trap. *p*-Deuteriotoluene was isolated from the distilled products by preparative GLC (80 × 0.75 in. ss column, 15% Apiezon L on 60–80 Chromosorb W, isothermal at 90 °C). The mass spectrum of reagent grade toluene at 70 eV ionization potential gave *m/e* (relative peak height) 94 (0.18), 93 (6.02), 92 (84.0), 91 (100), 90 (5.29), 89 (3.59). Lowering the ionization potential totally suppressed formation of the tropylium ion: *m/e* (relative peak height) 93 (7.5), 92 (100), and 91 (0.0). The mass spectrum of the isolated *p*-deuteriotoluene gave *m/e* (relative peak height) 95 (0.23), 94 (6.55), 93 (90.3), 92 (100), 91 (16.6), and 90 (3.42). The mass spectrum recorded at the lowered ionization potential gave *m/e* (relative peak height) 94 (7.5), 93 (100), and 92 (4.0). The proportions of *p*-deuteriotoluene and toluene in the isolated mixture were thus 96 and 4%, respectively.

**Synthesis of α,*o*-Dibromotoluene.**[26] *o*-Bromotoluene was brominated at the benzylic position by the method of Hahn[27] using a mixture containing 225 mL of $CCl_4$, 49.1 g (0.287 mol) of *o*-bromotoluene, 53.6 g (0.301 mol) of *N*-bromosuccinimide, and 0.6 g of benzoyl peroxide with refluxing for 22 h. Distillation through a 15-cm Vigreux column yielded 50.9 g (71%) of pure α,*o*-dibromotoluene: bp 67–69 °C (0.35 Torr) [lit.[26] bp 122–126 °C (10 Torr)]; NMR (neat) δ 4.40 (s, 2, $ArCH_2Br$) and 6.70–7.43 (m, 4, ArH).

**Effect of Solvent Viscosity on Reaction of Trimethylstannylsodium with *p*-Bromotoluene in the Presence of *tert*-Butyl Alcohol.** One-milliliter samples of 1.0 M trimethylstannylsodium in TG were added to 4-mL solutions of varying DME:TG composition. The resulting solutions of 0.2 M trimethylstannylsodium were 0, 20, 40, 60, and 80% DME by volume. One milliliter of each of these solutions was then added at 25.0 °C with stirring under nitrogen to 1-mL solutions of 0.396 M *p*-bromotoluene, 0.1264 M decane (as internal standard), and 0.992 M *tert*-butyl alcohol in glyme solvents with corresponding DME:TG ratios. After 5 min, the reaction vessels were fitted with glass stoppers and were then placed in the refrigerator until analysis. The samples were later analyzed by GLC (6 ft × 0.25 in. glass column, 5% Apiezon L on 60–80 Chromosorb G, temperature program 50–250 °C at 10 °C/min, digital integration). The order of elution was DME, PhMe, $C_{10}H_{22}$, *p*-MePhBr, *p*-$MePhSnMe_3$, and TG.

**Determination of Viscosities and Dielectric Constants.** Viscosities were determined with an Ostwald viscosimeter. Densities were determined by standard methods employing a pycnometer. The viscosimeter constant, β, was determined at 25.0 °C by timing the flow for water ($n$ = 0.8904 cP) and tetraglyme ($n$ = 3.67 cP).[28] Solutions of 0.2 M *p*-bromotoluene, 0.06 M decane, and 0.5 M *tert*-butyl alcohol in mixtures of DME:TG (0, 20, 40, 60, and 80% DME by volume) were prepared and their viscosities measured at 25 °C. Dielectric constants were determined on solutions of the same compositions using a Type DM01 Dipolemeter (Wissenschaftlich-Technische Werkstatten, GmbH).

**3-(*o*-Bromophenyl)propiophenone.** To sodium ethoxide prepared by adding 3.91 g (0.17 mol) of sodium to 100 mL of anhydrous ethanol was added 65.1 g (0.339 mol) of ethyl benzoylacetate with stirring. The reaction mixture was then brought to a gentle reflux and 42.4 g (0.17 mol) of α,*o*-dibromotoluene was added over 0.5 h. After 2 h of reflux, excess base was consumed by the addition of another 0.2 g of the dibromide. The reaction mixture was refluxed for another 1 h, cooled, filtered, and concentrated. Half of the concentrated mixture was subjected to acid hydrolysis and decarboxylation by refluxing for 8 h in a solution containing 40 mL of glacial acetic acid, 5 mL of concentrated sulfuric acid, and 10 mL of water. The reaction mixture was then neutralized with sodium hydroxide and extracted with dichloromethane. The extracts were dried ($MgSO_4$), concentrated, and distilled through a 15-cm column packed with glass helices to yield 15.9 g (65%) of pure product: bp 150–155 °C (0.1 Torr); mp (petroleum ether) 40–41 °C; NMR ($CCl_4$) δ 3.10 (broad s, 4, $ArCH_2CH_2$) and 6.75–8.0 (m, 9, ArH); IR (thin film), 1685 $cm^{-1}$ (CO).

Anal. Calcd for $C_{15}H_{13}BrO$: C, 62.30; H, 4.53. Found: C, 62.63; H, 4.54.

Further structural characterization of 4-(*o*-bromophenyl)propiophenone was obtained by adding small quantities of the shift reagent, $Eu(DPM)_3$. The NMR spectrum of a 10% solution of the ketone in $CCl_4$ was recorded after each addition. The broad singlet at 3.10 ppm changed to a multiplet centered at 4.5 ppm exhibiting a characteristic $A_2B_2$ pattern.[29]

**Reaction of Trimethylstannylsodium with 3-(*o*-Bromophenyl)propiophenone.** A 0.27 M (14.4 mmol) solution of trimethylstannylsodium in 54 mL of TG was added at room temperature over a 1.5-h period to a stirred solution containing 3.88 g (13.4 mmol) of 3-(*o*-bromophenyl)propiophenone (c) in 10 mL of TG. After stirring for 12 h, the reaction mixture was treated with water and extracted with petroleum ether. The organic extract was washed repeatedly with water. GLC analysis (10 ft × 0.125 in. ss column, 10% UCW98 on 80–100 Chromosorb W, isothermal at 250 °C) of the crude product mixture gave the following compounds in order of elution: 3-phenylindene (a), 3-phenylpropiophenone (b), 3-(*o*-bromophenyl)propiophenone (c), and 3-(*o*-trimethylstannylphenyl)propiophenone (d). Wet column liquid chromotography (3 × 50 cm column, neutral alumina activated at 165 °C, 40-mL fractions collected, order of eluting solvents (solvent (mL)) petroleum ether (280), 50:50 petroleum ether–$CCl_4$ (120), $CCl_4$ (1040), PhH (320), $Et_2O$ (240), MeOH (1500)) of the crude product mixture provided impure d in fractions 44–46: NMR ($CCl_4$) δ 0.317 (s, $^2J$(SnCH) = 54 Hz, ca. 9, $Sn(CH_3)_3$), 3.1 (broad t, ca. 4, $ArCH_2CH_2$), and 7.2–8.0 (m, ca. 9, ArH). GLC collection (6 ft × 0.25 in. ss column, 15% UCW98 on 60–80 Chromosorb W, isothermal at 185 °C) of fractions 44–46 provided pure d for a mass spectrum: *m/e* 359 ($M - CH_3$), 165 ($Me_3Sn^+$) for 120 Sn. The reduction (b) and ring closure (a) products were isolated by GLC collection (as above) of fractions 57–60. Compound a: 100-MHz pFT NMR ($CCl_4$) δ 3.44 (broad d, 2, $ArCH_2$), 6.46 (broad t, 1, CH) and 7.35 (m, 9, ArH); mass spectrum *m/e* 192 ($M^+$). Compound b: 100-MHz pFT NMR ($CCl_4$) δ 3.10 ($A_2B_2$ pattern, 4, $CH_2CH_2$) and 7.16–7.84 (m, 10, ArH) (identical with literature NMR).

**3-(*o*-Bromophenyl)propiophenone-*2,2-d*$_2$.** A mixture of 2.19 g (7.6 mmol) of 3-(*o*-bromophenyl)propiophenone, 2.6 g (130 mmol) of 99.8% deuterium oxide, and 100 mg of sodium carbonate in 50 mL of 1,4-dioxane was refluxed for 2 h. The reaction mixture was then extracted with petroleum ether, dried ($MgSO_4$), and concentrated. The NMR spectrum indicated 48% deuterium incorporation by integration of the methylene and aromatic protons. The above procedure was repeated with reflux for 15 h. The worked up mixture yielded 1.84 g of deuterated compound with ca. 98% deuterium incorporation: NMR ($CCl_4$) δ 3.1 (broad s, 2.04, $CH_2CD_2$) and 6.75–8.0 (m, 9.00, ArH).

**Reaction of 3-(*o*-Bromophenyl)propiophenone-*2,2-d*$_2$ with Trimethylstannylsodium.** The procedure was the same as that for the undeuterated compound. GLC analysis (10 ft × 0.125 in. ss column, 10% UCW98 on 80–100 Chromosorb W, isothermal at 255 °C) of the pentane extract gave, in order of elution [compound (% area)], 3-phenylindene (12.5), 3-phenylpropiophenone (50), and 3-(*o*-trimethylstannylphenyl)propiophenone (37.5). They were identified by coinjection with the pentane extract from the reaction of the undeuterated compound. GLC collection (6 ft × 0.25 in. ss column, 15% UCW98 on 60–80 Chromosorb W, isothermal at 200 °C) of a fraction which distilled at 120 °C (0.25 Torr) yielded pure 3-phenylpropiophenone: mass spectrum *m/e* 212 ($M^+$), 92 ($C_7H_6D$, 75%), and 91 ($C_7H_7$, 25%).

**3-Phenylindene** was prepared by the method of Bruson and Plant[30] in 57% yield: by 98–100 °C (0.025 Torr) [lit.[30] bp 121–126 °C (0.1 Torr)]; NMR ($CCl_4$) δ 3.44 (d, 2, $ArCH_2$), 6.46 (t, 1, CH), and 7.1–7.6 (m, 9, ArH).

**4-(*o*-Bromophenyl)butan-2-one** was prepared by the method of Boatman et al.[31] in 81% yield: bp 72–74 °C (0.05 Torr) [lit.[31] bp 139–140 °C (10 Torr)]; IR (thin film) 1720 $cm^{-1}$; NMR ($CCl_4$) δ 2.02 (s, 3, $CH_3$), 2.78 ($A_2B_2$ pattern, 4, $CH_2CH_2$), and 6.8–7.5 (m, 4, ArH) [lit.[34] NMR ($CCl_4$) δ 2.00 (s, 3), 2.43–3.13 ($A_2B_2$, 4), and 6.77–7.57 (m, 4)].

**Reaction of Trimethylstannylsodium with 4-(*o*-Bromophenyl)butan-2-one.** A 0.53 M (32 mmol) solution of trimethylstannylsodium in TG was added dropwise over 1.5 h at room temperature to 5 g (22 mmol) of 4-(*o*-bromophenyl)butan-2-one in 10 mL of TG. After stirring overnight, the reaction mixture was treated with 70 mL of

water and 10 mL of saturated ammonium chloride and then extracted with petroleum ether. The organic layer was washed repeatedly with water, dried ($MgSO_4$), and concentrated to yield 4 g of crude products. VPC analysis (5 ft × 0.125 in. ss column, 10% UCW98 on 80–100 Chromosorb W, isothermal at 200 °C) of the crude products indicated the following compounds in order of elution: 3-methylindene, 3-methyleneindan, 3-methylindanol, 4-phenylbutan-2-one, and 4-(*o*-trimethylstannylphenyl)butan-2-one. GLC collection (6 ft × 0.25 in. ss column, 15% UCW98 on 60–80 Chromosorb W, isothermal at 145 °C) of 3-methylindanol yielded a mixture of 3-methylindene and 3-methyleneindan. Distillation of the crude products gave two fractions, bp ca. 70 °C (20 Torr) and bp 90 °C (0.5 Torr). The first contained one major component which, upon GLC collection, was identified as 3-methylindene: 100-MHz pFT NMR ($CDCl_3$) $\delta$ 2.17 (d, $J(CHCH_3)$ = 1.7 Hz, 3, $CH_3$), 3.30 (t, $J(CHCH_2)$ = 2 Hz, 2, $ArCH_2$), 6.30 (M=[= CH), and 7.1–7.6 (m, 4, ArH) [lit.[32] NMR ($CCl_4$) $\delta$ 2.06 (d, $J(CHCH_3)$ = 1.66 Hz, $CH_3$), 3.13 (t, $J(CHCH_2)$ = 1.77 Hz, $ArCH_2$), 6.04 (m, 1, CH) aromatic not listed]. Treatment of the higher boiling fraction with solid sodium bisulfate on a steam bath for 1 h provided 3-methylindene. Preparative GLC collection as above of this fraction also yielded pure 4-phenylbutan-2-one: 100-MHz pFT NMR ($CDCl_3$) $\delta$ 2.11 (s, 3, $CH_3$), 2.81 ($A_2B_2$ pattern, 4, $ArCH_2CH_2$), and 7.2 (broad s, 5, ArH). Impure 4-(*o*-trimethylstannylphenyl)butan-2-one was obtained by distillation of the pot residue, bp ca. 100 °C (0.025 Torr). A pure sample was obtained by preparative GLC (30 ft × 0.25 in. ss column, 15% SE-30 on 60–80 Chromosorb W, isothermal at 220 °C) of the distillate: NMR ($CCl_4$) $\delta$ 0.300 (s, $^2J$(SnCH) = 53.9 Hz, 9, $Sn(CH_3)_3$), 2.06 (s, 3, $CH_3$), 2.50–2.95 ($A_2B_2$, 4, $CH_2CH_2$), and 6.95–7.4 (m, 4, ArH); IR (thin film) 1720 $cm^{-1}$ (CO).

Anal. Calcd for $C_{13}H_{20}OSn$: C, 50.30; H, 6.48. Found: C, 50.14; H, 6.57.

**Products from the Reaction of Trimethylstannylsodium with 4-(*o*-Bromophenyl)butan-2-one.** A solution containing 4.143 g (17.05 mmol) of 4-(*o*-bromophenyl) butan-2-one in 17 mL of TG was cooled to 0 °C. To this was added 24 mL of a 0.75 M (18 mmol) solution of trimethylstannylsodium in TG. Workup after 0.5 h was accomplished by adding 75 mL of water and extracting with petroleum ether. The organic extracts were washed repeatedly with water, dried ($MgSO_4$), and concentrated to yield 4.97 g of crude product. TLC on alumina gave two spots: $R_f$ 0.5 and 0.8–1.0. Separation of the crude mixture by dry column chromatography (15 × 1.3 in. column, deactivated alumina (5% water), developed with $CHCl_3$, 0.5% fluorescent indicator) gave two fractions. The first fraction (2.5–5.5 in.) yielded 394 mg (16%) of 3-methylindanol:[33] NMR ($CDCl_3$) $\delta$ 1.48 (s, 3, $CH_3$), 1.95–2.12 (m, 2, $CH_2$), 2.48 (broad s, 1, OH), 2.72–3.00 (m, 2, $CH_2$), and 7.1–7.37 (m, 4, ArH); IR (thin film) 3400 $cm^{-1}$ (OH). The second fraction (9.5–12 in.) yielded 1.732 g of a 50:50 mixture of 4-phenylbutan-2-one (22% yield by area of $CH_3$ protons in the NMR) and 4-(*o*-trimethylstannylphenyl)butan-2-one (22% yield by area of $CH_3$ protons in the NMR).

**4-(*o*-Bromophenyl)butan-2-ol.** To 30 mL of anhydrous diethyl ether was added 0.616 g (16.2 mmol) of lithium aluminum hydride. This was followed by the slow addition of 7.06 g (31.3 mmol) of 4-(*o*-bromophenyl)butan-2-one in 20 mL of anhydrous ether. After refluxing for 0.5 h, the excess hydride was quenched at 0 °C with 0.6 mL of water followed by 0.6 mL of 15% sodium hydroxide and then another 1.8 mL of water. The salts were stirred until granular, filtered, dried ($MgSO_4$), and concentrated to yield 6.79 g of crude product (96% pure, 92% yield): NMR ($CDCl_3$) $\delta$ 1.23 (d, 3, $CH_3$), 1.53–1.91 (m, 2, $CH_2$), 2.69–2.97 (m, 2, $CH_2$), 3.18 (broad s, 1, OH), 3.83 (m, 1, CH), and 6.8–7.55 (m, 4, ArH). This product was used without further purification.

**Reaction of Trimethylstannylsodium with 4-(*o*-Bromophenyl)-butan-2-ol.** To a 50-mL flask equipped with a magnetic stirrer and a nitrogen bubbler was added 2.262 g (9.88 mmol) of 4-(*o*-bromophenyl)butan-2-ol and 10 mL of TG cooled to 0 °C. A 1 M solution of trimethylstannylsodium in TG was slowly added with stirring until all of the aryl bromide had reacted. Progress of the reaction was followed by GLC. Workup after 0.5 h was achieved by adding water, extracting with petroleum ether, and washing the extracts repeatedly with water. The dried ($MgSO_4$) and concentrated extracts yielded 3.14 g of crude products. GLC analysis (6 ft × 0.25 in. glass column, 5% Apiezon L on 60–80 Chromosorb G, temperature program from 50–250 °C at 10 °C/min) of the crude product mixture indicated the following compounds in order of elution: $(Me_3Sn)_2$, 4-phenylbutan-2-ol, and 4-(*o*-trimethylstannylphenyl)butan-2-ol. TLC ($CHCl_3$) of the product mixture on alumina gave spots at $R_f$ 0.1, 0.4, 0.5, and 0.8. Purification of product mixture by dry column chromatography (23 × 0.5 in. column, deactivated alumina (5% water) with 0.5% fluorescent indicator, developed with $CHCl_3$) provided three fractions. The top fraction (5–10.5 in.) yielded 442 mg (30%) of 4-phenylbutan-2-ol:[33] NMR ($CDCl_3$) $\delta$ 1.18 (d, 3, $CH_3$), 1.75 (m, 2, $CH_2$), 2.65 (m, 2, $CH_2$), 3.0 (broad d, 1, OH), and 7.2 (broad s, 4, ArH). The second fraction (10.5–13.5 in.) yielded 464 mg of a mixture of 4-phenylbutan-2-ol (15% yield by NMR) and 4-(*o*-trimethylstannylphenyl)butan-2-ol (8% yield by NMR). The third fraction (13.5–17 in.) yielded 544 mg (18% yield) of tin substitution product which was purified by HPLC (8 ft × 0.125 in. column packed with Porasil A, eluted with $CHCl_3$ at 2 mL/min): NMR ($CCl_4$) $\delta$ 0.317 (s, $^2J$(SnCH) = 54.2 Hz, 9, $Sn(CH_3)_3$), 1.18 (d, $J$ = 6 Hz, 3, $CH_3$), 1.37–1.88 (m, 2, $CH_2$), 2.17 (broad s, 1, OH) and 6.92–7.43 (m, 4, ArH); IR (thin film) 3350 $cm^{-1}$ (OH).

Anal. Calcd for $C_{13}H_{22}OSn$: C, 49.88; H, 7.08. Found: C, 50.14; H, 7.21.

The above reaction was repeated on a small scale to determine whether any substitution product formed at 50% conversion of the halide. To 0.342 g (1.49 mmol) of 4-(*o*-bromophenyl)butan-2-ol in 1.5 mL of TG was added 0.75 mL of 1 M trimethylstannylsodium in TG. After 0.5 h 0.1 mL of water was added and the NMR spectrum was recorded: NMR (TG + $H_2O$) $\delta$ 0.06 (s, $Me_4Sn$), 0.204 (2, $(Me_3Sn)_2$), 0.304 (s, $^2J$(SnCH) = 54.0 Hz, $ArSn(CH_3)_3$), and 0.373 (s, $^2J$(SnCH) = 65.5 Hz, $(CH_3)_3SnOH$). Substitution product was indeed formed in this experiment.

***o*-Bromophenyldimethylcarbinol.** To a cooled solution (0 °C) containing 1.495 g (6.954 mmol) of methyl *o*-bromobenzoate in 15 mL of THF was added 21 mL (0.66 M, 13.9 mmol) of methylmagnesium bromide in THF. The reaction mixture was refluxed for 1 h, then decomposed with sufficient saturated ammonium chloride to totally precipitate all salts. The salts were then washed repeatedly with THF. The combined washings were dried ($CaCl_2$) and concentrated to yield 1.85 g of crude product. The NMR spectrum indicated the presence of some unreacted ketone and ester. TLC ($CHCl_3$) on alumina gave three spots: $R_f$ 0.5, 0.75, and 0.9. Purification by dry column chromatography (25 × 0.5 in. column, deactivated alumina (5% water) with 0.5% fluorescent indicator, developed with $CHCl_3$) yielded a fraction (12–21 in.) containing 0.995 g (66%) of pure *o*-bromophenyldimethylcarbinol: NMR ($CDCl_3$) $\delta$ 1.73 (s, 6, $CH_3$), 3.17 (s, 1, OH), and 6.83–7.80 (m, 4, ArH).

**Reaction of Trimethylstannylsodium with *o*-Bromophenyldimethylcarbinol.** To 72.3 mg (0.34 mmol) of *o*-bromophenyldimethylcarbinol in 0.34 mL of TG was added, with stirring at room temperature, 0.072 mL of 0.9 M (0.065 mmol) trimethylstannylsodium in TG. After standing overnight, 0.1 mL of water was added to the reaction mixture to solubilize the salts: NMR (TG + $H_2O$) $\delta$ 0.06 (s, $Me_4Sn$), 0.21 (s, $(Me_3Sn)_2$), and 0.403 (s, $^2J$(SnCH) = 61 Hz, $(CH_3)_3SnOH$), 1.49 (s, $COH(CH_3)_2$ from phenyldimethylcarbinol), and 1.70 (s, $COH(CH_3)_2$ from unreacted aryl bromide). There were no trimethylstannyl proton resonances due to arene substitution product.

The above experiment was repeated using an excess of stannyl anion. To 3 mL of 0.9 M (2.7 mmol) trimethylstannylsodium was added 199 mg (0.55 mmol) of *o*-bromophenyldimethylcarbinol. The reaction mixture was worked up after 0.5 h by adding water and extracting with petroleum ether. The ether extracts were washed repeatedly with water, then dried ($MgSO_4$) and concentrated to yield 0.38 g of crude product: NMR ($CDCl_3$) $\delta$ 0.06 (s, $Me_4Sn$), 0.22 (s, $^2J$(SnCH) = 49 Hz, $^3J$(SnSnCH) = 16 Hz, $(Me_3Sn)_2$), 0.33 (s, $^2J$(SnCH) not detectable owing to weak resonance, tentatively assigned to $ArSn(CH_3)_3$), and 1.55 (s, $COH(CH_3)_2$, reduction and/or substitution product).

***o*-Trimethylstannylphenyldimethylcarbinol.** To a stirred solution containing 2.39 g (7.98 mmol) of *o*-carbomethoxyphenyltrimethylstannane[9] in 5 mL of anhydrous ether was added 12.3 mL of 1.3 M (15.96 mmol) methyllithium in ether. After 0.5 h the reaction mixture was decomposed with 20 mL of petroleum ether followed by 8 mL of water. The dried ($MgSO_4$) and concentrated organic layer yielded 1.854 g of crude product. TLC ($CCl_4$) on alumina gave four spots: $R_f$ 0.1, 0.2, 0.3, and 0.5. Purification by dry column chromatography (24 × 0.5 in. column, deactivated alumina (5% water) with 0.5% fluorescent indicator, developed with $CCl_4$) yielded three fractions. The first (top) fraction (2–7 in.) provided 358 mg (33%) of phenyldimethylcarbinol and some impurities; NMR was comparable with that

of an authentic sample. The second fraction (9–11 in.) yielded 256 mg (11%) of *o*-trimethylstannylphenyldimethylcarbinol which was purified by HPLC (8 ft × 0.125 in. column packed with Porasil A, eluted with $CHCl_3$ at 2.0 mL/min): NMR ($CCl_4$) $\delta$ 0.201 (s, $^2J$(SnCH) = 53.1 Hz, 9, $ArSn(CH_3)_3$), 1.42 (s, 1, OH), 1.55 (s, 6, $CH_3$), and 7.1–7.7 (m, 4, ArH); IR (thin film) 3580 $cm^{-1}$ (OH).

Anal. Calcd for $C_{12}H_{20}OSn$: C, 48.21; H, 6.74. Found: C, 48.19; H, 6.86.

The third fraction (12.5–17 in.) provided 546 mg (24%) of *o*-acetylphenyltrimethylstannane which was further purified by preparative GLC (30 ft × 0.25 in. ss column, 15% SE-30 on 60–80 Chromosorb W, isothermal at 180 °C): NMR ($CDCl_3$) $\delta$ 0.233 (s, $^2J$(SnCH) = 55.5 Hz, 9, $ArSn(CH_3)_3$), 2.63 (s, 3, $COCH_3$), and 7.25–8.15 (m, 4, ArH); IR (thin film) 1670 $cm^{-1}$ (CO).

Anal. Calcd for $C_{11}H_{16}OSn$: C, 46.67; H, 5.70. Found: C, 46.75; H, 5.76.

**Phenyldimethylcarbinol.**[34] A solution of phenylmagnesium bromide in ether, prepared from 3.7 g (0.15 mol) of magnesium turnings and 15.6 g (0.1 mol) of bromobenzene, was added to a cooled solution (0 °C) containing 6.5 g (0.11 mol) of acetone in 20 mL of ether. The reaction mixture was decomposed after 1 h with 15 mL of saturated ammonium chloride. The salts were washed repeatedly with ether, then the washings were combined, dried ($MgSO_4$), and concentrated. The concentrated extracts yielded 11.5 g (80% yield, 95% pure by VPC) of phenyldimethylcarbinol: NMR ($CDCl_3$) $\delta$ 1.47 (s, 6, $CH_3$), 3.18 (s, 1, CH), and 7.03–7.65 (m, 5, ArH). This product was used without further purification.

***o*-Trimethylstannylphenylcarbinol.** To a slurry containing 0.23 g (6.06 mmol) of lithium aluminum hydride in 20 mL of ether was added 1.418 g (4.74 mmol) of *o*-carbomethoxyphenyltrimethylstannane in 10 mL of ether. The reaction mixture was refluxed for 10 min and then cooled to 0 °C. The excess hydride was destroyed by successive addition of 0.23 mL of water, 0.23 mL of 15% sodium hydroxide, and 0.69 mL of water. The salts were stirred until granular and were then filtered and washed with ether. The filtrate and combined washings were dried ($MgSO_4$) and concentrated to yield 1.17 g of crude product. TLC ($CHCl_3$) on alumina gave two spots: $R_f$ 0.2 and 0.45. Dry column chromatography (20 × 0.5 in. column, deactivated alumina (5% water) with 0.5% fluorescent indicator, developed with $CHCl_3$) provided a fraction (10–15 in.) containing 851 mg (66%) of pure *o*-trimethylstannylphenylcarbinol: NMR ($CDCl_3$) $\delta$ 0.292 (s, $^2J$(SnCH) = 54.5 Hz, 9, $ArSn(CH_3)_3$), 2.13 (broad s, 1, OH), 4.61 (broad s, 2, $CH_2$), and 7.13–7.62 (m, 4, ArH); IR (thin film) 3360 $cm^{-1}$ (OH). An analytically pure sample was obtained by HPLC (8 ft × 0.125 in. column packed with Porasil A, eluted with $CHCl_3$ at 2.0 mL/min).

Anal. Calcd for $C_{10}H_{16}OSn$: C, 44.33; H, 5.95. Found: C, 44.47; H, 6.08.

**Reaction of Trimethylstannylsodium with *o*-Bromophenylcarbinol.** A solution containing 0.933 g (4.99 mmol) of *o*-bromophenylcarbinol and 0.2375 g (1.049 mmol) of hexadecane (internal standard) in 5 mL of TG was added to a 25-mL flask equipped with a magnetic stirrer and nitrogen bubbler. To this solution was added 0.77 M trimethylstannylsodium in TG in increments of 1 mL. After each addition GLC analysis (6 ft × 0.25 in. ss column, 15% polyphenyl ether (6r) on 60–80 Chromosorb W, isothermal at 175 °C for 7 min, then programmed to 225 °C at ca. 15 °C/min) determined the extent of reaction. The following components were found in order of elution: $Me_4Sn$, $(Me_3Sn)_2$, $PhCH_2OH$, $C_{16}H_{34}$, *o*-$BrPhCH_2OH$, and TG. All of the aryl bromide was consumed after adding 3.5 mL (2.7 mmol) of trimethylstannylsodium. The yield of benzyl alcohol by VPC analysis was 18%. The NMR spectrum of the reaction mixture revealed the following: NMR (TG + $H_2O$ + MeOH) $\delta$ 0.06 (s, $Me_4Sn$), 0.21 (s, $(Me_3Sn)_2$), and 0.33 (s, $^2J$(SnCH) = 64 Hz, $(CH_3)_3SnOH$). There was no resonance attributable to $ArSn(CH_3)_3$. Addition of authentic *o*-trimethylstannylphenylcarbinol gave a resonance at $\delta$ 0.23 (s, $^2J$(SnCH) = 54.5 Hz, $ArSn(CH_3)_3$) which persisted without change for longer than 72 h. Benzyl alcohol was isolated by GLC collection and was shown to be identical with an authentic sample by NMR spectroscopy. To the reaction mixture in the 25-mL flask another 2 mL of trimethylstannylsodium (4.24 mmol total) was added and the NMR spectrum recorded. A weak resonance at 0.23 ppm was attributed to the trimethylstannyl protons of substitution product presumably formed from the sodium salt of *o*-bromophenylmethanol.

**Effect of *tert*-Butyl Alcohol on the Reaction between *n*-Butyl Bromide and Trimethylstannylsodium. 1.** To 0.168 g (1.23 mmol) of *n*-butyl bromide was added 1 mL of TG containing 0.52 mmol of trimethylstannylsodium with stirring at 0 °C. GLC analysis of the reaction mixture indicated the formation of 0.53 mmol (100%) of trimethylphenylstannane.

**2.** A similar experiment in which the trimethylstannylsodium was added to a mixture of 0.99 mmol of *n*-butyl bromide and 3.34 mmol of *tert*-butyl alcohol resulted in the formation of 98.5% of trimethylphenylstannane.

**Reaction between Trimethylstannylsodium and *tert*-Butyl Alcohol.** To 1 mL of a 0.85 M solution of trimethylstannylsodium in TG was added 4.48 mmol of *tert*-butyl alcohol at 0 °C with stirring. After 90 min 0.85 mmol of *n*-butyl bromide was added and the reaction mixture analyzed by GLC, indicating the formation of 39% of trimethylphenylstannane. In a similar experiment 20% was found after 120 min, indicating that the reaction between these compounds is relatively slow.

**Reaction of Bromobenzene with Trimethylstannylsodium in the Presence of Trimethylstannane.** To a solution of 0.68 mmol of bromobenzene and 1.32 mmol of trimethylstannane stirred at 0 °C was added 2 mL of an 0.50 M solution of trimethylstannylsodium in TG. After 15 min the mixture was analyzed by GLC and found to contain a 98.7% yield of trimethylphenylstannane.

**Reaction of Trimethylstannylsodium with Bromobenzene in Liquid Ammonia.** Sodium (6.86 mmol) was dissolved in 20 mL of liquid ammonia at −78 °C. To this was added 3.44 mmol of hexamethyldistannane, and the mixture was allowed to warm up to −33 °C. Then 9.06 mmol of bromobenzene was added, followed 15 min later by 10 mL of petroleum ether. The ammonia was allowed to evaporate and the residual petroleum ether solution analyzed by GLC, which revealed relative yields of 96% benzene and 4% trimethylphenylstannane by the usual internal standard method.

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(11) Scheme I accounts qualitatively for the data in Table I. However, quantitative aspects are not entirely clear. For example, iodobenzene is the most reactive of the halides used and yet it yields larger amounts of the by-products than does bromobenzene. Step (a) to the right is slow as indicated by the methane-forming experiment described. Thus this reaction must be facilitated in some way during the course of reaction of the halobenzene and trimethylstannylsodium, or some alternate pathway is available for the formation of dimethyldiphenylstannane and tetramethylstannane.
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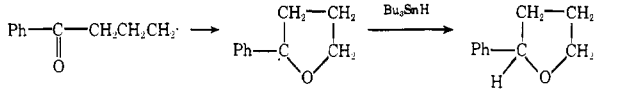

(21) In the experiments with trivinylstannylsodium the combined yields of benzene and phenyltrivinylstannane were uniformly greater than 90% when *tert*-butyl alcohol was present in the reaction mixture. However, in the absence of the alcohol only 4% of benzene and 48% of phenyltrivinylstannane were observed, and tetravinylstannane and diphenyldivinylstannane were present in substantial amounts. This observation provides substantiation for the dissociation step (a) of Scheme I, followed by step (b) and steps (c) and (d).
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# Three-Electron Oxidations. 13. Intramolecular Cooxidation of 2,7-Dihydroxyheptanoic Acid. Structure of the Transition State in the Chromium(VI) Oxidation of Alcohols[1,2]

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**Abstract:** The investigation of the chromic acid oxidation of a series of dihydroxy acids $HO(CH_2)_nCHOHCO_2H$ revealed that 2,7-dihydroxyheptanoic acid ($n = 5$) reacts entirely differently than other members of the series. It undergoes a very rapid cooxidation on both functional groups to yield carbon dioxide and the free radical $OCH(CH_2)_4\dot{C}HOH$ as primary products. The radical is subsequently oxidized to the dialdehyde 1,6-hexanedial. The reaction obeys a simple rate law $v = k[HCrO_4^-][C_7$ acid] over a $10^5$ range in hydrogen ion concentrations. Depending on the reaction conditions, 6-hydroxyhexanal and 1,6-hexanediol can also be formed. The formation of the free-radical intermediate is interpreted in terms of a three-electron transfer within the chromium(VI)–dihydroxy acid complex. None of the two neighboring homologues, 2,6-dihydroxyhexanoic and 2,8-dihydroxyoctanoic acids, give any evidence of oxidation of the terminal alcoholic group. The requirement that the two reaction centers are separated by a chain of four carbon atoms leads to the following conclusions: (1) the carboxylate group forms a ligand to chromium; (2) in the reaction intermediate chromium(VI) has at least five oxygen ligands; (3) the transfer of hydrogen in the oxidation of the alcoholic function is intramolecular; and (4) in the oxidation step hydrogen cannot be transferred as a proton. The last two points should hold generally for chromium(VI) oxidations of alcohols. A general procedure for the synthesis of the dihydroxy acids ($n = 2, 4, 5, 6$) is reported.

Several years ago we reported[3] that chromic acid reacts with a mixture of oxalic acid and isopropyl alcohol by several orders of magnitude faster than it does with either of the two substrates. We have shown that this rapid reaction is a cooxidation process in which both substrates are oxidized simultaneously. Later we found additional examples of cooxidation reactions involving oxalic acid[4] and, more recently, $\alpha$-hydroxy acids.[5] The rate-limiting step in all cooxidation reactions is the oxidative decomposition of a negatively charged termolecular intermediate complex. In this step chromium(VI) is reduced directly to chromium(III) by a synchronous three-electron transfer. While the kinetic data provided sufficient information about the composition and the charge of the activated complex, no definite conclusion could be derived about its detailed structure and geometry, about the coordination number of chromium(VI) in the intermediate, and about the nature of hydrogen transfer process.

We hoped that these questions could be answered if we succeeded in incorporating all functional groups into a single molecule and achieved an "intramolecular cooxidation". The structural requirements for a substrate capable of undergoing such an oxidation should provide considerable insight into the structure and configuration of the transition state. Further, since one component of the cooxidation reaction is the oxidation of an alcoholic hydroxyl group to a carbonyl group, the results and conclusions should be applicable to the important and much investigated chromium(VI) oxidation of alcohols.[6]

With this goal in mind we decided to investigate the chromic acid oxidation of a series of $\alpha,\omega$-dihydroxy acids of the general formula $HO(CH_2)_nCHOHCO_2H$.

## Experimental Section

**Materials.** Glycolic acid (99+%, Gold Seal, Aldrich) and glyceric acid (Aldrich) were used without further purification. Perchloric acid solutions were prepared from 70% perchloric acid (Fisher). Chromium solutions were prepared from sodium dichromate (J. T. Baker, reagent). Lactic acid (Baker analyzed reagent, 0.90 g, 0.01 mol) was dissolved in water (20 mL) and then refluxed for 3 h with calcium carbonate (Fisher reagent, 2.0 g, 0.020 mol). The solution was filtered hot and water removed on a rotary evaporator. The powdered calcium salt (1.6 g) was crystallized from MeOH (25 mL). The dried calcium salt was dissolved in water (20 mL) and passed through a cation-exchange resin column (Dowex 50W-X8, $H^+$ form, 20–50 mesh, 15 g). The resulting solution was evaporated in vacuo.

**Synthesis of $\alpha,\omega$-Dihydroxy Acids.** The dihydroxy acids of the general formula $HO(CH_2)_nCHOHCO_2H$ ($n = 2, 4, 5, 6$) required for the study were prepared by a four-step synthesis summarized in Scheme I (cf. Results). A typical experimental procedure is given for 2,7-dihydroxyheptanoic acid:

**$HO(CH_2)_5CN$.** 5-Chloro-1-pentanol (Aldrich, 12.25 g 0.10 mol) was added in 10–15 min to a rapidly stirred suspension of powdered potassium cyanide (Fischer, reagent grade, 9.76 g, 9.15 mol) in dimethyl sulfoxide (Fischer, reagent grade, 50 mL) at 110 °C, kept at

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