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(70) A 6 ft × 1/8 in. 3% SP-2401 on 100/120 Supelcoport column was used.

(71) A 8 ft × 1/4 in. 5% STAP on 80/100 Chromosorb WAW column was used.

(72) A 18 ft × 1/8 in. 10% Carbowax 20M on 80/100 Chromosorb WAW-DMCS column was used. A temperature program of 50–200 °C at 5 °C/min separated all the carbamate isomers and hydrolysis products.

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Free-Radical Participation in the Reactions of Selected Metalate Anions with Alkyl Halides[1]

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Abstract: The reactions of lithium, sodium, and potassium trimethyltin with *cis*- and *trans*-4-*tert*-butylcyclohexyl bromide (**1** and **2**), chloride, and tosylate and cyclopropylcarbinyl chloride, bromide, iodide, and tosylate (**5**, X = Cl, Br, I, OTs) have been examined. Treatment of $(CH_3)_3SnLi$, -Na, -K with **1** and **2** at 0 °C in THF produces a mixture of *cis*- and *trans*-4-*tert*-butylcyclohexyltrimethyltin (**3** and **4**), (**4**:**3**, Li, 72:28; Na, 64:36; K, 64:36). In DME at 0 °C somewhat different values are observed: **4**:**3**, Li, 79:21; Na, 47:53; K, 53:47. Thus, alkylation of these bromides proceeds in all instances with stereochemical equilibration. Intermediate 4-*tert*-butylcyclohexyl radicals are implicated. Product isomer ratios for reactions carried out at lower temperatures (−70 °C) indicate that the alkylation of both $(CH_3)_3SnNa$ and $(CH_3)_3SnK$ with **1** and **2** produce slightly different ratios of **4**:**3** than the values observed at 0 °C, but nonetheless still proceed with complete loss of stereochemical integrity. Under similar conditions, reaction of $(CH_3)_3SnLi$ with **1**, but not **2**, yields an enhanced predominance of the trans product **4**, corresponding to a net increase in inversion of configuration. These results suggest that at least one stereospecific pathway is operating at low temperatures in addition to any nonstereospecific reaction(s). By comparison, reaction of *cis*- and *trans*-4-*tert*-butylcyclohexyl tosylate with $(CH_3)_3SnLi$ produces only **4** and **3**, respectively, and thus proceeds with complete inversion of configuration. The reaction of $(CH_3)_3SnLi$ with *cis*- and *trans*-4-*tert*-butylcyclohexyl chloride presumably provides an intermediate in the transition between these two extremes, since it does not occur with complete stereochemical equilibration. The contention that the reaction of alkyl halides with $(CH_3)_3SnLi$, -Na, and -K proceeds by two (or more) competing reaction pathways, one of which involves intermediate free alkyl radicals, is supported by the observation that the reaction of lithium, sodium, and potassium trimethyltin with cyclopropylcarbinyl bromide and iodide, but not chloride or tosylate, yields two alkylation products: trimethyl(cyclopropylcarbinyl)tin (**6**) and trimethyl(allylcarbinyl)tin (**7**). The yield of **7** is a function of halide, temperature, solvent, gegenion, and concentration. These observations are compatible with a reaction mechanism involving free, noncaged, cyclopropylcarbinyl radicals as intermediates. A similar study of the reaction of $CpFe(CO)_2Na$ with **5** leads to the conclusion that only the reaction with cyclopropylcarbinyl iodide involves free cyclopropylcarbinyl radicals to any significant degree. In contrast, the reaction of PhSeNa with **5** produce only cyclopropylcarbinyl phenyl selenide and presumably does not proceed through the intermediacy of free alkyl radicals.

The displacement of halides and other groups from alkyl substrates by metalate anions represents one of the most important routes for the formation of metal-carbon σ bonds. Because of its importance, considerable attention has been paid to the mechanism of these reactions and their generally high stereoselectivity has been widely interpreted as evidence against the intermediacy of free alkyl radicals and in favor of an S_N2 pathway.[2,3]

Stereochemical studies provide the single most valuable type of information available in characterizing the mechanism of any transformation involving the rupture or formation of a bond at a tetrahedral carbon. However, the serious shortcomings associated with the application of traditional stereochemical studies to organometallic systems, particularly transition metal alkyls, are well known. Alternative procedures have been developed which circumvent some of these problems, although these alternatives are not without their own limitations.[2,4]

As an adjunct to information obtained from stereochemical studies of organometallic systems, we have employed the cyclopropylcarbinyl moiety. There are several practical advantages that accrue from the use of this system as a diagnostic probe with which to investigate the reaction of metalate anions. First, cyclopropylcarbinyl halides are generally stable compounds which are readily prepared in high purity. Second, the homoallyl rearrangement which characterizes the free cyclopropylcarbinyl radical is a particularly well understood radical rearrangement.[5-7] Rearrangement is too slow a process (k = 1.3×10^8 s^{-1} at 25 °C)[6] to compete effectively with diffusion of the intermediate radical out of the solvent cage in which it is initially formed:[8] homoallyl rearrangement in this system is not concerted with the formation of the radical. Thus, and most usefully for the interpretation of the work reported here, the origins of organometallic products containing the allylcarbinyl moiety can be couched in terms of a relatively straightforward reaction sequence involving kinetically free

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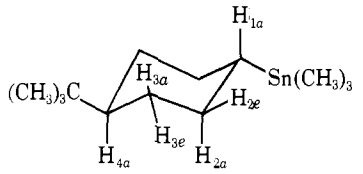
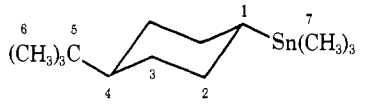
Table I. Description of the ^1H NMR Spectrum of 4[a]



δ	assignment[b]	J
1.06 (1 H, t, t)	H_{1a} (H_{1a})	J_1 = 13.0 J_2 = 3.5
1.20 (2 H, d, t)	H_{2a} (H_{3a})	J_1 = 13.0 J_2 = 13.0
1.88 (2 H, d, d)	H_{2e} (H_{3e})	J_1 = 13.0 J_2 = 2.3
(br, m)[c]	H_{3a} (H_{2a})	
1.77 (2 H, d, d)	H_{3e} (H_{2e})	J_1 = 11.0
(br, m)[c]	H_{4a} (H_{1a})	
0.82 (9 H, s)	$(CH_3)_3C$	
−0.01 (9 H, s)	$(CH_3)_3Sn$	J_{CH_3}, ^{119}Sn = 50.0

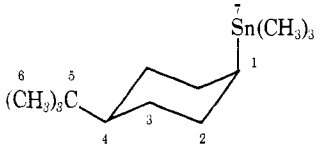
[a] Spectra were recorded at 270 MHz. Coupling constants are in hertz. Chemical shifts (δ) are in parts per million upfield (−) and downfield (+) from Me_4Si. Coupling constant assignments were confirmed by decoupling. Notation: *a* = axial; *e* = equatorial; br = broad; s = singlet; t = triplet; d,d = doublet of doublets; d,t = doublet of triplets; t,t = triplet of triplets; m = multiplet. [b] A definitive assignment of certain resonances could not be made. The assignments shown in parentheses represent alternative and equally reasonable assignments of these resonances. This ambiguity does not diminish the certitude of the associated conformational assignment. [c] Individual chemical-shift assignments were not made to these protons.

Table II. Description of the ^{13}C NMR Spectrum of 4 and 3[a]



4

assignment	δ	$J^{119}Sn$–C	$J^{117}Sn$–C
C_1	25.33	389.7	408.1
C_2	31.76	13.6	
C_3	29.96	66.6	
C_4	48.57	6.2	
C_5[b]	32.51		
C_6	27.48		
C_7	−12.01	291.1	304.5



3

assignment	δ	$J^{119}Sn$–C	$J^{117}Sn$–C
1	~27.5[c]	386.3	402.5
2	31.10	12.0	
3	26.85	13.8	
4	46.83		
5	32.69		
6	27.58		
7	−9.32	280	301.3

[a] Spectra were recorded at 20 MHz. Coupling constants are in hertz. Chemical shifts (δ) are in parts per million upfield (−) and downfield (+) from Me_4Si. [b] Assignment confirmed by off-resonance decoupling. [c] Carbons 1 and 6 exhibit equivalent chemical shifts in this compound.

cyclopropylcarbinyl radicals in solution, and need not be concerned with the subtleties of concerted rearrangements or radical cage reactions. Finally, the rearrangement of cyclopropylcarbinyl anion to allylcarbinyl anion has been studied extensively by Roberts and co-workers.[9] These authors report that the rearrangement of cyclopropylcarbinylmagnesium bromide to allylcarbinylmagnesium bromide is a first-order reaction with a half-life in dimethyl ether of 121 min at −24 °C. It follows that the value of the rate constant for this process is $k = 9.5 \times 10^{-5}$ s^{-1}. In the absence of rate data specific to the rearrangement of the cyclopropylcarbinyl anion under the conditions employed in the present study, it is not possible to rigorously exclude the possibility that the rearranged products reported therein do not proceed by way of a cyclopropylcarbinyl–allylcarbinyl anionic rearrangement. However, for such a process to compete effectively with the rearrangement of the cyclopropylcarbinyl radical would require a minimum increase of $\gtrsim 10^{10}$ in the rate of the intermediate cyclopropylcarbinyl anion over that observed for cyclopropylcarbinylmagnesium bromide. While perhaps not impossible, an increase of such magnitude seems physically unreasonable under the present circumstances. We, therefore, feel justified in concluding that the rearrangement leading to the product of allylcarbinyl products occurs essentially exclusively by a free-radical pathway.

In the work reported here, we describe chemical and spectroscopic evidence which establishes that the reaction of certain metalate anions, specifically trimethyltin and cyclopentadienyl(dicarbonyl)iron, with the more reactive alkyl halides proceeds in varying degrees through the intermediacy of free alkyl radicals.

Results

Chemical Studies. $(CH_3)_3Sn^-$. The trimethyltin anion is a strong nucleophile. Previous investigations have suggested that the reaction of lithium trimethyltin with certain alkyl bromides, specifically *cis*-4-*tert*-butylcyclohexyl bromide[10] and 3,3-dimethylbutyl-*1,2-d*$_2$ bromide,[2] proceeds respectively with predominant *retention* and inversion of configuration at carbon. The interpretation of the former work is clouded by the fact that only one diastereomer of the possible pair of alkyl bromides was examined. In an effort to resolve these divergent stereochemical conclusions, we examined the reaction of trimethyltin anion with both *cis*- and *trans*-4-*tert*-butylcyclohexyl bromide (**1** and **2**) as well as the corresponding tosylates.

In brief, assignment of the configuration for **3** and **4** is based on interpretation of the data in Tables I and II in light of generalizations derived from prior studies of the ^1H and ^{13}C NMR spectra: first, cis and trans configurations in 4-substituted cyclohexanes are easily distinguished on the basis of the magnitude of the vicinal coupling constant, with representative ranges for coupling constants being $J_{a,a}$ = 8–14, $J_{a,e}$ = 1–7, and $J_{e,e}$ = 1–7 Hz;[11] second, all other factors being equal, equatorial protons absorb at lower field than do their epimeric axial counterparts;[11] third, it has been recently demonstrated that a Karplus-type dependence exists of ^{119}Sn–^{13}C coupling

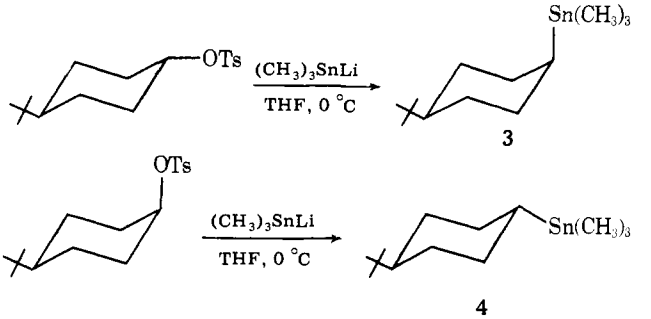


Table III. Reaction of *cis*- and *trans*-4-*tert*-Butylcyclohexyl Bromide (**1** and **2**) with $(CH_3)_3SnM$ (M = Li, Na, K)

entry	substrate (concn, M)	$(CH_3)_3SnM$ (concn, M)	solvent	temp °C	yield, % $(CH_3)_3SnR$	isomer distribution trans:cis
1	**1** (0.5)	M = Li (0.04)	THF	0	71	68:32
2		(0.2)	THF	0	60	72:28
3		(0.4)	THF	0	76	70:30
4		(0.8)	THF	0	75	73:27
5		(0.4)	THF	−70	83	82:18
6		(0.4)	DME	0	80	78:22
7		(0.4)	DME	−70	70	85:15
8	**2** (0.5)	M = Li (0.04)	THF	0	83	69:31
9		(0.2)	THF	0	84	73:27
10		(0.4)	THF	0	86	74:26
11		(0.8)	THF	0	79	71:29
12		(0.4)	THF	−70	65	70:30
13		(0.4)	DME	0	100	80:20
14		(0.4)	DME	−70	91	77:23
15	**1** (0.5)	M = Na (0.04)	THF	0	60	72:28
16		(0.2)	THF	0	82	65:35
17		(0.4)	THF	0	79	61:39
18		(0.8)	THF	0	50	53:47
19	**1** (0.5)	M = Na (0.4)	THF	−70	44	64:36
20		(0.4)	DME	0	87	48:52
21		(0.4)	DME	−70	78	45:55
22	**2** (0.5)	M = Na (0.04)	THF	0	60	74:26
23		(0.2)	THF	0	59	68:32
24		(0.4)	THF	0	59	64:36
25		(0.8)	THF	0	63	55:45
26		(0.4)	THF	−70	73	64:36
27		(0.4)	DME	0	83	46:54
28		(0.4)	DME	−70	88	49:51
29	**1** (0.5)	M = K (0.04)	THF	0	75	76:24
30		(0.2)	THF	0	82	68:32
31		(0.4)	THF	0	71	65:35
32		(0.8)	THF	0	78	62:38
33		(0.4)	THF	−70	60	68:32
34		(0.4)	DME	0	71	54:46
35		(0.4)	DME	−70	73	50:50
36	**2** (0.5)	M = K (0.04)	THF	0	91	76:24
37		(0.2)	THF	0	78	66:34
38		(0.4)	THF	0	88	64:36
39		(0.8)	THF	0	89	63:37
40		(0.4)	THF	−70	88	65:35
41		(0.4)	DME	0	88	52:48
42		(0.4)	DME	−70	75	52:48

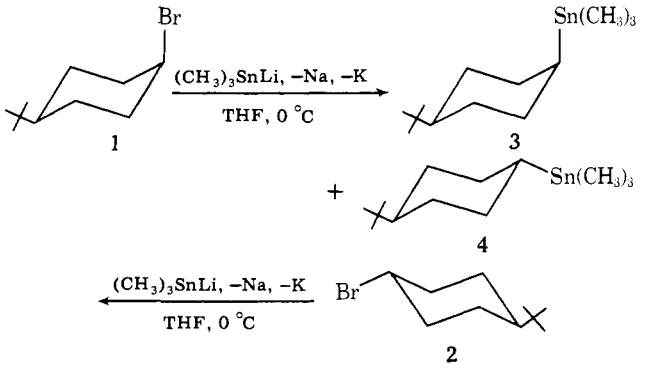
[a] Absolute yields are based on alkyl halide. Both absolute relative yields were determined by GLC analysis on a 6 ft × 0.125 in. column of UCW-98 on Chromosorb W. Control experiments established that neither starting halides **1** and **2** nor the products **3** and **4** suffer isomerization under reaction conditions. [b] Estimated error limits ±2%.

in a series of stereochemically rigid organotin compounds, the observed ranges being $J_{a,a}$ = 50–70, $J_{a,e}$, $J_{e,e}$ = 0–25 Hz.[12] Thus, the cis and trans configuration of **3** and **4**, respectively, is confirmed by the magnitude of the vicinal ^1H–^1H and ^{13}C–^{119}Sn coupling. These spectra, it should be noted, are substantially different from the corresponding spectra of independently synthesized trimethyl(3-*tert*-butylcyclohexyl)-tin.[13] Taken together, the internal consistency of these assignments provides compelling evidence for their correctness; reversal of assignments would require several unreasonable assumptions.[14]

Treatment of *cis*- and *trans*-4-*tert*-butylcyclohexyl tosylate with lithium trimethyltin in THF produces in low yield (≲5%) respectively *trans*-4-*tert*-butylcyclohexyltrimethyltin (**4**) and *cis*-4-*tert*-butylcyclohexyltrimethyltin (**3**). Thus, alkylation with these tosylates occurs with complete inversion of configuration at carbon.

The results in Table III establish that the reaction of lithium trimethyltin with the secondary bromides **1** and **2** proceeds, within experimental error, with essentially complete loss of stereochemical integrity at 0 °C, yielding equivalent ratios of **3**:**4**. A closer examination of entries 1–14 in Table III reveals several additional points concerning the reaction of lithium trimethyltin with **1** and **2**. Specifically, product isomer distribution is not significantly influenced by changes in reactant concentrations over the range investigated. However, product isomer distribution is influenced by solvent: although reaction in either THF or DME at 0 °C leads to equivalent isomer ratios for reactions conducted in the *same* solvent, reaction in DME results in a somewhat greater predominance of the trans isomer **4** (3.5:1) than does reaction in THF (2.5:1). It is further apparent that alkylation in THF at −70 °C no longer produces equivalent isomer distribution: reaction of the cis bromide **1** leads to a noticeable increase in the amount of trans alkylation product **4** over that observed for the equivalent reaction carried out at 0 °C. A similar redistribution of the product isomer ratio does *not* occur in the corresponding reaction of the trans bromide **2**. The fact that S_N2 displacements on 4-*tert*-butylcyclohexyl bromide are known to proceed substantially more favorably with the cis than the trans isomer[15] suggests a reasonable explanation of this result, viz., that at least two competing pathways are available for alkylation and that one of

Scheme I. Reaction of *cis*- and *trans*-4-*tert*-Butylcyclohexyl Bromide with Trimethyltin Anion in THF or DME at 0 °C

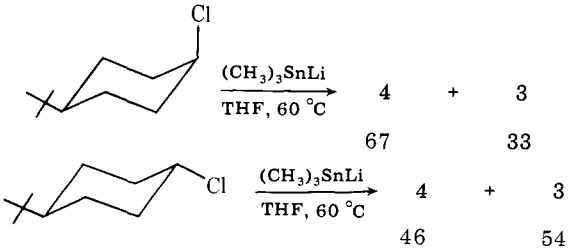


these is a S_N2 substitution process, which becomes kinetically favored, particularly for the cis isomer **1**, over other alkylation processes at lower temperatures.

For comparison, Table III contains the product isomer ratios observed on reaction of **1** and **2** with sodium and potassium trimethyltin. This comparison reveals the influence which gegenion has on the product formation. For example, it appears that, like $(CH_3)_3SnLi$, the reaction of **1** and **2** with $(CH_3)_3SnNa$ and $(CH_3)_3SnK$ leads to equivalent mixtures of **3** and **4**. However, although sodium trimethyltin and potassium trimethyltin yield essentially equivalent product isomer ratios under comparable conditions, there is a noticeable difference between the trans:cis product ratio produced in the reaction of lithium trimethyltin (2.5:1) and that observed for the equivalent reactions of $(CH_3)_3SnNa$ and $(CH_3)_3SnK$ (1.7-1.8:1).

Unlike $(CH_3)_3SnLi$, temperature has no significant influence on the product isomer ratios observed in reactions of either $(CH_3)_3SnNa$ and $(CH_3)_3SnK$, while solvent does affect the ratio of **3**:**4**, but in a significantly different way than it does the equivalent reaction with $(CH_3)_3SnLi$. Specifically, the reaction of either $(CH_3)_3SnNa$ or $(CH_3)_3SnK$ in DME produces a near statistical ratio of **3** and **4** corresponding to an increase in the production of the cis isomer relative to that observed with CH_3SnLi. Thus, although $(CH_3)_3SnNa$ and $(CH_3)_3SnK$ exhibit gross similarities in their reactivity toward **1** and **2**, there exist obvious finer differences between the equivalent reaction of these reagents and those of $(CH_3)_3SnLi$. Whatever the origin of these differences (vide infra), the obtainment of stereochemical equilibrium is best rationalized as resulting from the intermediacy of 4-*tert*-butylcyclohexyl radicals.

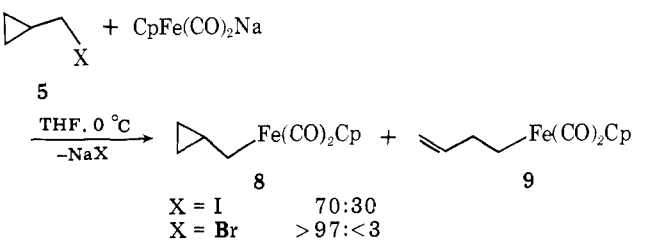
Finally, the contrast between the stereospecific reaction of $(CH_3)_3SnLi$ with *cis*- and *trans*-4-*tert*-butylcyclohexyl tosylate and the complete stereochemical equilibration observed for the reaction with the corresponding bromides **1** and **2** suggested the need to examine the stereochemical course of alkylation with *cis*- and *trans*-4-*tert*-butylcyclohexyl chloride. The results, summarized below, reveal that while alkylation



does occur with a loss of configuration at carbon, overall, a slight predominance of inversion of configuration is observed for both isomers. Thus, alkylation of $(CH_3)_3SnLi$ with *cis*- and *trans*-4-*tert*-butylcyclohexyl chloride bridges the gap between the two extremes of stereoselectivity observed for the corresponding tosylates and bromides.

Reaction of Cyclopropylcarbinyl Halides with Trimethyltin Anion. Although the products observed from reaction of **1** and **2** with trimethyltin anion implicate alkyl radicals as intermediates in these reactions, they do not clearly define the extent to which the generation and subsequent reaction of the intermediate radicals are confined to a solvent cage and the extent to which these radicals become "free" in solution. In an effort to resolve this question, we have examined the reaction of cyclopropylcarbinyl halides and tosylate, **5** (X = I, Br, Cl, OTs), with trimethyltin anion. The results, summarized in Table IV, reveal that a number of factors affect the extent of rearrangement. First, the nature of the leaving group is strongly influential in determining the degree of rearrangement: there is substantial rearrangement with the iodide, only modest rearrangement with the bromide, and no detectable rearrangement with the chloride or tosylate. This order is consistent with the recognized reactivity of these alkyl substrates in reactions that are known to proceed by way of an initial electron-transfer step.[16] Second, the nature of the gegenion influences the extent of rearrangement: under comparable conditions, considerably greater rearrangement is observed with sodium and potassium trimethyltin than with lithium trimethyltin. Third, there is a noticeable solvent effect: greater rearrangement is observed in the reaction of **5** (X = Br, I) with $(CH_3)_3SnLi$ in THF than in DME; however, the opposite effect is observed for the equivalent reaction with $(CH_3)_3SnNa$ and $(CH_3)_3SnK$. Finally, both concentration and temperature can affect the extent of rearrangement. Specifically, the extent of rearrangement increases as the concentration of trimethyltin anion decreases, but decreases as the the reaction tempeature is lowered. Both of these observations are in qualtitative accord with the intermediacy of free cyclopropylcarbinyl radicals in these reactions. Thus, all factors being equal, reducing the concentration of organotin species would diminish the rate of radical-radical coupling which, in turn, would increase the lifetime of the intermediate cyclopropylcarbinyl radical and, accordingly, the extent of rearrangement. Similarly, all factors being equal, lowering the temperature of reaction diminishes the rate of the cyclopropylcarbinyl-allylcarbinyl radical rearrangement.[6]

Reaction of $CpFe(CO)_2Na$ with Cyclopropylcarbinyl Halides. The cyclopentadienyldicarbonyliron anion, like $(CH_3)_3Sn^-$, is one of the strongest nucleophiles known.[2] Thus, it became a matter of some mechanistic interest to examine its reaction with cyclopropylcarbinyl halides. Treatment of cyclopropylcarbinyl iodide with sodium cyclopentadienyl(dicarbonyl)iron in THF at 0 °C produces a 70:30 mixture of cyclopropyl- and allylcarbinyl(cyclopentadienyl)(dicarbonyl)iron, **8** and **9**, re-



spectively, as ascertained by their characteristic ^1H NMR spectra. By contrast, the reaction of cyclopropylcarbinyl bromide with $CpFe(CO)_2Na$ in THF yields, within the limits of detection (>3%), only **9**. Thus, the alkylation of both $(CH_3)_3Sn^-$ and $CpFe(CO)_2^-$ by cyclopropylcarbinyl iodide proceeds to a significant extent through the intermediacy of nongeminate cyclopropylcarbinyl radicals. A similar reaction pathway is not operational, however, in the alkylation of $CpFe(CO)_2^-$ by cyclopropylcarbinyl bromide.

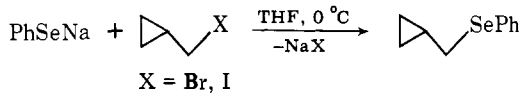
Reaction of PhSeNa with Cyclopropylcarbinyl Halides. We have also examined the reaction of sodium phenyl selenide with cyclopropylcarbinyl bromide and iodide. Examination of these

Table IV. Reaction of Cyclopropylcarbinyl Halides **5** (X = Cl, Br, I, OTs) with $(CH_3)_3SnM$ (M = Li, Na, K)

5 (concn, M)	$(CH_3)_3SnM$ (concn, M)	solvent	temp °C	product yield, %[a]	isomer distribution[b] **6:7**
X = OTs (0.5)	M = Li (0.4)	THF	0	90	>99:<1
X = Cl (0.5)	M = Li (0.4)	THF	0	85	>99:<1
(0.5)	(0.4)	DME	0	70	>99:<1
X = Br (0.5)	M = Li (0.4)	THF	50	71	74:26
(0.5)	(0.4)	THF	0	77	83:17
(0.5)	(0.4)	THF	−50	83	93:7
(0.5)	(0.04)	THF	0	82	86:14
(0.5)	(0.4)	DME	0	61	89:11
X = I (0.2)	M = Li (0.4)	THF	0	82	53:47
(0.5)	(0.4)	THF	0	78	54:46
(1.0)	(0.4)	THF	0	69	52:48
neat	(0.4)	THF	0	60	50:50
(0.5)	(0.4)	THF	−50	76	79:21
(0.5)	(0.4)	DME	0	68	37:67
X = Cl (0.5)	M = Na (0.4)	THF	0	65	>99:<1
		DME	0	62	>99:<1
	M = K (0.4)	THF	0	65	>99:<1
	(0.4)	DME	0	60	>99:<1
X = Br (0.5)	M = Na (0.4)	THF	0	85	85:15
	(0.04)	THF	0	45	84:16
	(0.4)	DME	0	62	95:5
	M = K (0.4)	THF	0	55	87:13
	(0.04)	THF	0	49	78:22
	(0.4)	DME	0	72	90:10
X = I (0.5)	M = Na (0.4)	THF	0	56	12:88
		DME	0	63	27:73
	M = K (0.4)	THF	0	73	21:79
		DME	0	55	40:60

[a] Absolute yields are based on alkyl halide. Both absolute and relative yields were determined by GLC analysis on a 6 ft × 0.125 in. column of UCW-98 on Chromosorb W. Control experiments established that neither the starting halide **5** nor the products **6** and **7** suffer isomerism under reaction conditions. [b] Estimated error limits: ±3%.

reaction mixtures revealed no detectable (<1%) rearrangement in the alkylation products. Previous studies[2] have shown that



X = Br, I

the alkylation of sodium phenyl selenide by 3,3-dimethyl-*1,2-d*$_2$ brosylate proceeds with >95% inversion of configuration at carbon. The present results are consistent with this observation: alkylation of PhSeNa with cyclopropylcarbinyl bromide and iodide does not proceed by a pathway involving free cyclopropylcarbinyl radicals.

ESR Studies. In addition to the chemical evidence presented in the preceding sections, we have sought adjunct physical evidence which would sustain our conclusions. In this vein we have examined the ESR spectrum of mixtures produced by mixing solutions of sodium cyclopentadienyl(dicarbonyl)iron with various alkyl halides in a flat mixing cell of simple design inserted into the ESR cavity so as to minimize the time between mixing and observation. As previously reported,[17] we observed an intense ESR spectrum of ethyl, *n*-butyl, isopropyl, *sec*-butyl, and *tert*-butyl radicals in the reaction of $CpFe(CO)_2Na$ with the corresponding alkyl iodides. Reaction with the analogous bromides and chlorides did not yield a detectable concentration of alkyl radicals. However, strong spectra of benzyl and allyl radicals were observed in reaction of $CpFe(CO)_2Na$ with benzyl and allyl bromide, respectively. No ESR signals attributable to organometallic radical species were observed in any of these reactions.

Discussion

The data presented here demonstrate that the mechanism of the reaction of alkyl halides with trimethyltin anion is sensitive to changes in the structure of the alkyl moiety, the halide center, the gegenion, and reaction solvent. Taken together with related studies, they establish the following reaction profile.

First, the loss of stereochemical integrity observed in the reaction of **1** and **2** with $(CH_3)_3SnM$ (M = Li, Na, K) argues against a concerted process and implies strongly that alkylation with this secondary alkyl bromide proceeds extensively by a free-radical pathway. A further comparison of the stereochemical results listed in Table III with those reported for the 4-*tert*-butylcyclohexyl halides produced by halogen transfer to 4-*tert*-butylcyclohexyl radicals is useful for it reveals that the latter reactions exhibit product isomer ratios ranging from near-statistical values to those showing a substantial predominance of the cis isomer.[18] Such behavior has been rationalized as corresponding to distributions expected on the basis of torsional strain considerations. In contrast, the stereochemical results seen in Table III reveal a product distribution which in most instances manifests a predominance of the trans isomer. Such results can be explained by invoking product development that is dominated by steric factors which favor reaction of bulky intermediate organotin species (Schemes II and III) from the less hindered trans side of the 4-*tert*-butylcyclohexyl radical. All other factors being equal, it follows that for those reactions which exhibit stereochemically equilibrated product distributions, the observed differences between trans:cis ratios is a direct reflection of the differences in the steric effects encountered in the carbon–tin bond-forming step.

Second, the reaction of the cyclopropylcarbinyl bromide, and by extension primary alkyl bromides in general, with $(CH_3)_3SnM$ proceeds in part by a pathway involving intermediate free radicals. Specifically, our results suggest that a minimum of 17% of the substitution product formed by the reaction of $(CH_3)_3SnLi$ with **5** (X = Br) in THF at 0 °C arises via a pathway involving nongeminate allylcarbinyl radicals.

Our confidence in this conclusion is sustained by the observation of Whitesides and co-workers,[2] who found that alkylation of $(CH_3)_3SnLi$ with the primary halide 3,3-dimethylbutyl-*1,2-d*$_2$ bromide occurs with ca. 80% inversion of configuration. Combined, these results suggest that the majority (80%) of the reaction of $(CH_3)_3SnLi$ with primary alkyl bromides takes place by a non-free-radical pathway (i.e., one involving an S_N2 process and/or fast coupling of primary geminate radicals) and that the remainder of the alkylation proceeds through the intermediacy of kinetically free alkyl radicals.

Finally, *if* this conclusion can be extended, unqualified, to the reaction of $(CH_3)_3SnLi$ with **5** (X = I), it follows that ca. 50% of the alkylation of $(CH_3)_3SnLi$ by primary alkyl iodides occurs by a non-free-radical pathway and ca. 50% by a mechanism involving kinetically free alkyl radicals as intermediates. Similarly, it can also be concluded that the alkylation of $(CH_3)_3SnLi$ by cyclopropylcarbinyl chloride, and by extension primary alkyl chlorides in general, does *not* involve free alkyl radicals as intermediates. Taken together with our earlier ESR observations,[2] these results allow a description of the influence which the nature of halogen and the structure of the alkyl groups bonded to the halogen exert on the degree of free-radical participation in the alkylation of $(CH_3)_3SnLi$ by alkyl halides, viz., I > Br > Cl > OTs; benzyl, tertiary > secondary > primary.

A reasonable mechanistic interpretation of these data is that at least one competing, nonstereospecific alkylation reaction is operating in addition to any stereospecific reaction(s) that may be occurring; however, any meaningful discussion of the mechanism of the reaction of trimethyltin nucleophiles with alkyl halides must first consider the structural nature of these organometallic reagents in solution. Reliable data for the molecular weight of lithium trimethyltin are not available. However, in view of the generally recognized association of organolithium reagents in solution,[19] it seems reasonable to assume that lithium trimethyltin is also associated in solution. In light of the documented ability or organolithium reagents to act as one-electron reducing agents toward suitable substrates (including organic halides),[16b] we propose the first step in this competing reaction to be a single electron transfer that leads to an alkyl radical, halide ion, and a cluster radical cation (Scheme II). Subsequent dissociation of a trimethyltin radical from these partially oxidized clusters followed by its combination with R′· (eq 4) and/or the direct reaction of $[R_3SnM]^{+}\cdot$ with R′· (eq 5) would provide a method of forming a carbon–tin bond.

Scheme II. Proposed Mechanism for the Free-Radical Component of the Reaction of $(CH_3)_3SnLi$, -Na, -K with Alkyl Halides

$$R'X + [R_3SnM]_n \rightarrow \overline{R'\cdot + X^- + [R_3SnM]_n^{+}\cdot} \quad (1)$$

$$\overline{R'\cdot + X^- + [R_3SnM]_n^{+}\cdot} \xrightarrow{k_d} R'\cdot + [R_3Sn]_n^{+}\cdot + X^- \quad (2)$$

$$[R_3SnM]_n^{+}\cdot + X^- \xrightarrow{k_3} [R_3SnM]_{n-1} + MX + R_3Sn\cdot \quad (3)$$

$$R'\cdot + R_3Sn\cdot \xrightarrow{k_c} R'SnR_3 \quad (4)$$

$$R'\cdot + [R_3SnM]_n^{+}\cdot \rightarrow R'SnR_3 + [(R_3Sn)_{n-1}M_n]^{+} \quad (5)$$

Alone, eq 4 cannot account for the observed influences of solvent on product isomer distribution: only minor variation in product stereochemistry is expected for a nongeminate, nonionic coupling process such as the radical–radical coupling reaction outlined in eq 4. It follows, therefore, that eq 5 or a combination of the processes represented by eq 4 and 5 describe the product-forming step in the reaction of $(CH_3)_3SnLi$ with **1** and **2**. Moreover, eq 5 involves the bimolecular reaction of R′· with $[R_3SnM]_n^{+}\cdot$, whose structure, like that of organolithium reagents in general, but unlike that of a simple free radical, is likely to be solvent dependent.[19] Solvent-induced structural changes of this sort could reasonably lead to changes in the steric factors that control the stereochemistry of the carbon–tin coupling product. Of course, factors other than solvent can influence the structure of organolithium reagents. Temperature and concentration, for example, can also play a role in this regard. Collectively, this interpretation of the differences in the product stereochemistries observed in the reaction of $(CH_3)_3SnLi$ with **1** and **2** is appealing in its simplicity and internal consistency. It also points out a useful additional fact, viz., the sensitivity of the 4-*tert*-butylcyclohexyl radical as a diagnostic probe with which to explore radical–radical reactions *in those instances* where thermodynamic and steric product control reinforce each other, resulting in a clear preference for the formation of the trans product isomer which, consequently, permits an interpretation of isomer distribution that is not beclouded by the conflicting factors which characterize those reactions of the 4-*tert*-butylcyclohexyl radical that produce a predominance of the sterically and thermodynamically disfavored cis product isomer.[18]

In addition to solvent, temperature, and concentration, gegenions can also influence the extent of anion association and, hence, structure, solubility, basicity, nucelophilicity, etc., of these reagents in solution. Thus, for example, it has long been recognized that, in contrast to the general solubility of organolithium reagents in many organic solvents (a fact attributed to the substantially covalent nature of the C–Li bond), corresponding organosodium and -potassium compounds, are generally quite insoluble, presumably as a consequence of the high degree of ionic character possessed by the carbon–metal bond. Indeed, there are numerous parallels between the physical and chemical properties of organosodium and -potassium compounds which clearly do not extend to organolithium reagents. It is, therefore, perhaps not surprising to find that the alkylations of $(CH_3)_3SnNa$ and $(CH_3)_3SnK$ exhibit reaction profiles which are similar to each other but distinctly different from that observed for $(CH_3)_3SnLi$. For example, as previously noted, the reaction of $(CH_3)_3SnNa$, -K with **1** and **2** in THF yields essentially equivalent product isomer distributions containing less of the trans isomer **4** than is produced in the equivalent alkylation employing $(CH_3)_3SnLi$. This difference is even more pronounced in the reaction of $(CH_3)_3SnNa$, -K with **1** and **2** in DME in which case an essentially statistical distribution of **3** and **4** occurs. In light of earlier discussion, it follows that these differences reflect differences in the steric factors that control the stereochemistry of C–Sn bond formation, and which presumably occur as a consequence of the differing influences that solvent, concentration, and temperature have on the structure of the reaction intermediates generated from $(CH_3)_3SnNa$, -K vs. those generated from $(CH_3)_3SnLi$.

Finally, the profile of the reaction of $CpFe(CO)_2Na$ with cyclopropylcarbinyl halide parallels in certain respects that observed for $(CH_3)_3SnLi$, -Na, -K. Thus, alkylation of $CPFe(CO)_2^-$ with cyclopropylcarbinyl iodide produces a substantial fraction (30%) of the allylcarbinyl product. It follows that a minimum of 30% of the alkylation product is produced by a process involving intermediate nongeminate cyclopropylcarbinyl radicals. However, in contrast to the reaction of $(CH_3)_3SnM$ with cyclopropylcarbinyl bromide, alkylation of $CpFe(CO)_2Na$ with **5** (X = Br) produced no detectable allylcarbinyl(cyclopentadienyl)(dicarbonyl)iron. We conclude that the alkylation of $CpFe(CO)_2Na$ by cyclopropylcarbinyl bromide and by extension, primary alkyl bromides in general, does not involve the coupling of nongeminate radicals. This conclusion is reinforced by the related observation of Whitesides and co-workers,[2] who report that the reaction of $CpFe(CO)_2Li$ with the unrelated primary bromide 3,3-

dimethylbutyl-*1,2-d*$_2$ bromide takes place with essentially complete (>95%) inversion of configuration.

There are two additional elementary processes which may proceed through the intermediacy of free alkyl radicals and, therefore, bear consideration in any discussion of the mechanism of alkylation of $(CH_3)_3SnM$. These involve a metal-halogen exchange involving S_N2 and/or S_H2 displacement on halogen producing, respectively, a carbanion and organometallic halide (eq 6) or an alkyl radical and the radical anion $[R_nMX]^{-}\cdot$ (eq 9). These processes are outlined in Scheme III.

Scheme III. Alternative Pathways Describing the Free-Radical Component Observed for the Alkylation of Certain Metalate Anions by Alkyl Halides[a]

$$R'X + R_nM^- \rightarrow R'^- + R_nM - X \quad (6)$$

$$R'^- + R_nM - X \rightleftharpoons R'\cdot + R_nM\cdot \rightarrow R'MR_n \quad (7)$$

$$R'^- + R_nM - X \rightleftharpoons R' - MR_n \quad (8)$$

$$R'X + R_nM^- \rightarrow R'\cdot + [R_nMX]^{-}\cdot \quad (9)$$

$$R'\cdot + [R_nMX]^{-}\cdot \rightarrow R'^- + R_nMX \rightarrow R'MR_n \quad (10)$$

$$R'\cdot + R_nM^- \rightarrow R'^- + R_nM\cdot \quad (11)$$

$$R'\cdot + R_nM\cdot \rightarrow R'MR_n \quad (12)$$

[a] For simplicity, the organometallic species presented here are represented as dissociated monomeric species.

In conclusion, it is evident that some of the suggestions presented in this section (Schemes II and III) are clearly speculative at this point. However, regardless of their ultimate correctness, the data from which they are derived indicate that solvent, gegenion, nature of the leaving group X, and structure of the organic group bonded to X can all influence, frequently substantially, the basic mechanism by which the alkylation of certain metalate anions take place.[28] In addition, the results reported here illustrate the utility of the cyclopropylcarbinyl group as a diagnostic probe of organometallic reactions mechanisms.

Experimental Section

General Methods. All reactions involving organometallic compounds were carried out under prepurified nitrogen that had been passed through a 12-in. tube containing Drierite. All solvents were reagent grade; THF and ether were distilled from lithium aluminum hydride. DME was distilled from a dark-purple solution of benzophenone dianion before use. Cyclopentadienyl(dicarbonyl)iron dimer was obtained from Alfa-Ventron and was recrystallized before use by dissolving in the minimum amount of acetone at room temperature, adding ⅓ that volume of water, and cooling at −20 °C. Trimethyltin chloride was purchased from Alfa-Ventron and ROC/RIC and used as received.

Melting points and boiling points are uncorrected. Infrared spectra were taken in sodium chloride cells on a Perkin Elmer 237 or 727B grating spectrometer. Routine ^{1}H NMR spectra were recorded on a Varian T-60 spectrometer; chemical shifts are reported in parts per million downfield from Me_4Si.

^{13}C NMR spectra were recorded on a Varian CFT-20 spectrometer; chemical shift are given in parts per million downfield (positive) and upfield (negative) from Me_4Si. Proton spectra at 270 MHz were recorded on a Bruker instrument. Analytical GLC analyses were performed on a Hewlett-Packard Model 5750 and Varian Model 90P instruments using internal standard techniques with response factors obtained using authentic samples.

Cyclopropylcarbinyl chloride, prepared by the reaction of cyclopropylcarbinol with phosphorus trichloride in ether similar to the method described by Meek and Rowe,[20] had bp 28.5–30.0 °C (84 Torr) [lit.[21] 87.0–89.0 °C (760 Torr)].

Cyclopropylcarbinyl bromide, prepared as described by Meek and Rowe,[20] had bp 52.5–53.5 °C (91 Torr) [lit.[20] 101.5–102.5 °C (627 Torr)].

Cyclopropylcarbinyl iodide was prepared by treating an acetone solution of cyclopropylcarbinyl bromide with sodium iodide.[20] It had bp 53.0–54.0 °C (53 Torr) [lit.[22] 88–90 °C (150 Torr)]. The ^{1}H NMR spectra of all three halides were similar and consistent with their assigned structure.

***cis*-4-*tert*-Butylcyclohexanol** was prepared by the literature procedure,[23] mp 80.5–81.5 °C (lit.[23] mp 82.0–83.5 °C).

***trans*-4-*tert*-Butylcyclohexanol** was prepared according to a literature procedure,[24] mp 72.5–74.0 °C (lit.[24] mp 75–78 °C).

***cis*- and *trans*-4-*tert*-butylcyclohexyl bromide** was synthesized by a modification of a literature procedure.[25] Into a three-necked, 2-L flask fitted with an overhead sitter, drying tube, and a 500-mL addition funnel were placed CH_2Cl_2 (100 mL) and bromine (90 g, 0.56 mol). The flask was cooled in an ice-water bath and phosphorus tribromide (150 g, 0.55 mol) in CH_2Cl_2 (150 mL) added dropwise over a 30-min period with efficient stirring. To the resulting yellow suspension of phosphorus pentabromide was added a solution of commercial 4-*tert*-butylcyclohexanol (77 g, 0.49 mol; ~80% trans, 20% cis) in CH_2Cl_2 (500 mL). Addition was carried out dropwise over a period of 1 h and was accompanied by vigorous stirring and efficient cooling. The resulting reaction mixture was allowed to warm gradually to room temperature with overnight stirring before 250 g of crushed ice in water (250 g) was cautiously added with stirring. After ca. 1.5 h the resulting mixture had separated into two layers. The bottom (organic) layer was separated and washed with one 300-mL portion of water, then cautiously with 300-mL portions of saturated aqueous sodium bicarbonate, and finally with one 300-mL portion of saturated brine. These aqueous layers were combined and extracted with one 300-mL portion of CH_2Cl_2. The organic layers were combined, dried ($MgSO_4$), and concentrated under reduced pressure. Preliminary distillation of this crude mixture produced a colorless liquid (39 g), bp 108–125 °C (16 Torr). Analysis by gas chromatography on a 6-ft × 0.25 in. column of SE-30 on Chromosorb W indicated two components. The lower boiling material (~80%) was an epimeric mixture of *cis*- and *trans*-4-*tert*-butylcyclohexyl bromide. Refractionation of this material on a 30-cm Teflon annular spinning band yielded four distinct fractions.[29] The first fraction (bp 72 °C, 8 Torr) was found to be essentially pure 4-*tert*-butylcyclohexene. The second fraction (bp 92 °C, 8 Torr) was identified as *cis*-4-*tert*-butylcyclohexyl bromide by its characteristic ^{1}H NMR (determined at 220 MHz): δ (CCl_4) 4.57 (1H, HCBr, quintet, J = 3.0 Hz), 2.11 (2 H, BrCC-$H_{equatorial}$, doublet of quintets, J = 14.5, 2.8 Hz), 1.82–1.48 (6 H, multiplet), 1.02 (1 H, multiplet, $(CH_3)_3CCH$), 0.89 (9H, s, $(CH_3)_3$-C); IR (neat) 2880 (vs), 1580 (m), 1375 (w), 1255 (m), 1240 (w), 1025 (w), 1005 (w), 910 (w), 775 (w), 680 cm^{-1} (w). GLC analysis on a 50-ft × 0.125-in. column of 10% Zonyl E-7 on Chromosorb W revealed an isomeric purity >98% *cis*-4-*tert*-butylcyclohexyl bromide and 2% *cis*-3-*tert*-butylcyclohexyl bromide. Fraction 3 (bp 92 °C, 8 Torr) was an intermediate fraction which GLC analysis revealed contained substantial amount of *trans*-3-*tert*-butylcyclohexyl bromide (vide infra). A fourth and final fraction (bp 92 °C, 8 Torr) was determined to be *trans*-4-*tert*-butylcyclohexyl bromide (**2**), based on an analysis of its 220-MHz ^{1}H NMR spectrum: δ (CCl_4) 3.86 (1 H, triplet of triplets, HCBr, J = 12.0, 4.5 Hz), 2.10 (2 H, BrCC$H_{equatorial}$, doublet of multiplets, J = 12–13 Hz), 15.4 (4 H, multiplet), 0.85 (3 H, multiplet), and 0.61 (9 H= S= $(CH_3)_3C$); IR (neat) 2850 (vs), 1470 (m), 1450 (m), 1400 (w), 1370 (s), 1355 (w), 1275 (m), 1240 (doublet, w), 1215 (m), 1175 (s), 1100 (w), 1040 (w), 895 (m), 875 (w), 805 (m), 755 (w), 685 cm^{-1} (s). GLC analysis of this fraction revealed the following isomeric distribution (in order of elution): *cis*-3-*tert*-butylcyclohexyl bromide (<1%), *cis*-4-*tert*-butylcyclohexyl bromide (1–2%), *trans*-3-*tert*-butylcyclohexyl bromide (1–2%), and *trans*-4-*tert*-butylcyclohexyl bromide (98%).

***cis*- and *trans*-4-*tert*-butylcyclohexyl chlorides** were prepared as described by Eliel and Martin.[30]

***cis*- and *trans*-3-*tert*-butylcyclohexyl bromides** were prepared from bromine (117 g, 0.732 mol), phosphorus tribromide (195 g, 0.720 mol), and 100 g (0.640 mol) of 3-*tert*-butylcyclohexyl alcohol (mixture of isomers) in 650 mL of CH_2Cl_2 using the procedure outlined above for the preparation of *cis*- and *trans*-4-*tert*-butylcyclohexyl bromide. Distillation of the crude produce mixture yielded 6 g of 3-*tert*-butylcyclohexene (bp 60 °C, 10 Torr) and 7.5 g of an isomeric mixture of 3-*tert*-butylcyclohexyl bromide (bp 88 °C, 4 Torr). GLC analysis on a 50 ft × 0.125 in. column of 10% Zonyl E-7 on Chromosorb W revealed four high-boiling components corresponding to (in order of increasing retention time) *trans*-3-bromocyclohexyl bromide (~70%), *cis*-4-*tert*-butylcyclohexyl bromide (~4%), *cis*-3-*tert*-butylcyclohexyl bromide (~23%), and *trans*-4-*tert*-butylcyclohexyl bromide (~3%). The assignment of *cis*- and *trans*-3-*tert*-butylcyclohexyl bromide

isomer was confirmed by examining their relative rates of base-induced dehydrohalogenation and by comparison of the 220-MHz spectra of individual samples isolated from GLC which showed *H*-C-Br (CCl_4) for the cis isomer at δ 4.72 (t of t, J = 4.5, 13.0 Hz) and 3.93 (br multiplet) for the trans isomer.

***cis*- and *trans*-4-*tert*-Butylcyclohexyl Tosylate.** *trans*-4-*tert*-Butylcyclohexyl alcohol (4.00 g, 25.6 mmol) and *p*-toluenesulfonyl chloride (7.14 g, 37.5 mmol) were placed in a 100-mL flask equipped with a Teflon-coated stirrer bar and a drying tube. Dry pyridine (30 mL) was added and the reaction mixture stirred at room temperature for 42 h. The resulting mixture was poured into 200 mL of ice–water containing 10% H_2SO_4. This mixture was extracted with three 100-mL portions of ether and the combined ether extracts were washed with 10% H_2SO_4 (50 mL) followed by saturated aqueous sodium bicarbonate (50 mL) and finally dried ($MgSO_4$). The volatiles were removed under reduced pressure at 25 °C and the residual tosylate was recrystallized from ether (50 mL) at −20 °C. Three crops were obtained for a total yield of 5.0 g (59%), mp 83.0–84.5 °C (lit.[26] mp 89.4–90.0 °C).

A similar procedure was employed to make *cis*-4-*tert*-butylcyclohexyl tosylate, mp 76.5–77.5 °C (lit.[26] mp 79.0–80.0 °C).

Cyclopropylcarbinyl tosylate was prepared in a manner similar to that described by Bergstrom and Siegel.[27]

Alkylation Reactions. Similar procedures were used in all alkylations. Representative procedures are given below.

Trimethyl(cyclopropylcarbinyl)tin. Lithium (50% dispersion, 200 μ, in mineral oil, 0.140 g as Li, 20.2 mg-atoms, Lithium Corp.) was placed in a flame-dried, 25-mL flask equipped with a Teflon-coated magnetic stirrer bar. The flask was capped with a rubber septum and flushed with helium. Deoxygenated petroleum ether (bp 30–60 °C, 10 mL) was added by syringe and the contents of the flask stirred briefly to dissolve the mineral oil. This supernatant liquid was removed through a stainless steel cannula under a positive pressure of helium and tetrahydrofuran (10 mL) and *n*-decane (internal standard, 0.4070 g) were added by syringe. The reaction vessel was subsequently placed in a water bath (25 °C and with rapid stirring a solution of trimethyltin chloride (0.783 g, 3.93 mmol) in THF (10 mL) added by syringe. The solution turned green and after 15 min the resulting solution was filtered through a 145–175 μ fritted glass filter under a positive pressure of helium. The clear green filtrate was collected in a two-necked, 50-mL, flame-dried flask equipped with a Teflon-coated stirrer bar and a 60-mL Kontes slow addition funnel stoppered with a rubber septum and containing a solution of cyclopropylcarbinyl chloride (0.549 g, 6.06 mmol) in THF (10 mL). The reaction flask was placed in an ice–water bath and the dropwise addition of halide solution carried out over a 20-min period accompanied by vigorous stirring. Upon completion of addition, the reaction mixture was treated with water (10 mL) and subsequently extracted with three 10-mL portions of ether. The combined organic layers were dried ($MgSO_4$) and concentrated. GLC on a 6 ft × 0.25 in. column of 10% SE-30 on Chromosorb W at 65 °C indicated a single, high-boiling component (85% yield), a collected sample of which exhibited the following ^1H NMR: δ (CCl_4) −0.05, 0.03 (11 H, singlet and complex multiplet, corresponding respectively to $(CH_3)_3Sn$ and cyclopropyl resonance), 0.43 (2 H, complex multiplet consisting of an overlapping ^{119}Sn satellite and cyclopropyl resonance), and 0.60–1.32 (3 H, complex multiplet, CH_2Sn and a cyclopropyl resonance). Mass spectrographic examination revealed a series of parent ions (M^+) consistent with the natural isotopic distribution of tin and expected for trimethyl(cyclopropylcarbinyl)tin.

Trimethyl(allylcarbinyl)tin. The above procedure was repeated using 1-bromobut-3-ene (0.480 g, 3.55 mmol). GLC analysis as described above revealed one high-boiling component; a collected sample had ^1H NMR δ (CCl_4) 0.03 (9 H, s, $(CH_3)_3Sn$), 0.90 (2 H, t, CH_2Sn), 2.27 (2 H, multiplet, CH_2CHCH_2), 4.80 (1 H, multiplet, vinyl), 5.02 (1 H, multiplet, vinyl), 5.84 (1 H, multiplet, vinyl).

Trimethyl(*cis*- and *trans*-4-*tert*-butylcyclohexyl)tin (3 and 4). Repetition of the above procedure employing 4-*tert*-butylcyclohexyl bromide (80% cis) yielded a reaction mixture which GLC analysis on a 6 ft × 0.125 in. column of UCW-98 indicated contained two principal high-boiling components that were collected. The second of these components to elute had ^1H and ^{13}C NMR described in Tables I and II and an IR (CCl_4) distinguished by the following bands: 2950 (vs), 1490 (m), 1455 (s), 1403 (m), 1380 (s), 1355 (w), 1243 (m), 1200 (m), 1160 (m), 1140 (w), 1075 (w), 1050 (m), 885 (w), 775 (s), 720 cm^{-1} (m). It was assigned the structure **4**. A collected sample of the first component had an IR (CCl_4) characterized by the following bands: 2950 (vs), 1480 (m), 1450 (m), 1400 (w), 1370 (s), 1355 (w), 1310 (w), 1293 (w), 1235 (w), 1188 (w), 1070 (w), 1038 (w), 865 (w), 765 (s), 710 cm^{-1} (m). It was assigned the structure **3**. The mass spectra of **3** and **4** are equivalent and displayed a molecular ion pattern consistent with their assigned structures.

Trimethyl(3-*tert*-butylcyclohexyl)tin. A sample of this material was prepared by reaction of 3-*tert*-butylcyclohexyl bromide with lithium trimethyltin as described above. The principal high-boiling component was isolated by preparative GLC on a 6 ft × 0.25 in. column of 10% SE-30 on Chromosorb W. Its mass spectrum was different than that observed for **3** and **4** but exhibited a parent ion and isotope distribution consistent with the assigned structure. Further characterization was not performed.

Cyclopropylcarbinyl Phenyl Selenide. Into a flame-dried, two-necked, 25-mL flask equipped with a Teflon-coated magnetic stirrer bar and a Kontes slow-addition funnel was placed diphenyl diselenide (0.615 g, 1.97 mmol). The exit arms were capped with rubber septa and the entire system was flushed with nitrogen before 10 mL of deoxygenated absolute ethanol was injected by syringe along with a weighed amount of an internal standard, *n*-dodecane. To the resulting clear yellow solution was added in portions with stirring 0.184 g (4.96 mmol) of $NaBH_4$. The flask containing the resulting clear, colorless solution was cooled in an ice–water bath and a solution of cyclopropylcarbinyl bromide (0.525 g, 3.89 mmol) in deoxygenated absolute ethanol (10 mL) was added dropwise accompanied by efficient stirring over a 20-min period. After an additional 15 min of stirring at room temperature, dry ether (10 mL) was added and the resulting salts were compacted by centrifugation. GLC analysis of the supernatant solution on a 6 ft × 0.125 in. column of UCW-98 at 120 °C revealed a single high-boiling component, characterized by its spectral properties as cyclopropylcarbinyl phenyl selenide: ^1H NMR δ (CCl_4) 7.20 (5 H, multiplet, C_6H_5), 2.79 (2 H, d, J = 7.0 Hz, CH_2Se), 0.00 (5 H, multiplet, cyclopropyl). The yield was 79%.

Allylcarbinyl Phenyl Selenide. Repetition of the above procedure employing 0.620 g (2.00 mmol) of diphenyl diselenide, 0.150 g (4.20 mmol) of $NaBH_4$, and 0.80 g (5.90 mmol) of 1-bromobut-3-ene produced allylcarbinyl phenyl selenide in 82% yield: ^1H NMR δ (CCl_4) 3.1–2.2 (4 H, multiplet, $-CH_2CH_2$), 5.10 (2 H, multiplet, vinylic), 5.90 (1 H, multiplet, vinylic), 7.2–7.7 (5 H, multiplet, C_6H_5).

π-Cyclopentadienyl(cyclopropylcarbinyl)(dicarbonyl)iron. A 100-mL flask was flame dried and equipped with a Teflon-coated magnetic stirrer bar, rubber septum, and nitrogen inlet. The flask was charged with 10 mL of mercury, rapid stirring was initiated, and 1.3 g (45 mg-atoms) of sodium was added. This reaction, which is preceded by a brief induction period, is characterized by suddenness and exothermicity. To this mixture was added (20 mL) by syringe THF followed by a solution of $[\pi\text{-CpFe(CO)}_2]_2$ (2.00 g, 5.65 mmol) in 50 mL of THF. The resulting reaction mixture was allowed to stir for 3 h at 25 °C at which time the cloudy supernatant solution was transferred under a positive pressure of nitrogen through a Teflon cannula into a flame-dried, 40-mL centrifuge tube equipped with a rubber septum. Following centrifugation, the clear yellow supernatant was transferred by cannula to a flame-dried 100-mL flask equipped with a Teflon-coated magnetic stirrer bar and a slow addition funnel charged with a solution of cyclopropylcarbinyl bromide (1.42 g, 10.5 mmol) in THF (25 mL) and stoppered with a rubber septum. The flask was placed in an ice–water bath and with efficient stirring the solution of cyclopropylcarbinyl bromide added dropwise over a 30-min period. The resulting reaction mixture was allowed to stir for an additional 2 h at 0 °C before the solvent was removed under reduced pressure at room temperature. The residue was treated with 50 mL of deoxygenated pentane and the resulting solution eluted (under nitrogen and using pentane) through a 1 × 15 in. column of acid-washed alumina. Those fractions which were yellow were collected and the pentane was removed in vacuo leaving a yellow-brown liquid which was characterized by ^1H NMR: δ (C_6H_6) 4.58 (5 H, s, π-C_5H_5), 1.43 (2 H, d, J = 6.1 Hz, $-CH_2Fe$), 0.55 (3 H, multiplet, cyclopropyl), 0.12 (2 H, multiplet, cyclopropyl).

π-Cyclopentadienyl(allylcarbinyl)(dicarbonyl)iron. A procedure similar to that given above, using 1-bromobut-3-ene (1.59 g, 11.8 mmol), was employed. The yellow-brown product had ^1H NMR δ (C_6H_6) 5.93 (1 H, multiplet, vinyl), 5.02 (2 H, multiplet, vinyl), 4.52 (5 H, s, C_5H_5), 2.23 (2 H, quartet, J = 7.0 Hz, allylic CH_2), 1.47 (2 H, triplet, J = 8.2 Hz, CH_2Fe).

Product Isomer Analysis. The ratio of **8** to **9** was determined by comparison of the integrated intensities of selected bands (specifically, those corresponding to the $-CH_2Fe$ and $CH_2{=}CH-$ protons) in the ^1H NMR spectrum of the product mixtures isolated as described above.

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Aminohaloborane in Organic Synthesis. 1. Specific Ortho Substitution Reaction of Anilines[1]

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Abstract: A new general process has been developed for specific ortho hydroxybenzylation and hydroxyalkylation of secondary anilines using secondary anilinodichloroboranes. Treatment of secondary anilinodichloroborane prepared in situ with benzaldehydes in the presence of tertiary amines with some steric hindrance gave secondary 2-(α-hydroxybenzyl)anilines in excellent yield via the cyclic transition state; in contrast, the analogous treatment with anilinodichloroalane proceeded intermolecularly affording 4,4′-diaminotriphenylmethane exclusively. Similarly, a new general process was developed for specific ortho acylation of anilines by the reaction of nitriles and anilinodichloroborane prepared in situ. This reaction was accelerated in most cases by the coexistence of aluminum trichloride. The distinctive exchange of the reaction site of anilines and nitriles in the presence of boron trichloride instead of other electrophilic metal halides is discussed.

2-Aminophenyl ketones (**1**), such as 2-aminobenzophenone (**1a**) and 2-aminoacetophenone (**1b**) and their substituted derivatives, have been used for a long time as important starting materials for the preparation of fluorenones,[2] acridines and acridones,[2,3] cinnolines,[2,4] quinazolines,[2,5] indazoles,[2,6] and quinolines.[7] Recently, use of 2-aminobenzophenones for the preparation of 3-phenylindoles[8] has been also reported. Among the various synthetic uses of these 2-aminobenzophenones (**1a**), their use in preparing 1,4-benzodiazepines[9] (**2**), which have become among the most important drugs in the clinical field of psychosis, is the most outstanding.

In spite of their versatility as reactive intermediates, a simple preparative route to **1** from anilines has not been known to date because the Friedel–Crafts acylation of anilines is usually unsuccessful and the same reaction of acylanilides with acyl halides gives 4-substituted acylanilides almost exclusively.[10] Also, the reaction of anilines with various acylating agents such as benzamide, benzonitrile, ethyl benzoate and benzoic acid in the presence of polyphosphoric acid gives only 4-aminobenzophenone.[11]

Consequently, the known synthetic routes to **1** involve three or four steps starting from 1,2-disubstituted benzene derivatives. Namely, treatment of 2-nitrobenzoyl chloride or 2-nitrobenzyl chloride with benzene derivatives in the presence of aluminum chloride followed by further appropriate treatment or the Grignard reaction of 1,3-benzoxazin-4-one or 2-aminobenzonitrile gives the desired product **1**.[2,12] Other minor synthetic routes are also reviewed in the same literature. Alternatively, the Friedel–Crafts reaction of phthalic anhydride with benzene followed by amidation and Hofmann degradation[13] or the oxidative cleavage of 3-substituted indoles[14] and subsequent hydrolysis gives **1**. Of course, there is no re-

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