overall from 2-acetylnaphthalene); mp 175–176 °C; NMR δ 1.83 (d, 3, CH_3, J = 7 Hz), 4.86 (d, 1, CH, J = 7 Hz), 6.75–8.65 (m, 13, aryl). Cyclization of the acid (0.89 g) with $ZnCl_2$ in the usual manner gave 14-acetoxy-7-methyldibenz[a,j]anthracene: 940 mg (99%); 249–250 °C; NMR δ 2.50 (s, 3, CH_3), 3.11 (s, 3, CH_3CO), 7.33–8.40 (m, 10, aryl), 9.50 (m, 2, $H_{1,13}$). Reduction of the phenol acetate (400 mg, 1.14 mmol) by the usual procedure afforded **11b**: 330 mg (96%); mp 243–244 °C; NMR δ 3.10 (s, 3, CH_3), 7.33–8.40 (m, 10, aryl), 9.06 (m, 2, $H_{1,13}$), 10.05 (s, 1, H_{14}).

Benzo[*a*]pyrene. Reaction of *N,N*-diethyl-2-lithiobenzamide with **16** (910 mg, 5 mmol was conducted by the general procedure employed in preceding syntheses. The crude lactone **17** (1.5 g) was utilized directly in the next step. Reduction of **17** with zinc and alkali afforded the acid **18**: 310 mg (22%); mp 149–150 °C; NMR δ 2.36 (br t, 2, CH_2), 3.10 (br t, 2, benzylic), 5.60 (t, 1, CH), 6.66–8.33 (m, 10, aryl).

A solution of **18** (300 mg), HI (1.6 mL of 56% solution), and H_3PO_2 (0.4 mL of 50% solution) in glacial acetic acid (50 mL) was heated at reflux for 24 h. The reaction mixture was poured into ice–water and the precipitate collected by filtration. The crude 11,12-dihydrobenzo[*a*]pyrene (250 mg) was shown by NMR analysis and TLC on 2,4,7-trinitrofluorenone[26] to contain benzo[*a*]pyrene and tetrahydrobenzo[*a*]pyrene. The crude **19** was taken up in benzene with excess DDQ and heated at reflux for 2 h. The reaction mixture was poured onto a column of silica gel. Elution with hexane gave benzo[*a*]pyrene: 180 mg (70%); mp 177–178 °C (lit.[1] mp 176.5–177.5 °C); a mixture melting point with authentic benzo[*a*]pyrene was not depressed.

Reductive Cyclization of 8b and 8c with HI. A solution of **8b** (200 mg, 0.67 mmol), HI (1.3 mL of 56% solution), and red P (240 mg) in glacial acetic acid (50 mL) was heated at reflux for 56 h and then poured into a 1% aqueous sodium bisulfite solution. The precipitate was collected by filtration, washed with water, and dried. Chromatography on silica gel gave dibenz[a,h]anthracene: 100 mg (54%); mp 264–265 °C (lit.[24] mp 262–263 °C); the NMR spectrum matched that of an authentic sample. A similar reaction conducted with hypophosphorus acid in place of red P gave a slightly lower yield (49%) of **10a**.

Analogous reaction of **8c** (with H_3PO_2) for 10 days afforded dibenz[a,j]anthracene (80%); a lower yield was obtained with shorter reaction times.

Acknowledgment. This research was supported by Grants No. CA 11968 and CA09183 from the National Cancer Institute, U.S. Department of Health and Human Services. The Bruker HX-270 NMR spectrometer was funded through the University of Chicago Cancer Research Center (Grant No. CA 14599).

Registry No. **3**, 24644-78-8; **3**-d_2, 81194-73-2; **4**, 81194-74-3; **5**, 78606-93-6; **5**-d_2, 81194-75-4; **6**, 78606-94-7; **7a**, 78606-95-8; **7b**, 56-49-5; **8a**, 81194-76-5; **8b**, 73540-67-7; **8c**, 73540-68-8; **8d**, 81194-77-6; **8e**, 81194-78-7; **9a**, 17526-28-2; **9b**, 2541-69-7; **10a**, 53-70-3; **10b**, 15595-02-5; **11a**, 224-41-9; **11b**, 78606-97-0; **15a**, 81194-79-8; **15b**, 81194-80-1; **16**, 518-85-4; **16**-d_2, 81194-81-2; **17**, 81194-82-3; **18**, 81205-70-1; **19**, 81194-83-4; **23**, 81194-84-5; acetophenone, 98-86-2; 2-(1-phenylethyl)-1-naphthoic acid, 81194-85-6; 1-naphthaldehyde, 66-77-3; 2-(1-naphthylmethyl)-1-naphthoic acid, 77321-47-2; 7-acetoxydibenz[a,h]anthracene, 63077-06-5; 2-naphthaldehyde, 66-99-9; 2-(2-naphthylmethyl)-1-napthoic acid, 81194-86-7; 14-acetoxydibenz[a,j]anthracene, 81205-71-2; 1-acetylnaphthalene, 941-98-0; 14-acetoxy-7-methyldibenz[a,h]anthracene, 81194-87-8; 2-acetylnaphthalene, 93-08-3; 14-acetoxy-7-methyldibenz[a,j]anthracene, 81194-88-9; benzo[*a*]pyrene, 50-32-8; *N,N*-diethyl-1-naphthamide, 5454-10-4.

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Reductive Alkylation/Arylation of Arylcarbinols and Ketones with Organosilicon Compounds

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Arylcarbinols react with certain organosilanes in the presence of boron trifluoride to yield hydrocarbons resulting from transfer of an R group from silicon to carbon. The transfer works well with aryl- and allylsilanes and fails with alkylsilanes. Allylation of ionizable carbinols is sometimes accompanied by cation-mediated oligomerization. This can be offset by converting the carbinols in question to their respective allyldimethylsilyl ethers followed by rearrangement of the ethers with BF_3. While diaryl ketones are sluggishly bisallylated, the corresponding ketals undergo smooth bisallylation at 0 °C with allytrimethylsilane/BF_3/CH_2Cl_2.

The reductive alkylation of carbinols and ketones is a synthetically useful transformation for which few direct methods are available.

Sequential methods such as the tandem alkylation–reduction of aromatic carbonyl compounds[1] and α,β,γ,δ-unsaturated ketones[2] or the phenylation–reduction of aldehydes and ketones[3] are limited in that only one alkyl group is introduced at the site of reduction. Geminal reductive alkylation of tosyl hydrazones via a sequence of nucleophilic followed by electrophilic attack has been described;[4,5] however, no direct reductive alkylation of carbinols or geminal reductive alkylation of ketones of general utility is known.[6] (Reductive alkylation of carbinols effectively constitutes a geminal reductive alkylation of ketones since the carbinols can be obtained by reaction of the ketone with a suitable organometallic reagent.)

The known reduction of carbinols in acidic media via hydride transfer from silicon[7] and the well-established[8]

(1) (a) S. S. Hall, C. K. Shar, and F. Jordan, *J. Org. Chem.*, **41**, 1494 (1976); (b) *ibid.*, **38**, 1735 (1973).

(2) J. S. R. Zilenouski and S. S. Hall, *J. Org. Chem.*, **44**, 1159 (1979).

(3) (a) F. J. McEnroe, C. K. Shar, and S. S. Hall, *J. Org. Chem.*, **41**, 3465 (1976). (b) S. S. Hall and F. J. McEnroe, *ibid.*, **40**, 271 (1975).

(4) R. H. Shapiro and T. Gadek, *J. Org. Chem.*, **39**, 3418 (1974).

(5) A geminal alkylation occurring from reaction of a lithium reagent with a tosylhydrazone has been reported: S. H. Bertz, *J. Org. Chem.*, **44**, 4967 (1979).

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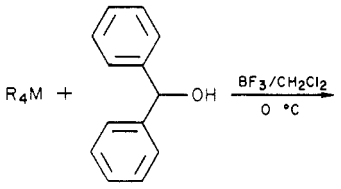
tendency for transfer of alkyl,[9,10] aryl,[11] and allyl[12-19] substituents from silicon and tin to electrophilic carbon centers led us to explore the possibility of effecting a reductive alkylation of ionizable carbinols in acidic media via transfer of a substituent from silicon (or tin) to the electrophilic site generated on ionization (eq 1).

$$\equiv M{-}R + \equiv COH \xrightarrow{H^+} \equiv CR + \equiv MOH \qquad (1)$$

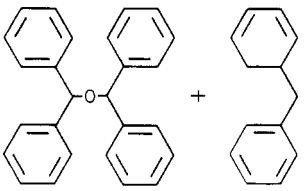
M = Si, Sn

Benzhydrol (1) was chosen as a readily ionizable substrate to test whether substituent transfer from silicon to the benzhydryl cation would occur.

Reaction of benzhydrol (1) with several tetraalkylsilanes and with tetramethyl tin in dichloromethane solution in the presence of anhydrous boron trifluoride (eq 2) produced no products resulting from alkyl transfer. The products in all cases were a mixture of dibenzhydryl ether (2) and diphenylmethane (3). The source of 3 in these reactions is uncertain. While the hydride transfer to the benzhydrylcation to produce 3 could be derived from the starting carbinol or the silane (stannane), the absence of benzophenone among the products suggests the silane as the hydride source.[20]

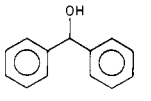
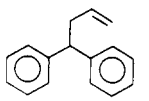
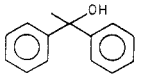
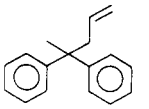
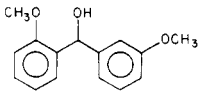
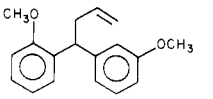
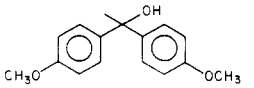
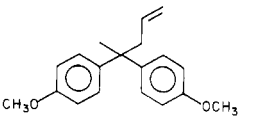
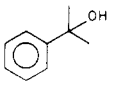
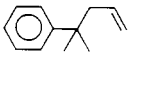
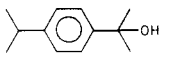
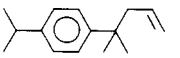
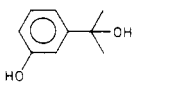
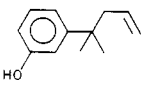
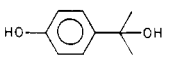
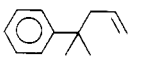
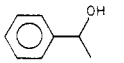
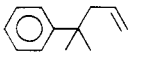
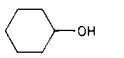
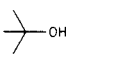


1

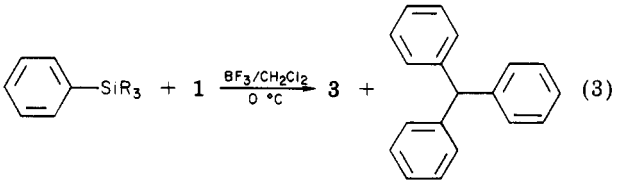


2 3 (2)

Table I. Allylation of Carbinols with Allyltrimethylsilane/BF_3

compd	product	yield, %
		100
		56
		100
		36
		87
		90
		79
		50
		22
	no reaction	
	no reaction	

Reaction of 1 with either phenyltrimethylsilane or tetraphenylsilane in methylene chloride–boron trifluoride at 0 °C produced a mixture of 3 and triphenylmethane, the product of aryl transfer (eq 3).



(3)

R = CH_3, Ph

Similar reaction of cumyl alcohol (4) with phenyltrimethylsilane or (*p*-methoxyphenyl)trimethylsilane in the presence of BF_3 produced no products resulting from aryl transfer to the cumyl cation. Olefin dimers 5 (mixture of isomers) and 6 were the only products detected under these conditions (eq 4).

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(12) (a) A. Hosami, M. Endo, and H. Sakurai, *Chem. Lett.*, 499 (1978); (b) I. Ojima and M. Kumagai, *ibid.*, 575 (1978).

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(17) (a) A. Hosomi and H. Sakurai, *Tetrahedron Lett.*, 1295 (1976); (b) G. Deleris, J. Donoques, and R. Calas, *J. Organomet. Chem.*, **93**, 43 (1975).

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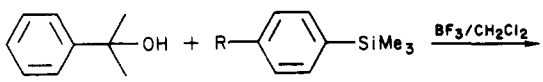
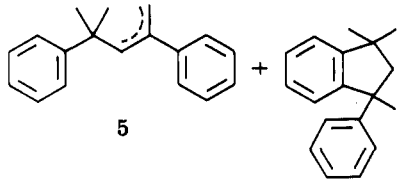
(19) (a) J. P. Pillot, J. Donoques, and R. Calas, *Tetrahedron Lett.*, 1872 (1976); (b) S. R. Wilson, L. R. Phillips, and K. J. Natalie, Jr., *J. Am. Chem. Soc.*, 3340 (1979); (c) B. Au Yeung and I. Fleming, *J. Chem. Soc., Chem. Commun.*, 79 (1977); (d) I. Fleming and I. Patterson, *Synthesis*, 446 (1979); (e) A. Hosomi and H. Sakurai, *Tetrahedron Lett.*, 2589 (1978); (f) A. Hosomi, M. Saito, and H. Sakurai, *ibid.*, 429 (1979); (g) T. K. Sarkar and N. H. Andersen, *ibid.*, 3513 (1978).

(20) β-Hydride transfer from a silane to carbon parallels similar reductions by metal alkyls; however, production of 3 from 1 is surprising.



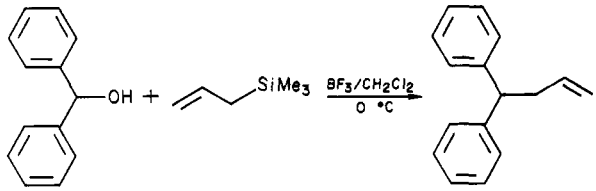
4 R = H, OCH_3



5 6 (4)

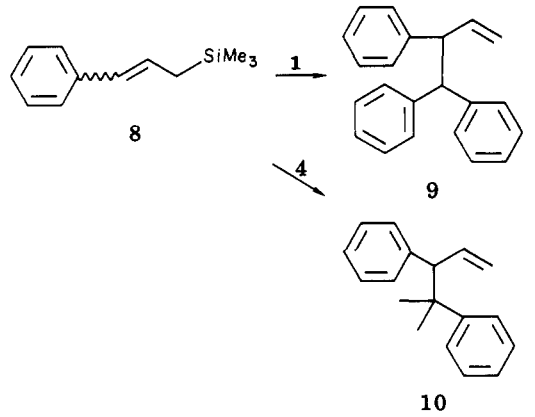
Interestingly, cumyl alcohol was recovered unchanged from treatment with BF_3–CH_2Cl_2 in the presence of tetraphenyltin.[21]

Reaction of **1** with allyltrimethylsilane (1.5 equiv) at 0 °C in BF_3/CH_2Cl_2 produced the allylated product 4,4-diphenyl-1-butene (**7**, eq 5) in quantitative yield. Using these conditions a number of aryl carbinols were allylated in good to excellent yield (Table I).



7 (5)

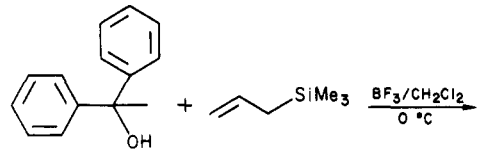
Electrophilic attack on the allyl system occurs regiospecifically at the carbon remote from silicon. For example, reaction of **1** or **4** with a mixture of (*cis*- and *trans*-3-phenylallyl)trimethylsilane (**8**) afforded allylation products **9** and **10**, respectively (eq 6). None of the regioisomers were detected in these reactions.

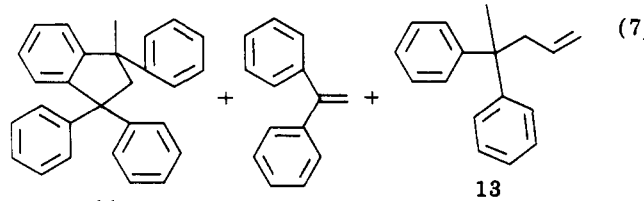


8 9 10 (6)

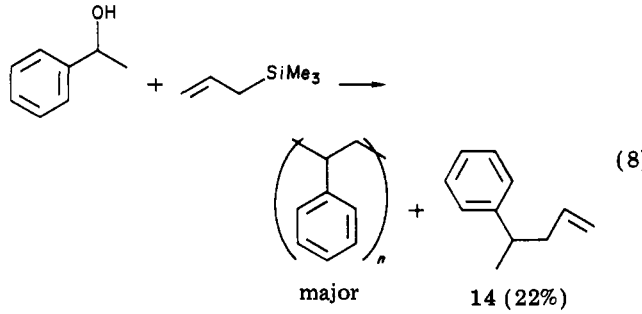
In cases where the yields of allylated products are low, the major competing processes are the result of carbenium ion mediated dimerization or polymerization. For example, 1,1-diphenylethanol reacts with the allyltrimethylsilane/BF_3/CH_2Cl_2 system at 0 °C to produce the indan **11**[22] and 1,1-diphenylethylene (**12**) in addition to the allylation product **13** (eq 7). The secondary alcohol, 1-phenylethanol, yields polystyrene as the major product along with a small amount of allylation product **14** (eq 8).

Simple aliphatic alcohols such as cyclohexanol and 2-methyl-2-propanol were not allylated under these conditions presumably because their ionization is precluded.[23]



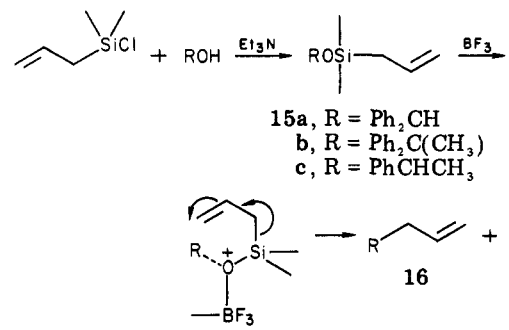


11 12 13 (7)



major 14 (22%) (8)

Oligomerization mediated by the cation can be partially offset by using excessive silane/substrate ratios.[24] This solution, however, is impractical when the allylsilane is valuable. An alternative is to conduct an intramolecular allyl transfer[25] which should be kinetically superior to the competing intermolecular processes. This is readily accomplished by employing allyl silyl ethers (**15**, eq 9) of the



16 (9)

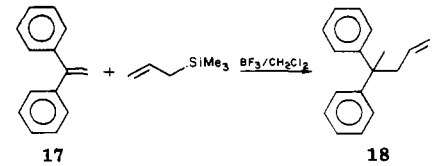
starting carbinol. The requisite ethers are easily prepared by reaction of the carbinol with allyldimethylchlorosilane[26] in the presence of triethylamine. Reaction of **15a–c** with BF_3/CH_2Cl_2 at 0 °C for 5–10 min afforded the requisite allylation products **16**. Rearrangement of **15a** at room temperature furnished, in addition to **16**, appreciable amounts of dimeric products **17** (mixture of isomers) resulting from attack of the benzhydryl cation on **16a** (eq

(21) Tetraphenyltin is an effective acid scavenger.

(22) Indan **11** is produced in high yield under these and similar conditions in the absence of allyltrimethylsilane.

(23) Cyclohexanol is reduced to cyclohexane by using BF_3/triethylsilane; however, the mechanism of this reduction may not necessarily involve the intermediacy of free carbocationic specids (see ref 7).

(24) Excess silane also converts olefin derived from the cations to the allylated product. For example, 1,1-diphenylethylene (**17**) is slowly converted to **18** on reaction with allyltrimethylsilane. This reaction, however, is much slower than direct allylation of the carbinol.

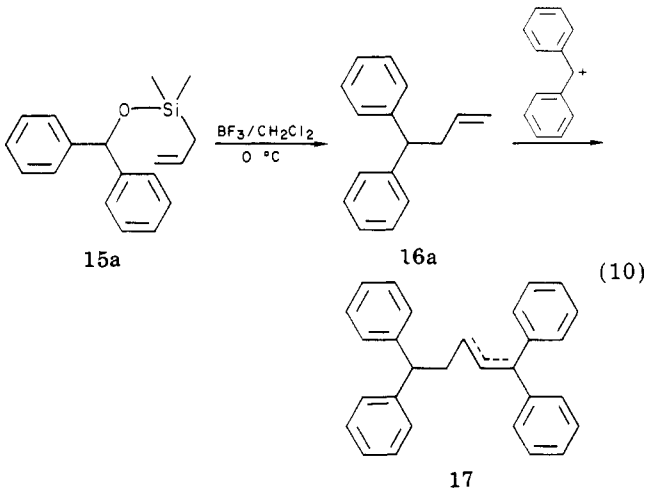


17 18

(25) Allyl transfer in this case is not strictly intramolecular but depends on the degree of rupture of the carbon–oxygen bond. The effectiveness of this method appears to be related to the requirement of the system for participation by the allyl moiety in the ionization of the ether (vide supra).

(26) Available commercially from Petrarch Systems, Inc.

10). These dimeric products are not detected in the in-



15a 16a 17 (10)

termolecular process where the benzhydryl cation is effectively scavenged by excess allytrimethylsilane. When rearrangement of **15a** was conducted at 0 °C, an 84% yield of **16a** was obtained.

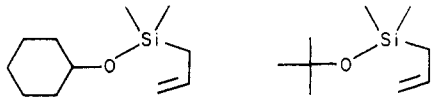
The rearrangement of silyl ether **15b** provides a means for studying the effects of certain variables on the competition between intramolecular allylation and intermolecular oligomerization reactions. Table II shows the relative proportions of allylation product (**13**), oligomerization product (**11**), and elimination product (**12**) from the rearrangement of **15b** under various conditions.

Formation of **13** is favored by dilution of the reaction mixture and by decreasing the solvent polarity. The latter effect is consistent with an increase in intramolecular participation in the ionization of the ether by the allyl group as the cation becomes less stable.

Acidic reagents other than BF_3 were examined for effecting the rearrangement of **15b**. None were found as effective as BF_3 for the production of **13**. The high yield of **12** when BF_3·Et_2O or $TiCl_4$ are used is noteworthy.

Rearrangement of **15c** afforded **16c** in 84% yield compared to a 22% yield produced via the intermolecular process using allyltrimethylsilane.

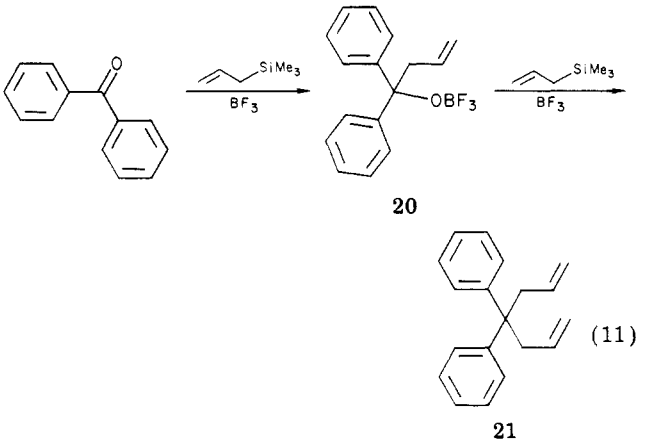
Evidently, advantage is gained by conducting the intramolecular allyl transfer with less readily ionizable substrates. Unfortunately, the allydimethylsilyl ethers of cyclohexanol and 2-methyl-2-propanol, **18** and **19**, did not



18 19

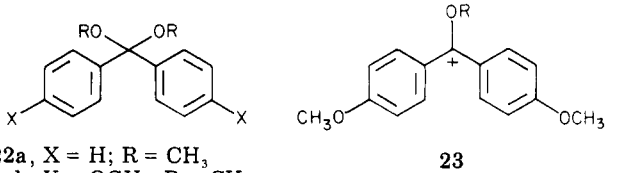
yield allylation products under normal rearrangement conditions. In the case of ether **18**, Si–O bond cleavage resulted in the formation of cyclohexanol. The success of the intramolecular process for allylation of carbinols depends on a very delicate balance of cation stability and reactivity.[27]

Geminal Allylation of Ketones and Ketals. The facile allylation of aryl carbinols with allytrimethylsilane/BF_3 suggested that geminal allylation of benzophenones should occur since the initially formed homoallylic complex **20** should readily ionize further and undergo a second allylation[18a] (eq 11).



20 21 (11)

Reaction of benzophenone with excess allyltrimethylsilane in the presence of BF_3 or $TiCl_4$ at 0 °C to room temperature failed to produce **21** to an appreciable extent. In refluxing methylene chloride and in the presence of $TiCl_4$, a 25% yield of **21** was obtained. In contrast, benzophenone dimethyl ketal **22a** reacts readily with BF_3/

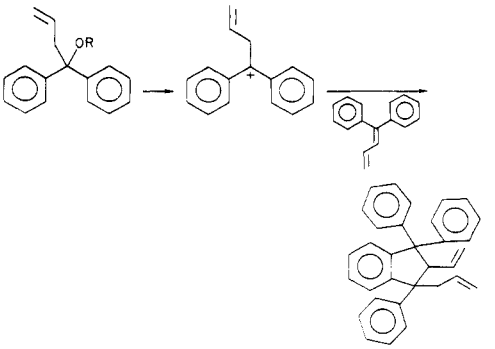


22a, X = H; R = CH_3
b, X = OCH_3; R = CH_3
c, X = OCH_3; R, R = $-CH_2C(CH_3)_2CH_2-$

23

CH_2Cl_2 at 0 °C to produce **21** in 75% yield.[28] Ketals **22b** and **22c** yielded only the corresponding ketone under these conditions. Cation **23** may be too stable to react with allyl trimethylsilane prior to cleavage to the ketone.

Conclusions. Aryl- and allylsilanes react with readily ionizable carbinols in a BF_3/CH_2Cl_2 system to afford products resulting from transfer of an aryl or allyl group from silicon to the carbenium ion generated in the ionization process. This reaction constitutes a formal reductive arylation (allylation) of the carbinol. The success of a particular arylation or allylation depends on the stability of the cation generated, its propensity for oligomerization, and the reactivity of the silane employed. The formation of undesired byproducts in the allylation reaction can be offset in some cases by utilizing an intramolecular allyl transfer from an allyl silyl ether. Reductive geminal al-



24

(27) We have also prepared benzyldimethylsilyl and phenyldimethylsilyl ethers of a number of carbinols, but their rearrangement reactions were complex and were not further pursued.

(28) Interestingly, dimeric products **24** resulting from elimination followed by cation addition were not found in the reaction of **22a** with allyltrimethylsilane.

(29) Allytrimethylsilane is undoubtedly consumed by BF_3 in a competitive process so that if cation **23** is cleaved faster than reaction with allyltrimethylsilane, and no allylation will be observed.

Table II. Rearrangement of 15b at 0 °C under Various Conditions

expt	catalyst	solvent	[15b][a]	% yield of products 13	12	11
1	BF_3	CH_2Cl_2	3.4	12.8	52.3	34.9
2	BF_3	CH_2Cl_2	2.3	18.5	61.2	20.3
3	BF_3	hexane	2.3	47.2	51.0	1.8
4	$BF_3 \cdot Et_2O$	CH_2Cl_2	3.4	1.7	95.9	2.3
5	$TiCl_4$	hexane	2.3	0.0	100.0	0.0
6	LiF	CH_2Cl_2[b]	20.4			
7	silica gel	CH_2Cl_2[b]	40.8			
8	$AgBF_4$	CH_2Cl_2/hexane	3.4	11.8	87.2	0
9	$BF_3/NaBF_4$[c]	CH_2Cl_2	2.3	17.8	45.8	37.4

[a] Molar concentration of 16b × 10^3. [b] Stirred at room temperature for 2 days. [c] $NaBF_4$ not soluble in this medium.

lylation of aryl ketals is possible when the homoallyl cation generated after the initial allylation is sufficiently reactive.

Experimental Section

General Methods. Melting points were determined by using a Mel-Temp apparatus and are uncorrected. Infrared spectra were obtained on a Perkin-Elmer 457 grating spectrophotometer. ^1H NMR spectra were recorded on a Varian T60 spectrometer with chemical shifts reported in parts per million relative to tetramethyl silane as an internal standard. Mass spectra were obtained in a Varian Mat 311 mass spectrometer operating in the EI mode.

All new compounds gave satisfactory elemental analysis. Most of the silanes or carbinols used in this study were obtained from commercial sources and used without purification. The mixture of *cis*- and *trans*-1-phenyl-3-(trimethylsilyl)propene was prepared from the reaction of (trimethylsilyl)methylphosphorane with benzaldehyde according to the method of Seyferth et al.[30]

General Procedure for Reductive Allylation/Arylation of Carbinols. Typically, a solution of the substrate (10 mmol) and the appropriate silane (12–15 mmol) in ca. 35 mL of solvent (usually CH_2Cl_2) was chilled in an ice bath to 0–5 °C. Dry, gaseous boron trifluoride was introduced into the solution by means of an inlet tube immersed in the solvent. The reaction solutions were magnetically stirred and maintained under a blanket of dry nitrogen. Reactions were monitored for disappearance of starting material (usually by TLC or GC). When no starting material remained, the mixtures were poured onto ice–water and extracted with methylene chloride. The dried organic extracts were concentrated to afford crude products which were purified by distillation, recrystallization, or column chromatography. Samples for analysis were further purified by passage through a Sep-Pak cartridge.[31]

4,4-Diphenyl-1-butene (7): ^1H NMR ($CDCl_3$) δ 2.8 (t, 2, allyl H), 4.0 (t, 1, benzylic H), 4.8–6.0 (m, 3, vinyl H), 6.97 (s, 10, Ar H).

3,4,4-Triphenyl-1-butene (9): ^1H NMR ($CDCl_3$) δ 4.2 and 4.75 (m, 3, vinyl H's), 4.28 (s, 1, allyl HO, 5.0 (s, 1, methine H), 1.18 (m, 15, Ar H); mass spectrum, *m/e* (relative intensity), 284 (0.34, $M^+ - C_9H_9$).

3,4-Diphenyl-4-methyl-1-pentane (10): ^1H NMR ($CDCl_3$) δ 1.35 (s, 6, gem-CH_3), 3.30 (d, 1, allyl H), 4.92 and 6.00 (m, 3, vinyl H), 7.0 (m, 10, Ar H); mass spectrum, *m/e* (relative intensity) 236 (1.79, M^+), 221 (10.7, M − 15), 119 (100, $M - C_9H_9$).

1,1,3-Triphenyl-3-methylindan (11): ^1H NMR ($CDCl_3$) δ 1.67 (s, 3, CH_3), 3.53 (AB q, J_{AB}^{gem} = 15 Hz, 2, ring CH_2), 7.53 (m, 19, Ar H).

4,4-Diphenyl-1-pentene (13): ^1H NMR ($CDCl_3$) δ 1.63 (s, 3, CH_3), 2.3 (d, 2, allyl CH_2), 5.23 (m, 1, vinyl HO), 7.33 (s, 10, Ar H); bp 157–160 °C (~0.1 mm).

4-Phenyl-1-pentene (14): ^1H NMR ($CDCl_3$) δ 1.23 (d, 3, $CHCH_3$), 2.37 (d, 2, allyl CH_2), 27 (m, 1, $CHCH_3$) 4.73–6.03 (m, 3, vinyl H), 7.20 (s, 5, Ar H).

4-(2-Methoxyphenyl)-4-(3-methoxyphenyl)-1-butene: ^1H NMR ($CDCl_3$) δ 2.70 (t, 2, allyl H), 3.6 (s, 6, OCH_3), 4.4 (t, 1, Ar CH–CH_2), 4.7–5.9 (m, 3, vinyl H), 6.8 (m, 8, Ar H).

4-(3-Hydroxyphenyl)-4-methyl-1-pentene: ^1H NMR ($CDCl_3$) δ 1.27 (s, 6, *gem*-CH_3), 2.30 (d, 2, allyl H), 5.03 (m, 3, vinyl H), 7.43 (m, 5, Ar H).

4-Phenyl-4-methyl-1-pentene: ^1H NMR ($CDCl_3$) δ 1.37 (s, 6, *gem*-CH_3), 2.43 (d, 2, allyl H), 4.83–6.17 (m, 3, vinyl H), 7.43 (m, 5, Ar H).

4-(*p*-Hydroxyphenyl)-4-methyl-1-pentene: ^1H NMR ($CDCl_3$) δ 1.27 (s, 6, *gem*-CH_3), 2.40 (d, 2, allyl H), 5.17 (m, 3, vinyl H), 7.1 (AB q, 4, Ar H).

4-(*p*-Isopropylphenyl)-4-methyl-1-pentene: ^1H NMR ($CDCl_3$) δ 1.24 (d, 6, isopropyl CH_3), 1.25 (s, 6, *gem*-CH_3), 2.40 (d, 2, allyl H) 2.95 (m, 1, benzylic H), 5.18 (m, 3, vinyl H), 7.33 (m, 4, Ar H).

Preparation of Allyldimethylsilyl Ethers. A representative procedure for the preparation of allyldimethylsilyl ethers is as follows. A solution of 4.60 g (25 mmol) of benzhydrol, 3.38 g (25 mmol) of allyldimethylchlorosilane, and 2.53 g (25 mmol) of triethylamine in 50 mL of dry ether was refluxed for 4 h. The cooled ethereal solution was washed with equal volumes of water, 1 N HCl, and brine and then dried by passage through a cone of anhydrous $CaSO_4$. Evaporation of the ether followed by purification by silica gel column chromatography (elution with CH_2Cl_2) afforded 5.87 g (83.2%) of allyldimethylsilyl benzhydryl ether (**15a**): ^1H NMR ($CDCl_3$) δ 0.23 (s, 6, $SiCH_3$), 1.50 (m, 2, Si allyl), 4.77 (m, 3, vinyl H), 5.43 (s, 1, benzyl H), 7.17 (s, 10, Ar H).

Similarly were prepared were the following.

Dimethylallylsilyl 1-phenylethyl ether (15c): ^1H NMR ($CDCl_3$) δ 0.33 (s, 6, $SiCH_3$), 1.66 (m, 2, Si allyl H, and d, 3, $CHCH_3$), 3.67 (q, 1, Ar $CHCH_3$), 5.0 (m, 2, vinyl $=CH_2$), 5.87 (m, 1, vinyl H), 7.37 (s, 5, Ar H).

Dimethylallylsilyl 1,1-diphenylethyl ether (15b): ^1H NMR ($CDCl_3$) δ 0.30 (s, 6, $SiCH_3$), 1.75 (m, 2, Si allyl H), 2.30 (s, 3, CH_3), 5.10 (m, 2, vinyl CH_2), 5.90 (m, 1, vinyl H), 7.65 (m, 10, Ar H).

Allyldimethylsilyl cyclohexyl ether (18): ^1H NMR ($CDCl_3$) δ 0.33 (s, 6, $SiCH_3$), 1.8 (center of br m, 13-H's, cyclohexyl and allylic protons), 5.2 and 6.0 (m, 3, vinylic H's).

Rearrangements of Silyl Ethers. The allyldimethylsilyl ethers (~1–2 mmol) were dissolved in 10–25 mL of solvent (usually CH_2Cl_2 or hexane), and the solution was chilled to 0–5 °C by using an ice–water bath. Dry gaseous BF_3 was introduced below the liquid surface for ca. 1 min. The disappearance of the silyl ether was monitored by gas chromatography and was usually complete in 2–5 min. Products were isolated by following the same procedures described for the intermolecular allylations.

Reaction of Benzophenone with Allyltrimethylsilane and Titanium Tetrachloride. Titanium tetrachloride (2.2 mL, 20 mmol) was added via syringe to a magnetically stirred solution of benzophenone (3.64 g, 20 mmol) and allyltrimethylsilane (10.0 g, 88 mmol) in 50 mL of dry chloroform. The dark mixture was heated at reflux for 4 h at which point thin-layer chromatographic analysis (silica gel, 1/1 v/v cyclohexane/methylene chloride) indicated that no more benzophenone remained. The usual aqueous workup afforded 4.31 g of a pasty oil which was chromatographed on 100 g of silica gel eluted with a gradient from 10% CH_2Cl_2 in cyclohexane to 25% CH_2Cl_2 in cyclohexane). Mobile components were rechromatographed to yield 3.0 g of an amber oil consisting of ca. 40% of the desired bisallylation product **21** (~25% yield). Pure **21** was obtained by repeated passage thru Sep-Pak cartridges: ^1H NMR ($CDCl_3$) δ 3.08 (d, 4, allyl H), 5.4

(30) D. Seyferth, K. R. Wursthorn, T. F. O. Lim, and D. J. Sepelak, *J. Organomet. Chem.*, 181, 293 (1979). See also D. Seyferth, K. R. Wursthorn, and R. E. Mammarella, *J. Org. Chem.*, 42, 3104 (1977).

(31) Available from Waters Associates.

(d, 6, vinyl H), 7.62 (s, 10, Ar H); ^{13}C NMR 147.78, 134.52, 128.06, 127.78, 125.67, and 117.63 (Ar and Vinyl C), 48.71 and 41.99 ppm (allyl and quaternary aliphatic carbons); mass spectrum, *m/e* (relative intensity) 248 (0.06, M^+), 207 (0.5, M - 41), 129 (100).

Reaction of Benzophenone Dimethyl Ketal with Allyltrimethylsilane and Boron Trifluoride. Dry boron trifluoride gas was introduced to a solution of benzopheone dimethyl ketal (2.28 g, 10 mmol) and allyltrimethyl silane (2.4 g, 21 mmol) in 30 mL of methylenechloride at 0 °C for 15 min. The cold organic solution was quenched with 40 mL of 1 M sodium carbonate solution, and the phases were separated. After drying and evaporation of the solvent, there was obtained 2.02 g of a light amber oil which was chromatographed on silica gel eluted with 1:1 cyclohexane/methylene chloride to yield 1.86 g (75%) of pure **21**.

Registry No. **1**, 91-01-0; **2**, 574-42-5; **3**, 101-81-5; **4**, 617-94-7; **5** (isomer I), 6258-73-7; **5** (isomer II), 6362-80-7; **6**, 3910-35-8; **7**, 4286-85-5; *cis*-**8**, 40595-35-5; *trans*-**8**, 40595-34-4; **9**, 81194-40-3; **10**, 81194-41-4; **11**, 19303-32-3; **12**, 530-48-3; **13**, 6480-80-4; **14**, 1075-74-7; **15a**, 81194-42-5; **15b**, 81194-43-6; **15c**, 81194-44-7; **16a**, 4286-85-5; **16c**, 10340-49-5; **17** (isomer I), 81194-45-8; **17** (isomer II), 81194-46-9; **18**, 81194-47-0; **19**, 7087-22-1; **21**, 81194-48-1; **22a**, 2235-01-0; **22b**, 2186-93-8; **22c**, 81194-49-2; triphenylmethane, 519-73-3; polystyrene, 9003-53-6; 4-(2-methoxyphenyl)-4-(3-methoxyphenyl)-1-butene, 81194-50-5; 4-(3-hydroxyphenyl)-4-methyl-1-pentene, 81194-51-6; 4-phenyl-4-methyl-1-pentene, 66622-39-7; 4-(*p*-isopropylphenyl)-4-methyl-1-pentene, 81194-52-7; benzophenone, 119-61-9; allyltrimethylsilane, 762-72-1; titanium tetrachloride, 7550-45-0; boron trifluoride, 7637-07-2; 1,1-diphenylethanol, 599-67-7; 4-(*p*-hydroxyphenyl)-4-methyl-1-pentene, 35029-26-6; (2-methoxyphenyl)(3-methoxyphenyl)methanol, 81194-53-8; 1,1-bis(4-methoxyphenyl)-ethanol, 728-87-0; 2-(4-isopropylphenyl)-2-propanol, 3445-42-9; 2-(3-hydroxyphenyl)-2-propanol, 7765-97-1; 2-(4-hydroxyphenyl)-2-propanol, 2948-47-2; 1-phenylethanol, 98-85-1; cyclohexanol, 108-93-0; 2-methyl-2-propanol, 75-65-0; 4,4-bis(4-methoxyphenyl)-1-pentene, 81194-54-9.

Canthaxanthin. A New Total Synthesis

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Received November 23, 1981

A new synthesis of canthaxanthin via a Wittig coupling of the C_{15} phosphonium salt **16** and the symmetrical dialdehyde **3** is reported. Several routes to the key phosphonium salt via substituted cyclohexenones **4** and **10** and α-ionone are described.

Recent results on the pharmacological effects of the coal-tar-based azo dyes has led to the withdrawl of the food coloring agent Red No. 2 from the certified list of dyes permitted for the use in foods and drugs. The need for safe red coloring agents for human use has generated renewed interest in canthaxanthin **1** (X = O), a natural carotenoid[1] which exhibits excellent tinctorial properties.[2]

The present commerical process used to manufacture canthaxanthin[1] is based on the oxidation of β-carotene[3] **1** (X = H: Figure 1) and proceeds through the intermediate acetate **1** (X = H, OAc) and alcohol **1** (X = H, OH). To provide a more convergent synthesis, we examined an approach to canthaxanthin based on the "C_{15} + C_{10}" (**2** + **3**) scheme which had been used previously for the synthesis of β-carotene.[4]

The most attractive feature of such a synthetic plan is that the final product is constructed in the last step from *small* fragments which avoids the problems associated with performing chemical transformations at the C_{40} level.[5]

Numerous avenues are available for the synthesis of the symmetrical dialdehyde **3**.[1] Our main task was the construction of the phosphorane **2**, which is described in this publication.[6]

Our first approach to build up the C_{15} carbon skeleton of **2** was to employ 2,6,6-trimethyl-2-cyclohexenone **4**[7] and the six-carbon acetylene derivative **5**.[8] Acetic acid treatment of adduct **6**, formed from **4** and **5**, readily gave acetate **7** (R = Ac) and diol **7** (R = H) after hydrolysis (Figure 2). Oxidation of **7** (R = H) then yielded ketone **8** which on treatment with acid gave the new ketone **9**. While the overall process works, the oxidation and acid rearrangement steps **7** (R = H)-**9** are poor and the final product **9** is a mixture of double bond isomers with the cis isomer predominating. To circumvent these problems, we used compound **10** in place of **4** and employed trans enyne **11** for the six-carbon unit (Figure 3).[8]

Substituted cyclohexenone **10** was prepared by condensing methyl isobutyrate with ethyl vinyl ketone to give keto ester **12** which on base cyclization yielded crystalline β-diketone **13** in 75% overall yield. Exposure of this material to isobutyl alochol and acid yielded only *one* enol ether, **10** (90%), the structure of which was established by reduction to trimethylcyclohexenone **14** with lithium aluminum hydride. Condensation of **11** with **10** followed by acid hydrolysis gave crystalline trans keto alcohol **9** in 90% yield. Hydrogenation of **9** resulted in the formation of alcohol **15** containing a cis double bond. Exposure of this material to phosphorus tribromide followed by triphenylphosphine gave the desired all-trans phosphonium salt **16** containing approximately 10% of the cis isomer.[9] Condensation of the crude salt **16** with dialdehyde **3** yielded canthaxanthin in 80% yield after isomerization of the mother liquor materials.[10]

Having shown that this route to canthaxanthin was viable, the next goal was to establish an economical route to **16**. This was achieved through the use of α-ionone (**17**),

(1) Isler, O. "*Carotenoids*", Birkhauser Verlag, Basel and Stuttgart, 1971.

(2) Isler, O.; Ofner, A.; Siemers, G. F. *Food Technol.* **1958**, *12*, 1. Bunnell, R. H.; Borenstein, B. *Ibid.* **1967**, *21*, 13. Emodi, A.; Scialpi, L.; Antoshkiw, T. *Ibid.* **1976**, 58. Emodi, A. *Ibid.* **1978**, 38.

(3) Petracek, F. J.; Zechmeister, L. *J. Am. Chem. Soc.* **1956**, *78*, 1427. Entschel, R.; Karrer, P. *Helv. Chim. Acta* **1958**, *41*, 402.

(4) Pommer, H. *Angew. Chem.* **1960**, *72*, 911.

(5) These are mainly solubility problems and the intrinsic instability of these polyenes.

(6) A preliminary account of this work was presented at the Fifth International Symposium on Carotenoids, Madison, WI, July 1978. Rosenberger, M.; McDougal, P.; Saucy, G.; Bahr, J. *Pure Appl. Chem.* **1979**, *51*, 871.

(7) Olson, G. L.; Cheung, H. C.; Morgan, K. D.; Borer, R.; Saucy, G. *Helv. Chim. Acta* **1976**, *59*, 567 and references cited therein.

(8) The free alcohol is a key intermediate used in the synthesis of vitamin A. Acid treatment yields (*Z*)-3-methyl-2-penten-4-yn-1-ol, the vitamin intermediate (see ref 1), and (*E*)-3-methyl-2-penten-4-yn-1-ol.

(9) The C_4 and C_5 protons appear as a singlet in the ^1H NMR spectrum; δ 6.35 (cis) and 6.16 (trans).

(10) Care has to be exercised in crystallizing **1** as the thermal isomerization into a mixture of double bond isomers is a facile process.

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