(56) H. Hepworth and H. W. Clapham, *J. Chem. Soc.*, 1193 (1921).
(57) W. T. Smith, Jr., and J. T. Sellas, "Organic Syntheses", Collect. Vol. IV, N. Rabjohn, Ed., Wiley, New York, N.Y., 1963, p 702.
(58) J. Hooz and S. S. H. Gilani, *Can. J. Chem.*, **46**, 86 (1968).
(59) C. L. Jenkins and J. K. Kochi, *J. Org. Chem.*, **36**, 3103 (1971).
(60) L. F. Fieser and M. Fieser, "Reagents for Organic Synthesis", Vol. I, Wiley, New York, N.Y., 1967, p 1180.
(61) D. E. Bergbreiter and G. M. Whitesides, *J. Org. Chem.*, **40**, 779 (1975).
(62) R. C. Weast, Ed., "Handbook of Chemistry and Physics", Chemical Rubber Publishing Co., Cleveland, Ohio, 1972, p C-396.
(63) H. Stone and H. Schechter, "Organic Syntheses", Collect. Vol. IV, N. Rabjohn, Ed., Wiley, New York, N.Y., 1963, p 543.

Reversible Grignard and Organolithium Reactions

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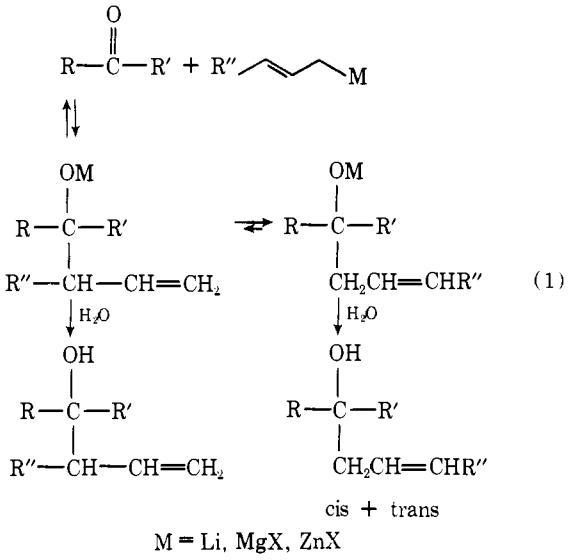
Abstract: Numerous examples are given of the reversible addition of allylic-type Grignard and organolithium reagents to a variety of ketone substrates. The role of steric hindrance in these reversible additions is clearly demonstrated. Procedures have been devised for the preparation of isomerically pure α-methallylcarbinols derived from the crotyl organometallic. The ketones which form occasionally when the alkoxides of the α-methallylcarbinols undergo reversal result from the formation of the ketone enolates. Finally, it has been shown that not *all* of the crotylcarbinols produced when crotyl organometallics react with hindered ketones *necessarily* result from an isomerization of the initially formed α-methallyl isomers.

Introduction

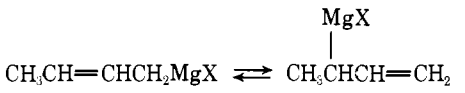
In recent years, there have been several disclosures of the reversible addition of unsaturated organometallics like the crotyl derivatives of lithium, magnesium, and zinc to carbonyl systems[1-5] (eq 1).



M = Li, MgX, ZnX (1)

A detailed study was initiated by us in an effort to correlate the rate of reversal with the steric bulk of the alkoxide (eq 1) and hopefully to develop a synthetic method for preparing isomerically pure α-methallyl adducts of hindered carbonyl compounds. Likewise the source of the free ketones which are produced in some of the alkoxide reversals was sought (see Table III).

These reversible additions stand in curious parallel to the abnormal behavior of allylic organometallics in general. Of all these compounds, the crotylmagnesium halides have been investigated most thoroughly and have been shown by NMR studies[6-9] to exist in solution as a rapidly equilibrating mixture of the primary and secondary forms with the equilibrium lying well to the primary side (eq 2). Quite remarkably, although the crotyl Grignard exists almost exclusively in the primary



(2)

form, it reacts with unhindered carbonyl systems such that essentially only α-methallyl products are formed.[10-12] As the steric bulk of the carbonyl system increases, however, there is a concomitant increase in crotyl products at the expense of the α-methallyl adducts.[13-15] When di-*tert*-butyl ketone is used as the substrate, for example, there is nearly exclusive formation of the crotyldi-*tert*-butylcarbinols. The pathway whereby the latter product is produced seemed extremely important to us since at least two modes of formation can be envisioned (vide infra).

Results and Discussion

The report of a reversible crotyl Grignard reaction,[1] in which a highly hindered α-methallyl adduct of the ketone reverts to its more stable and less hindered crotyl adduct (eq 1), could be interpreted as indicating that *all* crotyl adducts of hindered ketones form *exclusively* from the initially produced alkoxide salts of the α-methallylcarbinols as shown. Alternately, however, the crotyl products might be formed *both* from such a reversal process involving the α-methallyl adduct as well as *directly* from the ketone and the crotyl Grignard via a four-

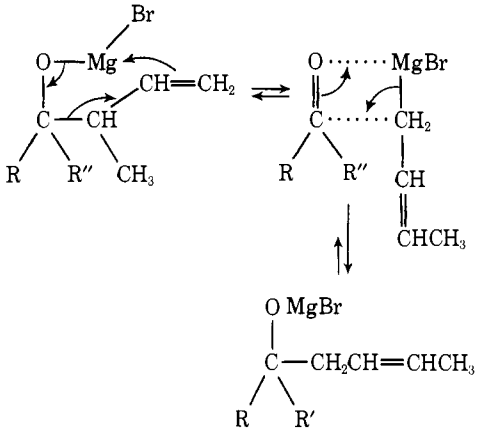


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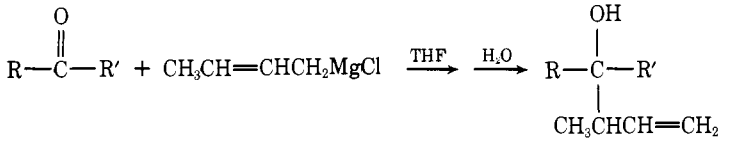
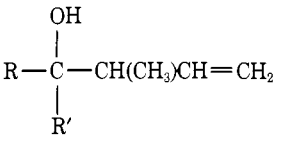
Table I. Isomerically Pure α-Methallylcarbinols



R	R′	Reaction temp, °C	Reaction time, min	Yield, %	Bp, °C (mmHg)	$n^{20}D$	Ref
t-C_4H_9	*i*-C_3H_7	−78	60	64	65-67 (2.2)	1.4669	32a
i-C_3H_7	*i*-C_3H_7	−78	60	61	62.5-63.3 (3)	1.4609	32b
C_2H_5	C_2H_5	25	10	73	62-64 (11)	1.4520	31
t-C_4H_9	c-C_6H_{11}	−78	240	74	89-92 (0.35)	1.4922	
i-C_3H_7	c-C_6H_{11}	−78	60	60	75-76 (0.28)	1.4872	
c-C_6H_{11}	c-C_6H_{11}	−78	60	90	*a*	1.5077	
t-C_4H_9	C_6H_5	15	3	91[b]	94-98 (0.6)	1.5226	
i-C_3H_7	C_6H_5	25	30	91[c]	87-96 (0.3)	1.5205	
C_6H_5	C_6H_5	0	2.5	78	*a,d*		14

[a] Purified by column chromatography: pentane wash, elution with 1:1 pentane-ether. [b] Diastereomers in the ratio 88:12. [c] Diastereomers in the ratio of 68:32. [d] MP 53-54 °C.

Table II. Spectral Data for New α-Methallylcarbinols



R	R′	IR (neat), μ	NMR (CCl_4), δ
t-C_4H_9	c-C_6H_{11}[a]	2.80 (OH) 6.14 (C=C)	0.80-2.20 (m, 11 H), 1.04 (superimposed s, 9 H), 1.22 (superimposed d, 3 H), 1.47 (superimposed s, 1 H, OH), 2.62 (m, 1 H), 4.86 (m, 1 H), 5.12 (m, 1 H), 6.07 (m, 1 H)
i-C_3H_7	c-C_6H_{11}[b]	2.90 (OH) 6.21 (C=C)	0.82-2.25 (m, 12 H), 0.96 (superimposed d, 6 H), 1.03 (superimposed d, 3 H), 1.17 (superimposed s, 1 H, OH), 2.55 (m, 1 H), 4.87 (m, 1 H), 5.09 (m, 1 H), 5.97 (m, 1 H)
c-C_6H_{11}	c-C_6H_{11}[c]	2.88 (OH) 6.17 (C=C)	0.80-2.18 (m, 22 H), 1.03 (superimposed d, 3 H), 1.16 (superimposed s, 1 H, OH), 2.65 (m, 1 H), 4.87 (m, 1 H), 5.11 (m, 1 H), 6.01 (m, 1 H)
t-C_4H_9	C_6H_5[d]	2.74 (OH) 6.11 (C=C) 6.24 (C=C, aromatic)	0.70 (d, 3 H), 0.96 (s, 9 H), 1.77 (s, 1 H, OH), 3.09 (m, 1 H), 5.08 (m, 2 H), 6.17 (m, 1 H), 7.33 (m, 5 H)
i-C_3H_7	C_6H_5[e]	2.90 (OH) 6.20 (C=C) 6.32 (C=C, aromatic)	0.80 (m, 9 H), 1.81 (broad s, 1 H, OH), 2.19 (sept, 1 H), 2.83 (m, 1 H), 4.90 (m, 1 H), 5.12 (m, 1 H), 5.77 (m, 1 H), 7.23 (m, 5 H)

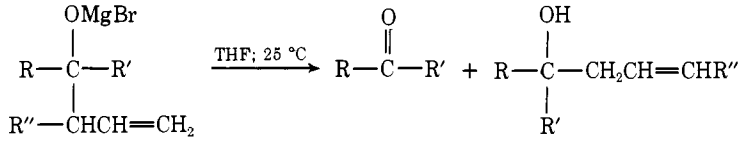
[a] Anal. Calcd for $C_{15}H_{28}O$: C, 80.29; H, 12.58. Found: C, 80.42; H, 12.60. [b] Anal. Calcd for $C_{14}H_{26}O$: C, 79.91; H, 12.48. Found: C, 79.74; H, 12.68. [c] Anal. Calcd for $C_{17}H_{30}O$: C, 81.54; H, 12.08. Found: C, 81.57; H, 12.27. [d] Anal. Calcd for $C_{15}H_{22}O$: C, 82.51; H, 10.16. Found: C, 82.49; H, 10.31. [e] Anal. Calcd for $C_{14}H_{20}O$: C, 82.30; H, 9.87. Found: C, 82.37; H, 10.15.

center transition state[1] in which the α-methallyl adduct is never involved.

Regardless of which mechanism is operative, it seemed that, under proper conditions, it should be possible to form only the pure kinetic product, the α-methallyl adducts of hindered carbonyl systems. Accordingly a reaction temperature of −78 °C was employed to suppress reversal of the kinetic product to the thermodynamic crotyl adducts as depicted in eq 3. Likewise THF was selected as the solvent since it seemed to enhance formation of the α-methallyl isomer.[15] The results are presented in Tables I and II.

Only di-*tert*-butyl ketone failed to give exclusively α-methallyl adduct under the aforementioned conditions. In one experiment, di-*tert*-butyl ketone was treated with crotylmagnesium chloride in THF at −78 °C *for only 30 min* and crotyldi-*tert*-butylcarbinol was obtained as the sole product in 57% yield. That this crotyl isomer was *not* a consequence of reversal (eq. 3) was proved by preparing di-*tert*-butyl-α-methallylcarbinol free of crotyl isomer by an alternate route (eq 4). This was converted into its magnesium bromoalkoxide at −78 °C (eq 5). After *2 h* at −78 °C, hydrolytic workup of the alkoxide afforded only starting material (eq 5). No trace of crotyldi-*tert*-butylcarbinols was observed. These results indicated rather conclusively that the 57% yield of crotyl product could not have arisen from an initially formed α-methallyl product. One must conclude that when steric hindrance in the carbonyl substrate is extremely severe (as with di-*tert*-butyl ketone), the crotyl Grignard can react directly via a four-center pathway. It follows, therefore, that crotyl products can be formed *both* from a reversal process involving the α-methallyl adduct (eq 3) and *directly* from the ketone and the crotyl Grignard via a four-center transition state.

Table III. Reversal of Magnesium Bromoalkoxides

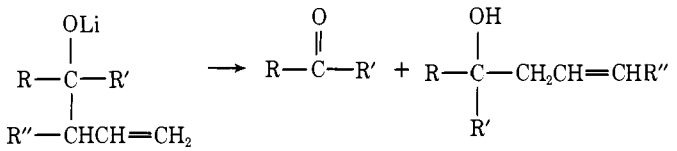


cis + trans

R	R′	R″	Time, h	Total yield of reversal products, %	Rel product distribution: Ketone, %	Carbinols %: Cis	Carbinols %: Trans
(1) [a] *t*-C_4H_9	*i*-C_3H_7	CH_3	96	96[b]	13	60	27
(2) *t*-C_4H_9	c-C_6H_{11}	CH_3	120	84	25	53	22
(3) *t*-C_4H_9	*t*-C_4H_9	CH_3	6	91	<1	66	33
(4) *i*-C_3H_7	*i*-C_3H_7	C_6H_5	12	95	<1	99[c]	

[a]Results of Broxterman (ref 1) shown for comparison purposes. [b]Recovered starting material amounted to 3%, GC yield. [c]Compound decomposed on GC, hence no cis, trans isomer ratio determined.

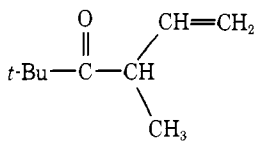
Table IV. Reversal of Lithium Alkoxides

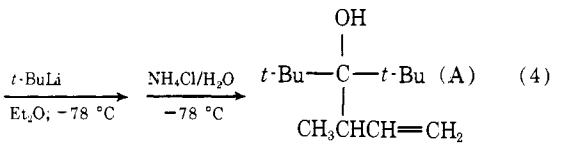


cis + trans

R	R′	R″	Solvent	Temp, °C	Time, h	Yield of reversal products, %	Rel product distribution: Ketone, %	Carbinols, %: Cis	Carbinols, %: Trans
(1) *t*-C_4H_9	*i*-C_3H_7	CH_3	THF	25	12	98[a]	0	81	19[a]
(2) *t*-C_4H_9	c-C_6H_{11}	CH_3	THF	25	12	81	<1	81	19
(3) *t*-C_4H_9	*t*-C_4H_9	CH_3	THF	25[b]	1.2	91	<1	86	14
(4) *i*-C_3H_7	*i*-C_3H_7	C_6H_5	THF	25[b]	0.7	78	0	100[d]	[c]
(5) C_2H_5	C_2H_5	CH_3	Diglyme	162	168	7	[93][e]	5	2
(6) C_6H_5	C_6H_5	CH_3	Diglyme	162	144	77	1-2	98-99[d]	
(7) *i*-C_3H_7	C_6H_5	CH_3	Diglyme	162	72	67	75[f]	9	6
(8) *t*-C_4H_9	C_6H_5	CH_3	Diglyme	162	48	92	6	76	18
(9) *i*-C_3H_7	*i*-C_3H_7	CH_3	Monoglyme	85	96	18	[81][e]	13	6
(10) *i*-C_3H_7	c-C_6H_{11}	CH_3	Monoglyme	85	96	82	72	20	8
(11) c-C_6H_{11}	c-C_6H_{11}	CH_3	Monoglyme	85	72	79	80	20[d]	
(12) *i*-C_3H_7	*i*-C_3H_7	*i*-C_3H_7	THF	65	48	86	0	50	50
(13) C_2H_5	C_2H_5	C_6H_5	THF	65	6	76	[0][e]	100[d]	
(14) C_2H_5	C_2H_5	*i*-C_3H_7	Diglyme	162	48	27	[73][e]	19	8

[a]Yields by GC; see Ref 16. [b]Alkoxide generated at −78 °C. [c]Reference 5. [d]No isomer distribution determined; carbinols not amenable to capillary GC. [e]Not isolated, water soluble. [f]10% isopropylphenylcarbinol was also isolated.





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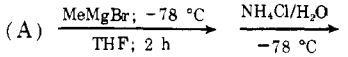


(5)

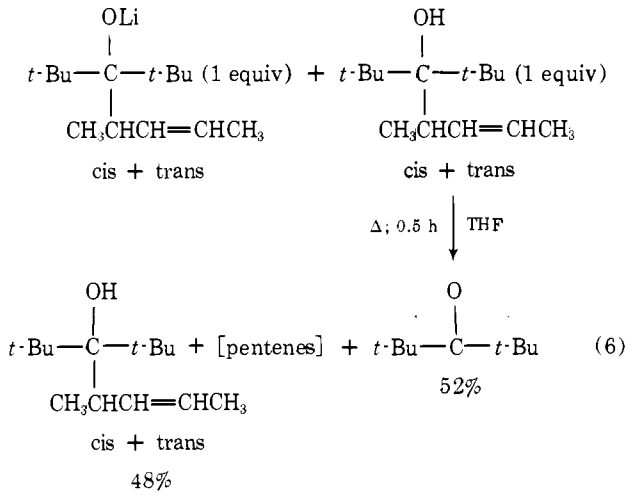
The effect of steric strain on the rate of reversal of a series of lithium and magnesium homoallylic alkoxides was examined (Tables III and IV). The alkoxides were generated by the addition of *n*-butyllithium or methylmagnesium bromide to the appropriate carbinol. The choice of solvent was dictated by the temperature needed to effect reversal at a reasonable rate. For room temperature reversals, THF was used, while for higher temperature, monoglyme or diglyme was used. The yields listed in Tables III and IV are for isolated products, unless otherwise indicated.

If one compares the four entries in Table III with the first four in Table IV, it is immediately apparent that the lithium alkoxides reverse about ten times faster than the corresponding magnesium bromoalkoxides. Other reports[18] indicate that zinc bromoalkoxides reverse even faster than those of lithium and magnesium. No satisfactory explanation has been offered for this unexpected order.

It is clear from Tables III and IV that as the steric bulk of the metal alkoxides increases, the rate of reversal also increases. In the α-methallyl series of alkoxides, the order found was *t*-Bu > *i*-Pr $\simeq$ cyclohex > Ph > Et, which might be expected on the basis of steric considerations.

One system which was studied by a different method was the reversal of the lithium alkoxides of di-*tert*-butyl-α,γ-dimethylallylcarbinol. Since, by symmetry, this compound yields a reversal product which is identical with the starting

material, protonation of the intermediate organometallic species[2] (eq 6) afforded a probe for the reversal. The ratio of

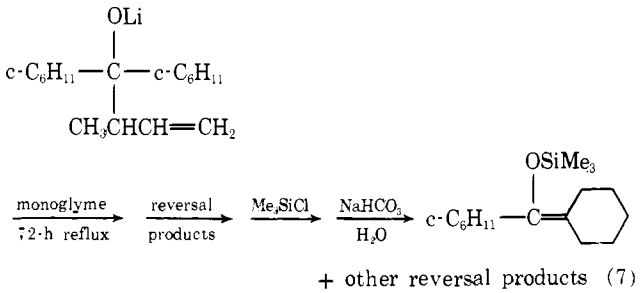


(6)

di-*tert*-butyl ketone to recovered carbinol was 52:48, close to the theoretical 50:50 ratio. The reversal of the corresponding magnesium bromoalkoxide was recently reported by Holm.[19]

The appearance of significant amounts of ketone in many of the alkoxide reversals was initially puzzling[1] (Tables III and IV). When the ketone was nonenolizable the amount formed was minimal. When enolizable, the amounts were again negligible when reversal of the alkoxide proceeded quickly at relatively low temperatures. At least two pathways for ketone formation appear possible.

It will be noted from both eq 1 and 3 that when alkoxides undergo reversal to their more stable form, the intermediate ketone produced is in the presence of at least two bases, namely, the crotyl organometallic and the alkoxide itself. In theory the enolate of the ketone (Figure 1) could be formed by a reaction with either of these bases. Since enolization of carbonyl substrates by allylic organometallics has never been observed,[20] we are inclined to believe that it is effected by the alkoxides present. The latter would thereby be converted to carbinols which would protonate the organometallic generating an olefin and regenerating alkoxide. Regardless of which pathway is followed, the net result would be the same: organometallic would be consumed and enolate produced. The latter would ultimately be converted to ketone by aqueous workup. That enolate was present *before* hydrolysis was established by trapping it as a trimethylsilyl enol ether (eq 7). See example



(7)

11, Table IV. The isolation and identification of this compound established unequivocally that the ketones were arising from hydrolysis of their corresponding enolates. Obviously, when there are no enolizable hydrogens on the ketones, this reaction cannot occur and hence no ketones are found in the final product. See example 3, Table III. Likewise when rearrangement to the more thermodynamic product is rapid, enolization is suppressed. See example 4, Table IV.

Though no formal mechanistic work on the reversibility of the alkoxides was attempted, one such reversible reaction was

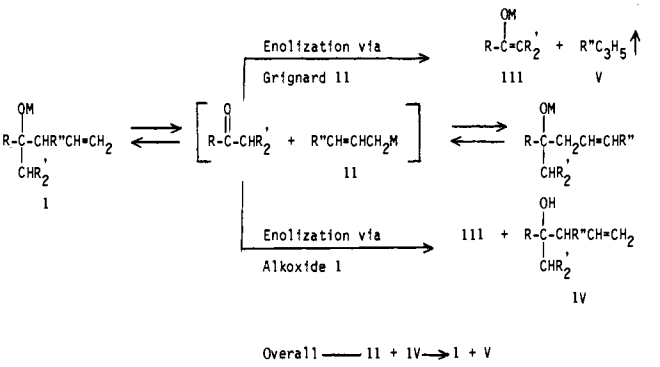
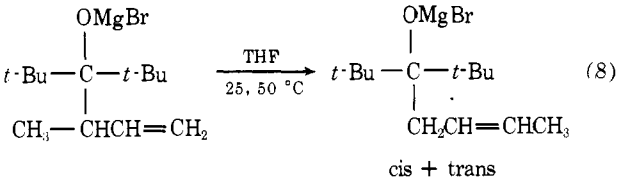


Figure 1. Mode of ketone enolate formation.



(8)

carried out in an ESR spectrometer as shown in eq 8. Although the solution developed a yellow color,[21] no signal was observed at either 25 or 50 °C, indicating that a radical mechanism for reversal was unlikely in this case at least.

Experimental Section

General Comments. Reagent grade tetrahydrofuran (THF), monoglyme, and diglyme (Ansul Chemical Co.) were distilled from lithium aluminum hydride prior to use. The magnesium used to prepare all Grignard reagents was standard Dow magnesium turnings. Methyl bromide (Matheson) was used as received. All allylic halides were distilled prior to use. Diethyl ketone (Mallinckrodt) and diisopropyl ketone (Aldrich) were used as received. *n*-Butyllithium in hexane (Alfa), *sec*-butyllithium in cyclohexane (Alfa), and *tert*-butyllithium in pentane (Aldrich) were used as received. The concentration of the lithium reagents was determined by the method of Watson and Eastham.[22] Infrared (IR) spectra were obtained on a Perkin-Elmer Model 127 Infracord spectrophotometer. Nuclear magnetic resonance (NMR) spectra was obtained on a Varian A-60 NMR spectrometer. Samples used to obtain IR and NMR spectra, refractive indexes, and elemental analyses were purified either by column chromatography on neutral alumina (Fisher Scientific) or collected on an F and M Model 500 gas chromatograph using ¼ or ⅜ in. stainless steel or aluminum tubing. The packing was either 10% QF-1 on Chromosorb W or 10% FFAP on Firebrick. The ratio of ketone to isomeric carbinols was determined by triangulation on the above instrument. Isomer distributions were also obtained by triangulation on a Perkin-Elmer Model 226 capillary gas chromatograph using 0.01-in. diameter tubing (polyphenyl ether or Carbowax 1540 as stationary phase). It was assumed that the response factors would be one within experimental error for isomers of this type (see ref 17b). Assignment of carbinol isomers was obtained by coinjection of pure material (α-methallyl) and using the previously discovered order of elution, i.e., trans precedes cis.[15,17] All allylic magnesium halides were prepared by a standard procedure.[23]

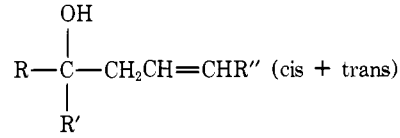
Preparation of Ketones. *tert*-Butyl phenyl ketone, bp 88–89 °C (2.5 mm), n^{20}_D 1.5093, was prepared[24] from benzonitrile (1.94 mol) and *tert*-butylmagnesium chloride in 48% yield.

Isopropyl phenyl ketone, bp 80–82 °C (5 mm), n^{20}_D 1.5174, was prepared[25] in 85% yield from isobutyronitrile (1 mol) and excess phenylmagnesium bromide.

Using a modification of the method of Cook and Percival,[26] the following ketones were prepared: di-*tert*-butyl ketone,[26] bp 150–155 °C (62%); *tert*-butyl isopropyl ketone,[27] bp 133–136 °C (63%); *tert*-butyl cyclohexyl ketone,[28] mp 23–24 °C, bp 100–101 °C (20 mm) (82%); isopropyl cyclohexyl ketone,[28] bp 81–84 °C (10 mm) (76%); dicyclohexyl ketone,[29] bp 120–121 °C (3 mm) (84%).

Using the procedure of Brown and Garg,[30] *tert*-butyl-α-methallylcarbinol[31] was oxidized to *tert*-butyl α-methallyl ketone:[15] bp 60–62

Table V. Data for Mixtures of New Cis and Trans Crotylcarbinols



R	R′	R″	IR (neat), μ	NMR (CCl_4), δ
(1) C_2H_5	C_2H_5	CH_3[a]	3.01 (OH) 6.09 (C=C)	0.84 (t, 6 H), 1.49 (m, 8 H), 2.13 (d, 2 H), 5.48 (m, 2 H)
(2) C_6H_5	C_6H_5	CH_3[b]	2.88 (OH) 6.13 (C=C) 6.36 (C=C arom)	1.50 (d, 3 H), 2.49 (s, 1 H), 2.90 (t, 2 H), 5.38 (m, 2 H), 7.23 (m, 10 H)
(3) *i*-C_3H_7	C_6H_5	CH_3[c]	2.83 (OH) 6.05 (C=C) 6.25 (C=C arom)	0.88 (d of d, 6 H), 1.54 (m, 3 H), 1.70-2.38 (m, 1 H), 1.89 (s, 1 H, OH), 2.38-3.00 (m, 2 H), 5.30 (m, 2 H), 7.25 (m, 5 H)
(4) *t*-C_4H_9	C_6H_5	CH_3[d]	2.83 (OH) 6.05 (C=C) 6.25 (C=C arom)	0.92 (s, 9 H), 1.60 (d, 3 H), 1.80 (s, 1 H), 2.67 (d, 2 H), 4.70-6.00 (m, 2 H), 7.31 (m, 5 H)
(5) *i*-C_3H_7	*i*-C_3H_7	CH_3[e]	2.87 (OH) 6.07 (C=C)	0.96 (d of d, 12 H), 1.23 (s, 1 H), 1.55-2.35 (m, 7 H), 5.48 (m, 2 H)
(6) *i*-C_3H_7	c-C_6H_{11}	CH_3[f]	2.84 (OH) 6.06 (C=C)	0.83 -2.10 (m, 16 H), 0.90 (superimposed d, 6 H), 2.19 (m, 2 H), 5.41 (m, 2 H)
(7) *t*-C_4H_9	c-C_6H_{11}	CH_3[g]	2.87 (OH) 6.10 (C=C)	0.80-2.10 (m, 15 H), 0.97 (superimposed s, 9 H), 2.30 (d, 2 H), 5.52 (m, 2 H)
(8) C_2H_5	C_2H_5	*i*-C_3H_7[h]	2.04 (OH)	0.88 (m, 12 H), 1.16-2.83 (m, 8 H), 5.44 (m, 2 H)
(9) *i*-C_3H_7	*i*-C_3H_7	*i*-C_3H_7[i]	2.91 (OH) 6.08 (C=C)	0.95 (m, 18 H), 1.08 (s, 1 H), 1.45-2.80 (m, 5 H), 5.35 (m, 2 H)

[a]Anal. Calcd for $C_9H_{18}O$: C, 76.00; H, 12.75. Found: C, 75.77; H, 12.90. [b]Anal. Calcd for $C_{17}H_{18}O$: C, 85.66; H, 7.63. Found: C, 85.61; H, 7.59. [c]Anal. Calcd for $C_{14}H_{20}O$: C, 82.30; H, 9.87. Found: C, 82.57; H, 9.77. [d]Anal. Calcd for $C_{15}H_{22}O$: C, 82.51; H, 10.16. Found: C, 82.68; H, 10.22 [e]Anal. Calcd for $C_{11}H_{22}O$: C, 77.58; H, 13.02. Found: C, 77.76; H, 13.25. [f]Anal. Calcd for $C_{14}H_{26}O$: C, 79.91; H, 12.48. Found: C, 79.71; H, 12.66. [g]Anal. Calcd for $C_{15}H_{28}O$: C, 80.29; H, 12.58. Found: C, 80.54; H, 12.50. [h]Anal. Calcd for $C_{11}H_{22}O$: C, 77.58; H, 13.02. Found: C, 77.39; H, 13.26. [i]Anal. Calcd for $C_{13}H_{26}O$: C, 78.72; H, 13.21. Found: C, 78.72; H, 13.28.

°C (28 mm); $n^{20}D$ 1.4252 (70%); IR (neat) 5.85 (C=O), 6.10 μ (C=C); NMR (CCl_4) δ 1.10 (d, 3 H), 1.11 (s, 9 H), 3.67 (m, 1 H), 5.00 (m, 2 H), 5.80 (m, 1 H). Anal. Calcd for $C_9H_{16}O$: C, 77.09; H, 11.50. Found: C, 77.37; H, 11.35.

Preparation of α-Methallylcarbinols. Di-*tert*-butyl-α-methallylcarbinol was prepared by the addition of 7.0 g (50 mmol) of *tert*-butyl α-methallyl ketone in 10 mL of ether over a 15-min period to 30 mL of 1.85 M (55 mmol) *tert*-butyllithium in pentane at −78 °C. After stirring for 1.5 h, the reaction mixture was hydrolyzed with saturated NH_4Cl solution and dried ($MgSO_4$). After removal of the solvents with a rotary evaporator, distillation through an 18-cm Vigreux column afforded 6.33 g (64%) of product: bp 58-60 °C (0.3 mm); $n^{20}D$ 1.4768; IR (neat) 2.86 (OH) and 6.12 μ (C=C); NMR (CCl_4) δ 1.13 (s, 18 H), 1.33 (d, 3 H), 1.48 (s, 1 H, OH), 2.96 (m, 1 H), 5.02 (m, 2 H), 6.13 (m, 1 H). Anal. Calcd for $C_{13}H_{26}O$: C, 78.72; H, 13.21. Found: C, 78.96; H, 13.21.

Other isomerically pure (crotyl isomer-free) α-methallylcarbinols (see Table I) were virtually all prepared by the same general procedure illustrated below for the preparation of *tert*-butylcyclohexyl-α-methallylcarbinol. Physical constants, analyses, reaction times, etc., can be found in Tables I and II.

***tert*-Butylcyclohexyl-α-methallylcarbinol.** Into a 250-mL flask equipped with a magnetic stirrer and addition funnel and under a positive nitrogen pressure was placed 100 mL of 0.56 M (56 mmol) crotylmagnesium chloride in THF. The flask was chilled to −78 °C and 8.4 g (50 mmol) of *tert*-butyl cyclohexyl ketone dissolved in 10 mL of THF was added over a 40-min period. The mixture was stirred at −78 °C for 4 h and then hydrolyzed at that temperature with saturated ammonium chloride solution. The liquid was decanted and combined with the pentane which had been used to wash the residue. These combined liquids were dried over magnesium sulfate. After solvent removal by a rotary evaporator, the remaining residue was distilled through an 18-cm Vigreux column, giving 8.3 g of isomerically pure product, bp 89-92 °C (0.35 mm), $n^{20}D$ 1.4922. A GC analysis (150 ft polyphenyl ether capillary column, block 180 °C, column 160 °C) showed the material to be 98% pure (74% yield). See Table II for pertinent physical data.

α-Isopropylallylcarbinols. Diisopropyl-α-isopropylallylcarbinol along with diisopropyl-γ-isopropylallylcarbinol (ratio 66:34) was prepared by the reaction of γ-isopropylallylmagnesium chloride[9] with diisopropyl ketone at 25 °C in 86% yield, bp 66-71 °C (0.6 mm). The isomers were not readily separable and hence were analyzed as a mixture. IR (neat) 2.80 (OH) and 6.09 μ (C=C). Anal. Calcd for $C_{13}H_{26}O$: C, 78.72; H, 13.21. Found: C, 79.00; H, 13.39.

Isomerically pure diethyl-α-isopropylallylcarbinol was likewise prepared in 62% yield; bp 64-67 °C (2.9 mm); $n^{20}D$ 1.4556; IR (neat) 2.91 (OH) and 6.16 μ (C=C); NMR (CCl_4) δ 0.84 (m, 12 H), 1.84 (m, 7 H), 5.07 (m, 2 H), 5.83 (m, 1 H). Anal. Calcd for $C_{11}H_{22}O$: C, 77.58; H, 13.02. Found: C, 77.73; H, 13.31.

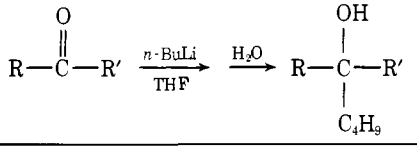
Preparation of α-Phenylallylcarbinols.[33] From 7.26 g (0.300 mol) of magnesium, 22.2 g (0.150 mol) of cinnamyl chloride in THF, and 17.1 g (0.150 mol) of diisopropyl ketone was isolated 28.7 g of at least 95% pure (NMR) diisopropyl-α-phenylallylcarbinol, bp 100-118 °C (0.28 mm), 83% yield. The material was purified by column chromatography with neutral alumina, using a pentane wash followed by elution with 1:1 pentane-ether. Isomeric purity was not less than 98% by NMR. IR (neat) 2.76 (OH), 6.10 (C=C), 6.23 μ (C=C aromatic). NMR (CCl_4) δ 0.94 (m, 12 H), 1.30 (s, 1 H, OH), 1.95 (m, 2 H), 3.70 (d, 1 H), 4.98 (m, 2 H), 6.37 (m, 1 H), 7.22 (m, 5 H). Anal. Calcd for $C_{16}H_{24}O$: C, 82.76; H, 10.34. Found: C, 82.65; H, 10.12.

Using the same procedure, diethyl-α-phenylallylcarbinol[5] was prepared in 82% yield, bp 86-88 °C (0.25 mm), $n^{20}D$ 1.5243.

Preparation of *cis*- and *trans*-Di-*tert*-butyl-α,γ-dimethylallylcarbinols.[33] From 12.5 g (0.500 mol) of magnesium, 26.1 g (0.25 mol) of 2-chloro-3-pentene in THF, and 25.9 g (0.18 mol) of di-*tert*-butyl ketone was obtained after distillation 34.5 g of *cis*- and *trans*- (46:54) di-*tert*-butyl-α,γ-dimethylallylcarbinol[17] (89% yield), bp 72-73 °C (0.18 mm). IR (neat) 2.82 (OH) and 6.13 μ (C=C). NMR (CCl_4) δ 0.90-1.19 (m, 18 H), 1.30 (d of d, 3 H), 1.58-1.82 (m, 4 H), 3.04 (m, 1 H), 5.56 (m, 2 H). Anal. Calcd for $C_{14}H_{28}O$: C, 79.18; H, 13.29. Found: C, 79.05; H, 13.43.

Reversal of Magnesium Bromoalkoxides (Table III). The magnesium bromoalkoxides were generated in a concentration of 0.5-1.0 M in THF by reaction of 1 equiv of the indicated carbinol with 1 equiv of methylmagnesium bromide at 0 °C. The mixture was stirred for the indicated time at 25 °C, then hydrolyzed (NH_4Cl) and dried ($MgSO_4$). After solvent removal with a rotary evaporator, the crude products were purified by column chromatography on alumina, using a pentane wash followed by elution with 1:1 pentane-ether, which afforded both reversal carbinols and ketone, if any. This material was

Table VI. Preparation of *n*-Butylcarbinols



R	R′	Yield, %	Bp, °C (mmHg)	n^{20}_D	Ref
i-C_3H_7	C_6H_5	53	93-96 (0.5)	1.5075	37
t-C_4H_9	C_6H_5[a]	92	106-111 (0.7)	1.5073	
i-C_3H_7	*i*-C_3H_7	68	72-74 (3.5)	1.4481	38
i-C_3H_7	c-C_6H_{11}[b]	63	76-81 (0.1)	1.4762	
t-C_4H_9	c-C_6H_{11}[c]	81	100-104 (0.5)	1.4769	

[a]Anal. Calcd for $C_{15}H_{24}O$: C, 81.76; H, 10.98. Found: C, 81.71; H, 11.11. IR (neat) 2.75-2.81 (OH), 6.29 μ (C=C arom). [b]Anal. Calcd for $C_{14}H_{28}O$: C, 79.21; H, 13.29. Found: C, 79.10; H, 13.54. IR (neat) 2.89 μ (OH). [c]Anal. Calcd for $C_{15}H_{30}O$: C, 79.58; H, 13.16. Found: C, 79.76; H, 13.41. IR (neat) 2.79-2.86 μ (OH).

examined by GC. See Table III.

Reversal of Lithium Alkoxides (Table IV). The lithium alkoxides were generated in a concentration of 0.6-0.8 M in the indicated solvent by reaction of 1 equiv of carbinol with 1 equiv of *n*-butyllithium in hexane at 0 °C. When the solvent was diglyme or monoglyme, the hexane was distilled off. The reaction mixture was stirred for the indicated time and temperature, then hydrolyzed (NH_4Cl) and dried ($MgSO_4$) when the solvent was THF or monoglyme. When diglyme was the solvent, following hydrolysis the material was shaken with water to remove the diglyme. Pentane was then added to facilitate handling, and the material was dried. The solvents were removed with a rotary evaporator and the crude product was distilled through a short-path still at reduced pressure. The distillate was examined for product and isomer distributions by GC, Tables IV and V. Any ketone produced was isolated and its IR spectrum was matched to that of an authentic sample. The reversal alcohols were isolated and characterized, then hydrogenated to their saturated analogues using a Parr hydrogenator and Pt as the catalyst. The IR spectra of the hydrogenated samples were matched to those of authentic samples or compounds in the literature.[35]

Preparation of Authentic Samples. Some compounds of the type RR′C(OH)-*n*-C_4H_9 were prepared by the addition of *n*-butyllithium to the appropriate ketone in THF; these are given in Table VI. Diphenyl-*n*-butylcarbinol,[14] bp 170-174 °C (9 mm), n^{20}_D 1.5632, was prepared from phenylmagnesium bromide and methyl valerate.

3-Isopropyl-2-methyl-6-phenyl-3-hexanol was prepared in 62% yield by the reaction of 3-phenyl-1-propylmagnesium bromide with diisopropyl ketone: bp 112-122 °C (0.2 mm); n^{20}_D 1.5074; IR (neat) 2.90 (OH) and 6.29 μ (C=C aromatic); NMR (CCl_4) δ 0.85 (d of d, 12 H), 0.99 (s, 1 H, OH), 1.29-2.20 (m, 6 H), 2.55 (m, 2 H), 7.16 (s, 5 H). Anal. Calcd for $C_{16}H_{26}O$: C, 81.99; H, 11.18. Found: C, 81.70; H, 11.19. In a similar fashion, 3-ethyl-6-phenyl-3-hexanol[34] was prepared in 66% yield, bp 91-100 °C (0.1 mm), n^{20}_D 1.5077.

2,7-Dimethyl-3-isopropyl-3-octanol[17] was prepared in 31% yield by the reaction of 4-methyl-1-pentylmagnesium bromide with diisopropyl ketone: bp 68-69 °C (0.2 mm): n^{20}_D 1.4486; IR (neat) 2.85 μ (OH); NMR (CCl_4) δ 0.90 (d of d, 18 H), 0.90-2.20 (m, 10 H). Anal. Calcd for $C_{13}H_{28}O$: C, 77.93; H, 14.09. Found: C, 77.86; H, 14.31. In a similar fashion, 3-ethyl-7-methyl-3-octanol was prepared in 50% yield: bp 79-81 °C (3.4 mm); n^{20}_D 1.4408; IR (neat) 2.86 μ (OH); NMR (CCl_4) δ 0.85 (m, 12 H), 1.08-1.78 (m, 11 H), 1.80-2.40 (broad, 1 H, OH). Anal. Calcd for $C_{11}H_{24}O$: C, 76.67; H, 14.04. Found: C, 76.71; H, 14.04.

Enolate Trapping Experiment. A solution of 2.50 g (10.0 mmol) of dicyclohexyl-α-methallylcarbinol in 20 mL of monoglyme was treated with 5.0 mL of 2 M (10 mmol) *n*-butyllithium in hexane. After refluxing for 72 h to effect reversal, the solution was cooled to 0 °C and quenched with 10 mL of chlorotrimethylsilane solution, prepared by the method of House et al.[36] The reaction mixture was stirred at room temperature for 15 min, then partitioned between pentane and 5% aqueous $NaHCO_3$ and dried ($MgSO_4$). The solvents were removed by rotary evaporator, affording 2.57 g of crude material which contained 67% (GC) of the trimethylsilyl enol ether of dicyclohexanone (65% yield), and small amounts of dicyclohexyl ketone and *cis*- and *trans*-crotyldicyclohexylcarbinols.

An authentic sample of the trimethylsilyl enol ether of dicyclohexyl ketone was prepared in 77% yield using the procedure of House et al.[36] bp 91-92 °C (0.2 mm); n^{20}_D 1.4884; IR (neat) 6.01 μ (C=C); NMR (CCl_4, $CHCl_3$ reference) δ 0.28 (s, 9 H), 0.9-2.7 (m, 21 H). Anal. Calcd for $C_{16}H_{30}OSi$: C, 72.09; H, 11.37; Si, 10.54. Found: C, 72.13; H, 11.39; Si, 10.51.

The authentic sample of the trimethylsilyl enol ether of dicyclohexyl ketone was identical in all respects (retention time and IR) with that isolated by GC from the trapping experiment.

Reversibility in an ESP Spectrometer. A solution containing 2.46 mmol of methylmagnesium bromide in 2.2 mL of dry THF was added to 0.495 g (2.5 mmol) of di-*tert*-butyl-α-methallylcarbinol (neat). A small sample of this mixture was added to a nitrogen-flushed ESR tube and was examined in a Varian E 109 X-band instrument at 25 °C. No resonance was observed. The temperature of the sample was raised to 50 °C and still no resonance was observed. This would indicate that probably no radicals were present at either temperature. After 6 and 12 h an aliquot of the remainder of the solution was hydrolyzed and examined by capillary GC. At the end of 6 h, only a trace of the starting material remained (~0.1%), indicating that the reaction was essentially complete by this time.

References and Notes

(1) R. A. Benkeser and W. E. Broxterman, *J. Am. Chem. Soc.*, **91**, 5162 (1969).
(2) R. A. Benkeser and M. P. Siklosi, *J. Org. Chem.*, **41**, 3212 (1976).
(3) P. Miginiac, *Bull. Soc. Chim. Fr.*, 1077 (1970).
(4) F. Gerard and P. Miginiac, *Bull. Soc. Chim. Fr.*, 1924 (1974).
(5) F. Gerard and P. Miginiac, *Bull. Soc. Chim. Fr.*, 2527 (1974).
(6) J. E. Nordlander, W. G. Young, and J. D. Roberts, *J. Am. Chem. Soc.*, **83**, 494 (1961).
(7) G. M. Whitesides, J. E. Nordlander, and J. D. Roberts, *Discuss. Faraday Soc.*, **No. 34**, 185 (1962).
(8) G. M. Whitesides, J. E. Nordlander, and J. D. Roberts, *J. Am. Chem. Soc.*, **84**, 2010 (1962).
(9) D. A. Hutchison, K. R. Beck, R. A. Benkeser, and J. B. Grutzner, *J. Am. Chem. Soc.*, **95**, 7075 (1973).
(10) J. D. Roberts and W. G. Young, *J. Am. Chem. Soc.*, **67**, 148 (1945).
(11) W. G. Young and J. D. Roberts, *J. Am. Chem. Soc.*, **67**, 319 (1945).
(12) J. F. Lane, J. D. Roberts, and W. G. Young, *J. Am. Chem. Soc.*, **66**, 543 (1944).
(13) R. A. Benkeser, W. G. Young, W. E. Broxterman, D. A. Jones, Jr., and S. J. Plaseczynski, *J. Am. Chem. Soc.*, **91**, 132 (1969).
(14) K. W. Wilson, J. D. Roberts, and W. G. Young, *J. Am. Chem. Soc.*, **72**, 218 (1950).
(15) W. E. Broxterman, Ph.D. Thesis, Purdue University, West Lafayette, Ind., 1969.
(16) R. T. Roche, Ph.D. Thesis, Purdue University, West Lafayette, Ind., 1974.
(17) D. A. Jones, Jr., Ph.D. Thesis, Purdue University, West Lafayette, Ind., 1968; R. A. Benkeser and D. A. Jones, Jr., *J. Org. Chem.*, **32**, 1625 (1967).
(18) F. Gerard and P. Miginiac, *C. R. Hebd. Seances Acad. Sci.*, **273**, 674 (1971). See also ref 20, pp 21-22.
(19) T. Holm, *Acta Chem. Scand., Ser. B*, **30**, 985 (1976).
(20) G. Courtois and L. Miginiac, *J. Organomet. Chem.*, **69**, 1 (1974).
(21) The presence of a yellow color in another reversible system has been cited by Holm[19] as an indication that perhaps a radical pathway is involved in these reversible reactions.
(22) S. C. Watson and J. F. Eastham, *J. Organomet. Chem.*, **9**, 165 (1967).
(23) "Organic Syntheses", Collect. Vol. IV, Wiley, New York, N.Y., 1963, p 749.
(24) A. Willemart, *Bull. Soc. Chim. Fr.*, **2**, 867 (1935).
(25) C. R. Hauser, W. J. Humphlett, and M. J. Weiss, *J. Am. Chem. Soc.*, **70**, 426 (1948).
(26) N. C. Cook and W. C. Percival, *J. Am. Chem. Soc.*, **71**, 4141 (1949).
(27) M. F. Ansell, M. A. Davies, J. W. Hancock, W. J. Hickenbottom, P. G. Holton, and A. A. Hyatt, *J. Chem. Soc.*, 2705 (1955).
(28) E. P. Burrows, F. J. Welch, and H. S. Mosher, *J. Am. Chem. Soc.*, **82**, 880 (1960).
(29) P. Sabatier and A. Maihle, *Bull. Soc. Chim. Fr.*, **33**, 74 (1905).
(30) H. C. Brown and C. P. Garg, *J. Am. Chem. Soc.*, **83**, 2952 (1961).
(31) D. Abenhaim, E. Henry-Basch, and P. Freon, *Bull. Soc. Chim. Fr.*, 4038, 4043 (1969).
(32) (a) The reaction affords a 40/60 α-methallyl-/crotylcarbinol ratio when carried out at 25 °C in diethyl ether. (b) The reaction affords a 66/34 α-methallyl/crotylcarbinol ratio when carried out at 25 °C in diethyl ether.
(33) The Barbier-Grignard technique was employed here. See M. P. Dreyfuss, *J. Org. Chem.*, **28**, 3269 (1963).
(34) R. T. Arnold and G. Smolinsky, *J. Am. Chem. Soc.*, **81**, 6443 (1959).
(35) The IR spectrum of 3-ethyl-3-heptanol was found to match Sadtler IR no. 32006, "Sadtler Standard Spectra", Sadtler Research Laboratories, Philadelphia, Pa. The IR spectrum of di-*tert*-butyl-*n*-butylcarbinol matched that of Jones.[13,17]
(36) H. O. House, L. J. Czuba, M. Gall, and H. D. Olmstead, *J. Org. Chem.*, **34**, 2324 (1969).
(37) I. N. Nazarov and I. L. Kotlyarevsky, *Zh. Obshch. Khim.*, **20**, 1501 (1950).
(38) I. N. Nazarov and L. N. Pinka, *Zh. Obshch. Khim.*, **19**, a-331 (1949).