

Transition Metal Catalysis in Allene Formation from Grignard Reagents and Propargyl Chlorides¹

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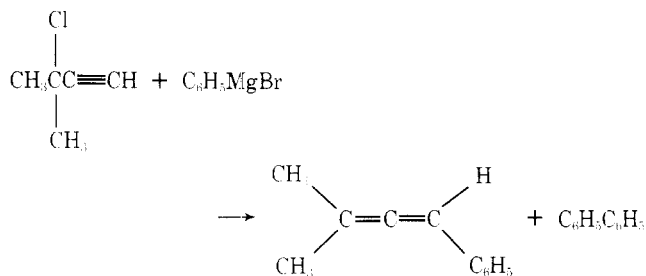
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In the presence of catalytic quantities of iron, cobalt, nickel, and copper salts Grignard reagents react with propargyl chlorides to produce allenes. Alkynes are generally not formed. Chromium, manganese, rhodium, and silver salts do not catalyze the reaction. A mechanism for allene formation is proposed involving initial formation of a low valence state metal species from reaction of the Grignard reagent with the metal salt, which undergoes oxidative insertion into the carbon-chlorine bond of the propargyl chloride. Displacement of halogen by alkyl from the Grignard reagent forms a bisorganometal species which is proposed to decompose to allene. Evidence in support of this mechanism is discussed.

Introduction

In the preceding article,² a brief review was given of the diverse results reported on the reactions of propargylic halides with Grignard reagents, and the results of studies in our laboratories on the reactions of terminal, tertiary propargylic halides with Grignard reagents were presented and discussed. In that study it was shown that the terminal propargylic halides react slowly with Grignard reagents to form a zwitterion-allene carbene intermediate which undergoes nucleophilic attack by a second molecule of the Grignard reagent at either the propargylic or allenyl carbon atoms to produce new organomagnesium species. The newly formed Grignard species either abstract a proton from the propargylic halide or under hydrolysis to produce mixtures of two isomeric alkynes and allene.

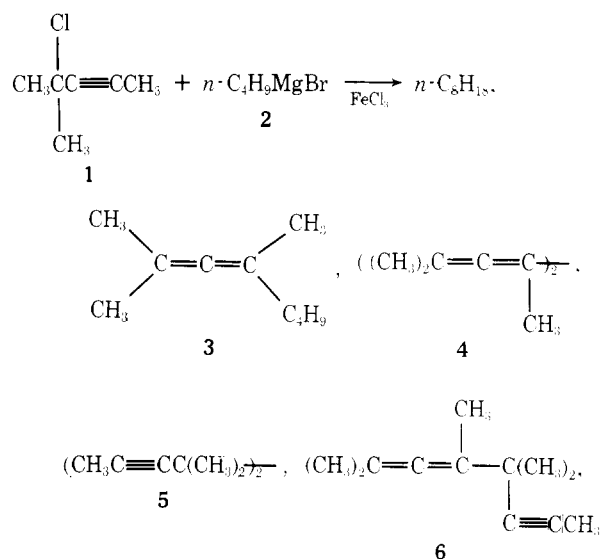
During our initial studies it was observed that 3-chloro-3-methyl-1-butene reacted with phenylmagnesium bromide to form 1,1-dimethyl-3-phenylallene and biphenyl in excellent yield. The formation of the biphenyl initially suggested that



a single electron transfer (SET), free-radical process was occurring. Utilizing the observation of Ashby and co-workers that ferric ion catalyzes SET reactions between Grignard reagents and benzophenones,³ ferric chloride was added to the reactions of propargylic halides with alkyl Grignard reagents in an attempt to catalyze the supposed electron transfer, free-radical process in those cases. The rates of the reactions in the presence of ferric chloride were tremendously accelerated, and excellent yields of allenes uncontaminated by alkynes were obtained.⁴ Although it was initially thought that these reactions were SET, free-radical processes, further considerations (vide infra) militated against this, and an organometallic intermediate, catalytic cycle mechanism evolved. Our initial studies with ferric chloride catalysis have been extended to include other transition metal salts, the results of which are reported herein along with a discussion of the catalysis mechanism. With the discovery of the transition metal catalysis the seemingly contradictory results previously reported for the reactions of propargylic halides with Grignard reagents are readily understood.

Results

Initial studies were carried out on the reaction of 4-chloro-4-methyl-2-pentyne (1) with *n*-butylmagnesium bromide in ether solution at 0 °C to determine optimum conditions for formation of allene. Addition of 0.07 mol of 1 to 0.085 mol of Grignard reagent containing as little as 2.5×10^{-6} mol of ferric chloride or ferric acetylacetonate [Fe(Acac)₃] resulted in a nearly instantaneous reaction. Immediate analysis by GLPC after completion of the addition of 1 showed the reaction to be complete. GLPC analysis of the product showed the presence of octane (up to 5%), allene 3, and four C₁₂ dimers



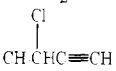
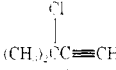
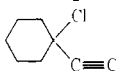
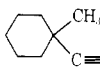

and rearranged dimer

of 1 (up to 5% total yield). Three of the dimers are assigned structures 4–6 on the basis of their NMR spectra. The fourth dimer is believed to be an allene rearrangement product of either 4 or 6. GLPC analysis of a hydrolyzed aliquot of the Grignard solution before addition of 1 showed the presence of only trace amounts of *n*-butyl bromide or octane. Inverse addition of 2 to 1 yielded the same results.

In addition to the facile iron(III) catalyzed reactions of 1 with primary alkylmagnesium halides, secondary alkyl Grignard reagents also react in a similar, but slower manner. Higher yields of the propargyl dimers 4–6 are formed during the reactions with the secondary alkyl Grignard reagents. Alkylation with *tert*-butylmagnesium bromide could not be affected.

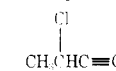
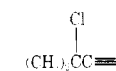
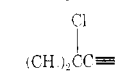
All structural variations of propargyl chlorides have been studied. Terminal primary, secondary, and tertiary propar-

Table I. Reactions of Propargylic Chlorides with Grignard Reagents in the Presence of Fe(III)^a

Entry	Propargyl chloride	Registry no.	Grignard reagent	Catalyst	Addition time, min	Product	Yield, %
1	ClCH ₂ C≡CH	624-65-7	<i>n</i> -C ₄ H ₉ MgBr	FeCl ₃	10	H ₂ C=C=CH(<i>n</i> -C ₄ H ₉)	85
2	ClCH ₂ C≡CH		<i>sec</i> -C ₄ H ₉ MgBr	FeCl ₃	60	H ₂ C=C=CH(<i>sec</i> -C ₄ H ₉)	70
3		21020-24-6	<i>n</i> -C ₄ H ₉ MgBr	FeCl ₃	10	CH ₃ CH=C=CH(<i>n</i> -C ₄ H ₉)	80
4		1111-97-3	C ₂ H ₅ MgI	FeCl ₃	10	(CH ₃) ₂ C=C=CHC ₂ H ₅	80
5	7		<i>n</i> -C ₄ H ₉ MgBr	FeCl ₃	10	3	80-90
6	7		<i>n</i> -C ₄ H ₉ MgBr	Fe(Acac) ₃	30	3	60
7	7		<i>sec</i> -C ₄ H ₉ MgBr	FeCl ₃	60	(CH ₃) ₂ C=C=CH(<i>sec</i> -C ₄ H ₉)	75
8	1	999-79-1	CH ₃ MgI	FeCl ₃	10	(CH ₃) ₃ CC≡CCH ₃ , (CH ₃) ₂ C=C=C(CH ₃) ₂	90 ^b
9	1		<i>n</i> -C ₄ H ₉ MgBr	FeCl ₃	20	(CH ₃) ₂ C=C=C(CH ₃)(<i>n</i> -C ₄ H ₉)	87
10	1		<i>i</i> -C ₃ H ₇ MgBr	FeCl ₃	60	(CH ₃) ₂ C=C=C(CH ₃)(<i>i</i> -C ₃ H ₇)	88
11	1		<i>t</i> -C ₄ H ₉ MgBr	FeCl ₃	240 ^c
12		60820-36-2	CH ₃ MgI	FeCl ₃	10	 	90 ^b

^a Reaction temperature 25 °C. Catalyst added as THF solution. ^b Alkyne and allene formed in a 1:1 ratio. ^c No reaction after the indicated time.

Table II. Relative Reactivities of Propargyl Chlorides with *n*-Butylmagnesium Bromide in the Presence of Fe(III)

Propargyl chloride	Relative reactivity
ClCH ₂ C≡CH	30
	19.7
	8
	1

gylid chlorides react with methyl, primary, and secondary alkyl Grignard reagents in the presence of iron(III) to produce good to excellent yields of allene. Nonterminal tertiary propargylic halides react with methylmagnesium iodide in the presence of iron(III) to produce 1:1 mixtures of alkyne and allene (entries 8 and 12 in Table I). In contrast, these same chlorides react with *n*-butyl, isopropyl, or *sec*-butyl Grignard reagents in the presence of iron(III) to produce only allene.

Relative reactivities of variously substituted propargyl chlorides with *n*-butylmagnesium bromide in the presence of iron(III) have been determined using competitive reaction techniques under identical reaction conditions and extrapolated to zero reaction time. The results are given in Table II.

A number of other transition metal halides and acetylacetonates have been tested for catalytic activity in the reaction of **1** and **7**, the results of which are given in Table III. It is particularly interesting to note that both Fe(III) and Fe(II), and Cu(II) and Cu(I), salts catalyze the reaction, in each case with the same apparent degree of efficiency. Of the transition metals which did catalyze the reaction, the catalytic efficiency decreases markedly in the sequence Fe > Co > Ni > Cu. In the reactions catalyzed by iron, the reaction proceeded very rapidly, regardless of whether the Grignard reagent was added to the chloride or vice versa. With cobalt, the reaction proceeded less rapidly, but still proceeded in the presence of excess Grignard reagent. In the case of nickel and

Table III. Reactivity of Transition Metal Catalysts on the Reaction of **1 and **7** with **2****

Catalyst	Propargyl chloride	Addition time, min	Allene yield, %	Dimer yield, %
FeBr ₂	1	20	80	8
CoBr ₂	1	60	55	... ^a
Co(Acac) ₂	7	60	30-40	... ^a
NiBr ₂	7	60	90	... ^a
Ni(Acac) ₂	7	60	95	<2
CuCl	7	30	55	... ^a
CuCl	1	30	50	30
CuBr ₂	7	30	90	... ^a
CuBr ₂	1	30	50	23
MnCl ₂	7		... ^b	
CrCl ₃	7		... ^b	
RhCl ₂	7		... ^b	
Rh[P(C ₆ H ₅) ₃]Cl	7		... ^b	
AgO ₂ CCH ₃	7		... ^b	

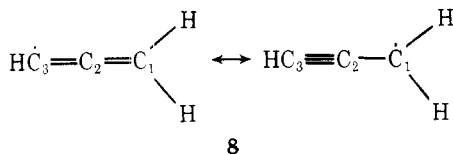
^a Not measured. ^b No observed catalytic reaction.

copper, catalytic activity is maintained *only* when the Grignard reagent is added very slowly to the chloride-catalyst solution in order to avoid the presence of an excess of the Grignard reagent. When the Grignard reagent is added too rapidly, catalytic activity is lost. Addition of more catalyst at this point fails to generate catalytic activity. Addition of nickel and copper catalysts to a premixed solution of chloride and Grignard reagent is ineffective.

Attempts were made to detect catalytic coupling of *n*-butylmagnesium bromide (**2**) with halides. None was observed. The direct reaction of **2** with allyl bromide is sufficiently rapid that possible Fe(III) catalysis could not be observed. No catalysis was evident in the reaction of **2** with benzyl bromide.

Discussion

Although it was first thought that allene formation was occurring via a SET, radical intermediate process, the properties of the intermediate propargyl-allenyl radical (**8**) were not consistent with the formation of only allene in a radical abstraction or combination process. Ab initio calculations on



8 indicate slightly greater spin density exists on C₁.⁵ INDO calculations carried out in our laboratories on 8 and 1,1-dimethyl radical indicate that ~61% and ~56% of the spin density resides on C₁, respectively. ESR data are consistent with a delocalized species with considerable spin density at C₁ and C₃.⁶ Experimentally, it is observed that alkynes are formed as the major product in reactions of the propargyl-allenyl-type free radicals. Free-radical chlorination of propyne⁷ or allene,⁷ and 2-butyne,⁸ produces only the propargyl chloride; tri-*n*-butyltin hydride reacts with propargyl chlorides to produce mixtures of alkyne and allene in which the former is always dominant;⁹ in gas-phase radical combination reactions methyl radical reacts with 8 in one case to give a 1:1 mixture of butyne and 1,2-butadiene,¹⁰ and in the other a 3.5:1 mixture.¹¹ Thus, the formation of *only* allene in the reactions of Grignard reagents with propargyl chlorides in the presence of Fe(III) is not consistent with a SET, free-radical process.

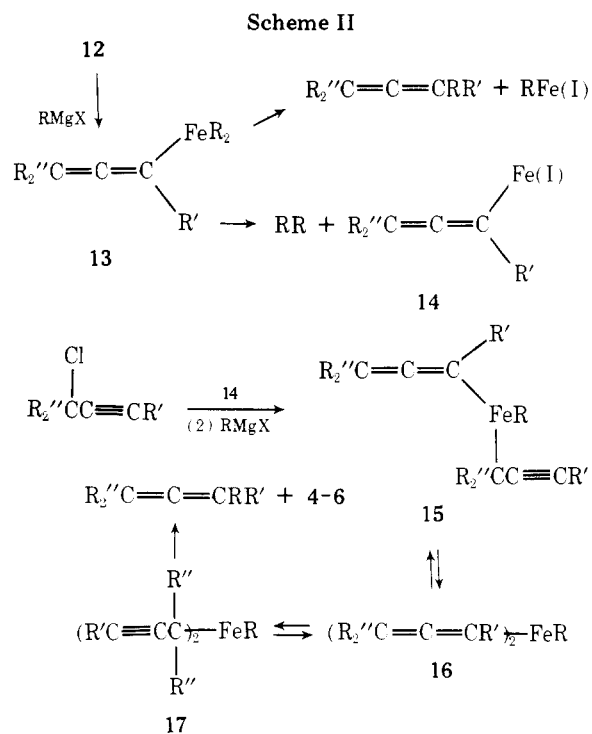
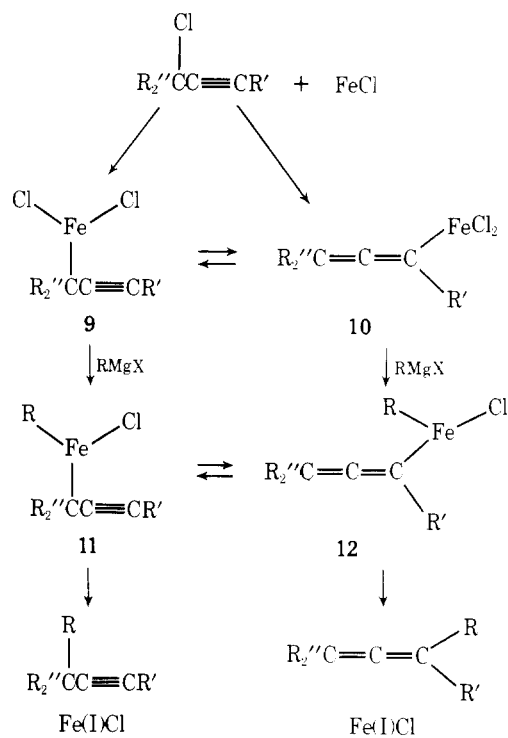
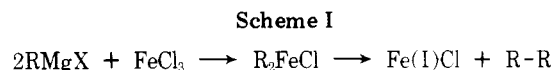
The formation of allenes in the catalyzed process is proposed to occur via the mechanism illustrated in Scheme I incorporating a catalytic cycle involving low valence state transition metal species similar to those proposed by Tamura and Kochi.¹² Although the scheme outlined is based on an Fe(III)–Fe(I) cycle, an Fe(II)–Fe(0) cycle is also possible in that Fe(II) is also an active catalyst. Because of the possible redox capabilities of the reaction system it cannot be unambiguously specified which couple is active in the catalytic cycle.¹³ Similar catalytic cycles can be written for the other active transition metals involving Co(II)–Co(0), Ni(II)–Ni(0), and Cu(II)–Cu(0) cycles.

The oxidative insertion of Fe(I)Cl into the propargyl chloride can occur to produce the propargyl iron species (9), which then undergoes rearrangement to the allenyl tautomer 10, or by insertion with concomitant rearrangement to form directly 10. The observation that both alkyne and allene are formed in the reactions of 1 and 1-propynylcyclohexyl chloride with methylmagnesium iodide suggests that a direct oxidative insertion to form 9 occurs. The observation that as the degree of substitution at the propargyl carbon increases the reactivity of the propargyl chloride decreases is consistent with a steric effect on the rate of direct insertion to form 9. Displacement of chloride in 9 or 10 by alkyl of the Grignard reagent produces the bisorganoiron species 11 and 12 which then decompose to alkyne or allene with regeneration of the low oxidation state metal species. Morrell and Kochi¹⁴ have reported on the formation and thermal decomposition of a bisorganonickel(II) complex which would be similar to that formed in the Ni(II) catalyzed process reported herein. Evidence for the intermediacy of allenyl transition metal compounds such as 12 has been derived from studies on the reactions of dialkylcuprates with propargyl chlorides.¹⁵

Whether tautomeric equilibrium is established between 9 and 10 and/or between 11 and 12 cannot be specified and must await the results of further studies. The exclusive formation of allene with the primary and secondary alkyl Grignard reagents can be attributed to a steric effect on the tautomeric equilibrium between 11 and 12.

The decreased reactivity of the secondary alkyl Grignard reagents relative to the primary alkyl reagents, and the total lack of reactivity of *tert*-butylmagnesium bromide, is probably due to increased steric effects in the displacement of chloride in 9 and/or 10 by the Grignard reagent.

The formation of the minor products octane and the dimers 4–6 can be visualized as occurring via an extension of the



mechanism in Scheme I to include trisorganometal species (Scheme II). Displacement of the remaining chloride in 12 would produce 13 which can decompose either to give allene and an alkyliron(I) species or to octane and the iron(I) species 14. Oxidative insertion of 14 into the propargyl chloride forms the trisorganometal species 15–17 which decompose to the dimers 4–6. Decomposition of 13 must occur to approximately the same extent via the two pathways shown as evidenced by the similarity in yields of octane and the dimers.

Critical to the operation of the catalytic cycle is the rate of decomposition of the bisorganometal species similar to 11 and

12 in Scheme I. The decrease in catalytic activity in the sequence Fe > Co > Ni > Cu is probably due to the increasing stability of bisorganometal species on going from iron to copper.¹⁶ The loss of catalytic activity in the nickel and copper systems when an excess of Grignard reagent is present suggests that some nickel or copper species is formed by reaction with the Grignard reagent which is not capable of entering the catalytic cycle. The lack of catalytic activity by chromium, manganese, rhodium, and silver must also be due to greater stability of the alkylmetal species.^{17,18} Further studies must be carried out to clarify this point.

It is interesting to compare the catalytic activity described herein with that reported by Tamura and Kochi for the iron,^{12a} copper^{12b} and silver^{12c} catalyzed reactions of Grignard reagents with alkyl and vinyl halides. Silver catalyzes the coupling of Grignard reagents with alkyl halides via a free-radical pathway.^{12c} Copper catalyzes coupling via a nonradical pathway, as well as disproportionation.^{12b} Iron catalyzes disproportionation with alkyl halides and coupling with vinyl halides.^{12a} In the present work silver as a catalyst was ineffective, while both iron and copper catalyzed coupling, but not disproportionation. This unique catalytic reactivity must be due to the presence of the C≡C. The presence of an adjacent C=C or aromatic ring does not result in coupling with these catalysts.

Although many studies have indicated that the addition of cobalt chloride to Grignard reagents induces free-radical reaction,¹⁹ the evidence presented herein indicates that such reactions need not necessarily proceed via free-radical mechanisms. For example, Coulomb-Delbecq and co-workers have suggested very recently that the reactions of propargylic acetates with methylmagnesium iodide in the presence of cobalt chloride to produce allenes occur via a free-radical process.²⁰ It is critical to note that no alkynes are formed, and thus it is very doubtful if a free-radical process is involved in those reactions.

Experimental Section

Iron(III) Catalyzed Reaction of 4-Chloro-4-methyl-2-pentyne

(1) with *n*-Butylmagnesium Bromide. To a solution of 5 g (0.067 M) of 1 in 50 mL of ether, to which has been added 5.0 mL of 5×10^{-6} M ferric chloride or ferric acetylacetonate in tetrahydrofuran, maintained at 0 °C under a helium atmosphere is added 2 molar equiv²¹ of 0.5 M *n*-butylmagnesium bromide in ether.²² The reaction mixture was hydrolyzed by the addition of 5 mL of water. The organic layer was decanted from the aqueous phase, dried (MgSO₄), and the solvent removed by distillation. Analysis by GLPC on a 10-ft Carbowax 20M on firebrick column indicated the presence of two short retention-time peaks and four longer retention-time peaks. The six components were isolated by preparative GLPC and identified as octane (≤5%), 2-methyl-2,3-octadiene (90%), dimers 4-6 (total ~4%) and an apparently rearranged dimer (~1%) by high-resolution mass spectrometry and NMR. 4: *m/e* 162; NMR (CDCl₃) δ 1.56 (s, 12 H) and 1.67 (s, 6 H). 5: *m/e* 162; NMR (CDCl₃) δ 1.27 (s, 12 H) and 1.80 (s, 6 H). 6: *m/e* 162; NMR (CDCl₃) δ 1.25 (s, 6 H), 1.66 (s, 6 H), 1.77 (s, 3 H), and 1.80 (s, 3 H). Unknown dimer: *m/e* 162; NMR (CDCl₃) δ 1.47 (s), 1.55 (s), 1.81 (s).

General Procedure for Transition Metal Catalyzed Reactions of Propargyl Chlorides with Grignard Reagents. The quantities and procedure outlined above were employed as standard reaction conditions. The optimum rates of addition of the Grignard reagent to the chloride-catalyst solution were determined in preliminary runs

by monitoring the extent of reaction by GLPC techniques. Optimum addition times are given in Table I. The product mixtures were analyzed by GLPC and the yields were calculated using an internal standard. The allenes were purified by preparative GLPC²³ and characterized by high-resolution MS and NMR. All of the substituted allenes prepared in this study have been reported previously in the literature.

Competitive Reactivity Experiments. All competitive reactivity experiments were carried out in the following manner. To 1:1 molar mixtures of the two substrates in ether (1 M) containing the appropriate concentration of the catalyst was added, in portions, a total of 0.5 molar equiv of the Grignard reagent. After addition of the portions of the Grignard reagent an aliquot of the reaction mixture was removed, hydrolyzed, and analyzed by GLPC. Product identification was carried out by comparison of retention times with the products derived on reaction of each of the substrates individually.

Registry No.—4, 17553-34-3; 5, 17553-33-2; 6, 65150-08-5; butyl bromide, 109-65-9; *sec*-butyl bromide, 78-76-2; ethyl iodide, 75-03-6; methyl iodide, 74-88-4; isopropyl bromide, 75-26-3; *tert*-butyl bromide, 507-19-7.

References and Notes

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- (13) See also ref 12a.
- (14) D. G. Morrell and J. K. Kochi, *J. Am. Chem. Soc.*, **97**, 7267 (1975).
- (15) See accompanying article on the reactions of dialkylcuprates with propargyl chlorides [D. J. Pasto, S.-K. Chou, E. Fritzen, R. H. Shults, A. Waterhouse, and G. F. Hennion, *J. Org. Chem.*, following article in this issue].
- (16) Attempts to prepare alkyl- and aryliron compounds indicate that such species undergo decomposition at low temperatures (see M. Tsutsui, *Ann. N.Y. Acad. Sci.*, **93**, 133 (1961)). An alkylarylnickel(II) complex has been prepared and its decomposition studied (see ref 14). Alkylcopper compounds are well known.
- (17) Trimethylchromium has been prepared in ether solution and is reasonably stable at 0 °C (K. Claus and C. Beermann, *Angew. Chem.*, **71**, 627 (1959)). Dimethylmanganese has also been prepared and is stable in ether at 0 °C but explodes when dry at higher temperatures (C. Beermann and K. Claus, *Angew. Chem.*, **71**, 627 (1959)).
- (18) Alkyl and aryl derivatives of second row transition metals have been prepared and show reasonable stability (see J. Chatt and B. L. Shaw, *J. Chem. Soc. A*, 1836 (1966), and references contained therein).
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- (21) The use of 50–100% excess of the Grignard reagent results in the maximum yield of allene.
- (22) GLPC analysis immediately after completion of the addition of the Grignard reagent showed that the reaction had gone to completion.
- (23) Purification of the more highly substituted allenes by distillation must be carried out at pot temperatures below 100 °C in order to avoid cyclodimerization and rearrangement of the allenes to conjugated dienes. The injection port, detector block, and column must be kept below 150 °C during preparative GLPC isolation procedures.