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Concerning the Mechanism of Grignard Reagent Formation. Evidence for Radical Escape and Return to the Surface of Magnesium

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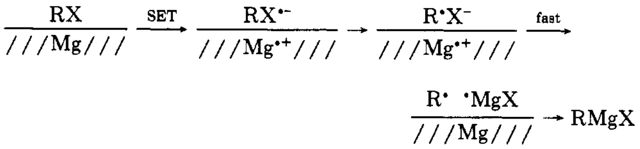
A study of the mechanism of formation of Grignard reagents using alkyl halide radical probes has been conducted. The effects of activation of the magnesium, temperature, concentration of the alkyl halide, magnesium to alkyl halide ratio, magnesium purity, the nature of the alkyl group, the nature of the halide group, and solvent (viscosity and basicity) on the formation of Grignard reagent were studied. The data obtained were used to test the earlier report by Garst that alkyl radicals, generated in the reaction of an alkyl halide with magnesium, diffuse freely into the solvent phase and return to the magnesium surface to form Grignard reagent. In this study cyclizable radical probes and radical traps were employed to study the extent to which radicals leave and return to the surface of magnesium to form Grignard reagent. In the particular system reported here, the data indicate that ~25% of the Grignard reagent is formed from radicals that diffuse into the solvent phase and then return to the magnesium surface to form Grignard reagent.

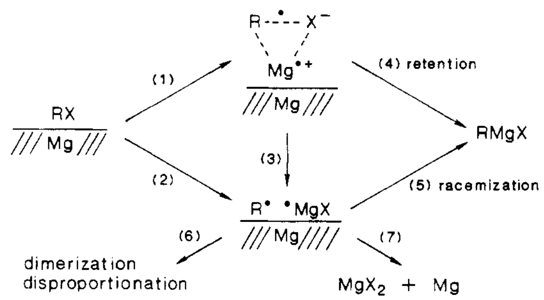
Introduction

It is apparent from previous work that the mechanism of Grignard reagent formation is radical in nature.[1-10] It has been suggested (Scheme I) that single electron transfer (SET) occurs from the magnesium surface (Mg) to the alkyl halide (RX) to form the alkyl halide radical anion ($RX^{\bullet -}$), which rapidly dissociates to form $R^{\bullet}$ and X^{-}. Then X^{-} immediately combines with the electron-deficient magnesium surface ($Mg^{\bullet +}$)[6c] to form surface-bound magnesious halide radical ($MgX^{\bullet}$). At this point $R^{\bullet}$ can react with $MgX^{\bullet}$ on the surface to form RMgX; however, some $R^{\bullet}$ escapes the surface of the magnesium. This $R^{\bullet}$ in solution can dimerize, abstract hydrogen from solvent, or possibly even return to the surface of the magnesium to form more RMgX as has been suggested by Garst.[11]

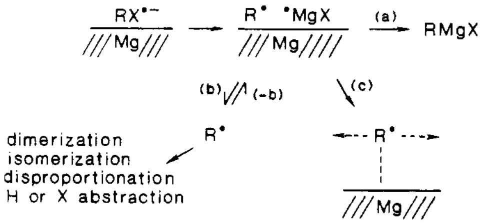
Scheme I



Scheme II



Scheme III



Walborsky[1] has studied the reactions of optically active 1-methyl-2,2-diphenylcyclopropyl halides with magnesium and described the initial steps of the reaction as the competition between two paths (Scheme II). It was suggested that the alkyl halide (RX) reacts with magnesium to produce $RX^{\bullet -}$ in close association with $Mg^{\bullet +}$ (path 1). The resulting intermediate then can collapse with complete retention of stereochemistry to form the Grignard reagent (path 4) or may dissociate (path 3) to form a loosely associated alkyl radical–magnesious halide intermediate in which $R^{\bullet}$ has lost its stereochemistry. The loose radical pair can then form racemic Grignard reagent (path 5) or further dissociate to form $R^{\bullet}$ and X^{-} (paths 6 and 7). $R^{\bullet}$ is bound to the magnesium surface, but it is still able to move about so as to disproportionate, dimerize, isomerize, or attack products or solvent. The loose radical pair may

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(1) (a) Walborsky, H. M.; Young, A. E. *J. Am. Chem. Soc.* **1961**, *83*, 2595. (b) *Ibid.* **1964**, *86*, 3288. (c) Walborsky, H. M.; Aronoft, M. S. *J. Organomet. Chem.* **1973**, *51*, 31. (d) Walborsky, H. M.; Banks, R. B. *Bull. Soc. Chim. Belg.* **1980**, *89*, 849.

(2) Ruchardt, C.; Trautwein, H. *Chem. Ber.* **1962**, *95*, 1197.

(3) Patel, D. J.; Hamilton, C. L.; Roberts, D. J. *J. Am. Chem. Soc.* **1965**, *87*, 5144.

(4) Lamb, R. C.; Ayers, P. W.; Toney, M. K.; Garst, J. F. *J. Am. Chem. Soc.* **1966**, *88*, 4261.

(5) Walling, C.; Coiffair, A. J. *J. Am. Chem. Soc.* **1970**, *92*, 6609.

(6) (a) Grootveld, H. H.; Blomberg, C.; Bickelhaupt, F. *Tetrahedron Lett.* **1971**, 1999. (b) Bodewitz, H. W. H. J.; Blomberg, C.; Bickelhaupt, F. *Tetrahedron Lett.* **1972**, 251. (c) Bodewitz, H. W. H. J.; Blomberg, C.; Bickelhaupt, F. *Tetrahedron* **1973**, *29*, 719. (d) Bodewitz, H. W. H. J.; Blomberg, C.; Bickelhaupt, F. *Tetrahedron* **1975**, *31*, 1053. (e) Schaart, B. J.; Bodewitz, H. W. H. J.; Blomberg, C.; Bickelhaupt, F. *J. Am. Chem. Soc.* **1976**, *98*, 3712. (f) Bodewitz, H. W. H. J.; Schaart, B. J., Van der Niet, J. D.; Blomberg, C.; Bickelhaupt, F.; Den Hollander, J. A. *Tetrahedron* **1978**, *34*, 2523.

(7) Buske, G. R.; Ford, W. T. *J. Org. Chem.* **1976**, *41*, 1998.

(8) Grovenstein, E.; Cottingham, A. B.; Gelbaum, L. T. *J. Org. Chem.* **1978**, *43*, 3332.

(9) (a) Rogers, H. R.; Hill, C. H.; Fujiwara, Y.; Rogers, R. J.; Mitchell, H. L.; Whitesides, G. M. *J. Am. Chem. Soc.* **1980**, *102*, 271. (b) Rogers, H. R.; Deutch, J.; Whitesides, G. M. *J. Am. Chem. Soc.* **1980**, *102*, 226. (c) Rogers, H. R.; Rogers, R. J.; Mitchell, H. L.; Whitesides, G. M. *J. Am. Chem. Soc.* **1980**, *102*, 231. (d) Root, K. S.; Deutch, J.; Whitesides, G. M. *J. Am. Chem. Soc.* **1981**, *103*, 5475.

(10) (a) Dubois, J. E.; Molle, G.; Tourillon, G.; Bauer, P. *Tetrahedron Lett.* **1979**, 5069. (b) Molle, G.; Bauer, P.; Dubois, J. E. *J. Org. Chem.* **1982**, *47*, 4120.

(11) Garst, J. F.; Deutch, J. E.; Whitesides, G. M. *J. Am. Chem. Soc.* **1986**, *108*, 2490.

(12) (a) Mishra, S. P.; Symons, M. C. R. *J. Chem. Soc., Perkin Trans. 2* **1973**, 391. (b) Wentworth, W. E.; George, R.; Keith, H. *J. Chem. Phys.* **1969**, *51*, 1791. (c) Wentworth, W. E.; Becker, R. S.; Tung, R. *J. Phys. Chem.* **1967**, *71*, 1653. (d) Andrieux, C. P.; Gallardo, I.; Saveant, J.; Su, K. *J. Am. Chem. Soc.* **1986**, *108*, 638. (e) Barber, J. J.; Whitesides, G. M. *J. Am. Chem. Soc.* **1980**, *102*, 239.

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be alternatively formed directly from RX (path 2) when it is adsorbed onto the magnesium surface. The tendency of RX to form a tight radical pair (path 1) rather than a loose radical pair (path 2) is a function of the strength of the carbon halogen bond (Cl > Br > I).[1c]

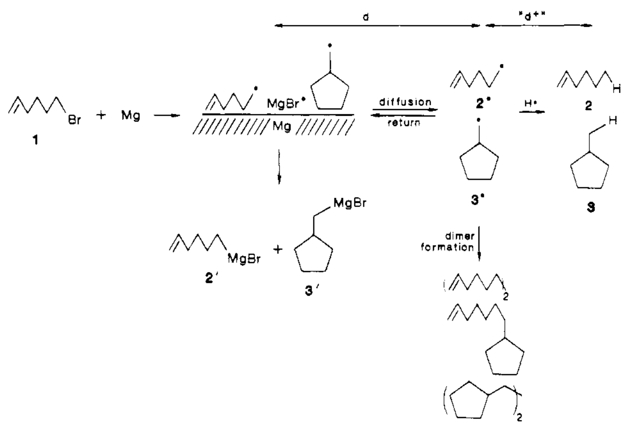
Bodewitz, Blomberg, and Bickelhaupt[6d] through their extensive solvent studies on the 6-bromo-1-hexene/magnesium system concur with Walborsky concerning the intermediate formation of a radical anion ($RX^{\bullet -}$) and $Mg^{\bullet +}$ via SET. They have stated (Scheme III) that once $RX^{\bullet -}$ is formed it then is adsorbed onto the magnesium surface at the reaction site and then rapidly dissociates to X^- (which combines with $Mg^{\bullet +}$ to form $MgX^{\bullet}$) and $R^{\bullet}$. Then $R^{\bullet}$ can react immediately with $^{\bullet}MgX$ to produce RMgX (path a), diffuse from the surface to abstract hydrogen or halogen, disproportionate, dimerize, isomerize, or return to the reaction site to form RMgX (path b) or form weak, nonlocalized σ bonds with the magnesium surface which allows $R^{\bullet}$ some "surface mobility"[13] that would ultimately allow formation of RMgX (path c). The actual combination of $R^{\bullet}$ and $^{\bullet}MgX$, where $^{\bullet}MgX$ is drawn off the surface during or just before combination with the solvent (path a), is considered to be the most important path.

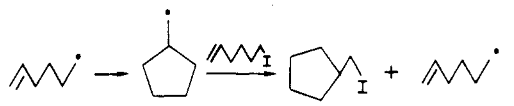
The formation of the Grignard reagent (once formed, RMgX disproportionates rapidly to the Schlenk equilibrium product: $2RMgX \rightleftarrows R_2Mg + MgX_2$) should be dependent on the solvent's basicity, viscosity, and π-electron-donating ability. The more basic the solvent, the greater should be its ability to solvate $^{\bullet}MgX$, which is necessary for reaction with $R^{\bullet}$ (path a). As the basicity decreases, $R^{\bullet}$ is less likely to react with $^{\bullet}MgX$ and therefore is more able to leave the reaction site (path b); thus the yield of side reaction products (dimerization, isomerization, etc.) should increase. The viscosity of the solvent should be important in determining the amount of cyclized products formed when a cyclizable radical probe is used. As the viscosity increases, the diffusion of $R^{\bullet}$ from the surface of magnesium is slowed so that the formation of dimer products should decrease. Solvents, such as benzene, that are able to donate π-electrons, stabilize alkyl radicals.[14] This stabilization of $R^{\bullet}$ decreases its tendency to react with $^{\bullet}MgX$, thus allowing it to diffuse from the surface of the magnesium. This diffusion is indicated by a constant ratio of cyclized versus uncyclized hydrocarbon in the dimer products while the total yield of dimers increases as the π-electron donating ability of the solvent increases.[6d]

Garst, Deutch, and Whitesides[11] have reported that $R^{\bullet}$ freely diffuses from the magnesium surface into solution and thus is not always adsorbed onto the magnesium surface prior to the formation of RMgX. It has been suggested that $R^{\bullet}$ is generated so close to the active $^{\bullet}MgX$ that most of the $R^{\bullet}$ will form RMgX without any type of isomerization (cyclization or loss of stereochemistry) or side reaction (dimerization, disproportionation, or hydrogen atom abstraction). The possibility of diffusion of $R^{\bullet}$ from the magnesium surface and return to form RMgX was implied by Bickelhaupt;[6d] however, Bickelhaupt does not specifically state that $R^{\bullet}$ diffuses readily from the magnesium surface and returns to form Grignard.

The present study was undertaken in an attempt to resolve the dichotomy as to whether RMgX is formed entirely on the magnesium surface or whether $R^{\bullet}$ diffuses readily into solution and then returns to the magnesium surface to form RMgX. It would appear that the use of cyclizable radical probes and trapping agents would be ideal for such a study. Even though some work has been carried out with 6-halo-1-hexenes, much more information could be obtained if a variety of radical probes were used. We feel that the observation of the ratio of cyclized/uncyclized products should be very informative with respect to answering the question as to whether or not $R^{\bullet}$ leaves the surface of the magnesium metal prior to Grignard reagent formation. Furthermore, by performing studies using cyclizable alkyl bromide radical probes rather than the corresponding iodides, one can interpret the amount of cyclized product formed without being concerned about halogen exchange to produce cyclized halide (eq 1).[15]

Scheme IV





(1)

Different methods of magnesium activation, temperature, concentration, purity of magnesium, and stoichiometry were also examined in the belief that these variables might be critical with respect to the specific mechanistic course followed when an alkyl halide is allowed to react with magnesium. The role of the solvent and the nature of the alkyl and halogen moieties were also addressed in order to determine their effect on the mechanistic course of the reaction. All reactions were carried out in duplicate or triplicate and all results were reproducible within 3% (relative).

Results and Discussion

The reaction of 6-bromo-1-hexene (1) with magnesium to form (5-hexen-1-yl)magnesium bromide is believed to proceed at least partially through a radical mechanism since the radical nature of the Grignard formation reaction has been definitely established by CIDNP spectroscopy.[6] It is suggested in Scheme IV that the 5-hexen-1-yl radical ($2^{\bullet}$), once generated, can diffuse from the magnesium surface where it can undergo a characteristic[16] radical cyclization to the methylcyclopentyl radical ($3^{\bullet}$). Both $2^{\bullet}$ and $3^{\bullet}$ can then return to the surface to react with the surface-bound magnesious halide to form Grignard reagents (2′ and 3′). Alternatively both $2^{\bullet}$ and $3^{\bullet}$ can couple to form three different dimers. The data to be presented indicate that cyclization and dimer formation take place

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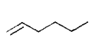
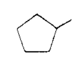
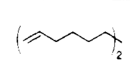
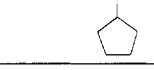
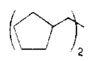
[13] Kharasch, M. S.; Reinmuth, L. *Grignard Reactions of Nonmetallic Substances*; Prentice-Hall, Inc.: New York, 1954.

[14] (a) Burkhart, R. D. *J. Chem. Phys.* **1969**, *73*, 2703. (b) Burkhart, R. D.; Wong, R. J. *J. Am. Chem. Soc.* **1973**, *95*, 7203. (c) Bargon, J. *J. Am. Chem. Soc.* **1971**, *93*, 4630. (d) Niki, E.; Kamiya, Y. *J. Am. Chem. Soc.* **1974**, *96*, 2129.

[15] Ashby, E. C.; Goel, A. B.; Wenderoth, B.; Pham, T. N. *J. Org. Chem.* **1984**, *49*, 3545.

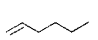
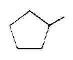
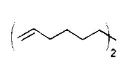
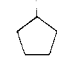
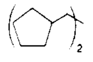
[16] (a) Julia, M. *Acc. Chem. Res.* **1971**, *4*, 386. (b) Carlsson, D. J.; Ingold, K. U. *J. Am. Chem. Soc.* **1968**, *90*, 7047.

Table I. Effect of Activation on the Reaction of 6-Bromo-1-hexene with Magnesium[a]

expt	method					
1	none	89.9 (94.1)	5.4 (66.6)	trace	1.2	1.2
2	EtBr	91.3 (98.2)	5.4 (86.0)	trace	0.7	1.0
3	I_2	92.1 (96.9)	5.9 (65.8)	trace	0.94	0.6
4	·)))[b]	88.6 (98.5)	5.3 (84.2)	0.6	1.1	1.4
5	EtBr/·)))	91.0 (98.5)	5.8 (87.0)	trace	0.9	0.8
6	I_2/·)))	86.4 (94.4)	5.2 (74.1)	2.1	1.4	0.7

[a] Reaction time 3 h in THF at 22 °C. Numbers in parentheses indicate the percent deuterium incorporation. [b] ·))) = sonication.

Table II. Effect of Temperature on the Reaction of 6-Bromo-1-hexene with Magnesium[a,b]

expt	T, °C					
1	22	88.6 (98.5)	5.3 (84.2)	0.6	1.1	1.4
2	42	91.2 (94.2)	4.4 (81.9)	trace	1.0	1.3
3	61	91.8 (94.0)	5.3 (77.8)	trace	0.6	0.8

[a] Magnesium was not preactivated with bromoethane. [b] Reaction time 3 h in THF with sonication. Numbers in parentheses indicate the percent deuterium incorporation.

at a distance (d) from the surface and that dimerization is competitive with cyclization. Of course, straight-chain and cyclized hydrocarbons (**2** and **3**) are formed to a lesser extent at distance d since hydrogen atom abstraction from solvent is somewhat slower than cyclization or dimer formation. On the other hand, as the radicals diffuse even further from the magnesium surface ("d^{+*}"), mainly cyclized radical remains, which tends mainly to abstract hydrogen from the solvent to form methylcyclopentane. Grignard reagents **2′** and **3′** are stable under the experimental conditions[17] so that quenching the reaction mixture with D_2O determines the absolute percent Grignard reagent of each isomer. The sum of the amounts of cyclization, dimerization, and hydrogen atom abstraction products represents the least amount of radical that has escaped the surface of magnesium. We will return to this point later in the paper.

In order to appreciate all of the factors relevant to the mechanism of this reaction, we decided to study the effects of all variables in the Grignard reaction on the ratios of products formed. In this way trends in the product ratios could be evaluated in terms of the correctness of the model propose in Scheme IV. Our first study involved the effect of activating the magnesium surface on the product ratio. The initiation process in the formation of Grignard reagents, although unclear, has been stated best by Kharasch.[13] He suggested that electron transfer from magnesium to the alkyl halide takes place at points of unsaturation on the magnesium surface (these might be considered crystal lattice irregularities[9d]). Preliminary reaction of the magnesium with an alkyl halide or iodine is thought to activate the magnesium surface by increasing the number of unsaturation sites, which in turn should increase the rate of formation of the desired Grignard reagent. Sonication of the reaction mixture is also thought to activate magnesium by continuously cleaning the surface, thus making the sites of potential electron transfer more accessible to the alkyl halide.

Each of these methods of activation of the magnesium surface was examined in order to determine its effect on the reaction of **1** with magnesium in THF (Table I). Activation with bromoethane did not (within experimental error) increase the amount of 1-hexane (**2**), methylcyclopentane (**3**), or dimer products formed on hydrolysis of the reaction mixture; however, it did increase the deuterium content (d_1) of **2** and **3** (expt 1, 2). This increased amount of Grignard (**2′** and **3′**) is probably a result of increased unsaturation sites, which in turn causes the radicals **2**$^\bullet$ and **3**$^\bullet$ to react at or very near the magnesium surface at a higher rate to form the corresponding Grignard reagents **2′** and **3′**. Of course, an increase in the rate of Grignard formation should decrease the amount of dimer formed, which is observed to a slight extent. Activation of the magnesium surface with iodine (expt 3) produced results similar to the activation with bromoethane except that iodine activation hindered the reaction of the methylcyclopentyl radical with $MgBr^\bullet$ or $MgI^\bullet$ at or near the surface of the magnesium to produce **3′**. Activation of the magnesium surface using sonication (expt 4) slightly increased the deuterium content of **2** and **3** (indicating an increase in the formation of **2′** and **3′**) over that observed without magnesium activation and also increased the amount of straight-chain dimer produced. Sonication, in addition to increasing the reactivity of magnesium with the alkyl halide (**1**), also increases the diffusion of the radicals, which allows the second-order process of **2**$^\bullet$ coupling to occur to a greater extent. Using a combination of these activation methods resulted in an average of the respective effects (expt 5 and 6). In summary, it is concluded that activation of magnesium has a distinguishable, but not substantial, effect in the cases presented, except in the amount of cyclized Grignard (**3′**) formed in the reaction. From the data presented in Table I we concluded that all further reactions studied would be carried out by using magnesium activated by using a small amount of bromoethane followed by reaction with the appropriate alkyl halides using sonication.

Since many syntheses of Grignard reagents employ the initial application of external heat, the effect of temperature (22 °C, 42 °C, and 61 °C) on the course of reaction was determined in the reaction of **1** with magnesium in THF (Table II). As the reaction temperature was increased, the yield of **2** increased while that of **2′** and **3′** decreased slightly (expt 1–3). Slightly more of **2** and less of **2′** was produced at 44 °C and 61 °C than at 22 °C because at the higher temperatures the 5-hexen-1-yl radical diffuses more rapidly from the surface of the magnesium and is more susceptible to cyclization and eventually hydrogen atom abstraction (expt 3). The dimer formation at 61 °C decreased slightly since some of the alkyl radicals that coupled to form dimers at 22 °C at distance d traveled

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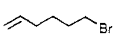
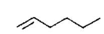
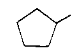
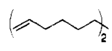
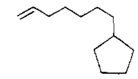
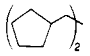
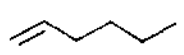
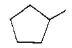
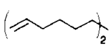
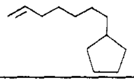
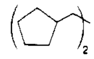
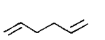
(17) Kossa, W. C.; Rees, T. C.; Richey, H. G., Jr. *Tetrahedron Lett.* **1971**, 3455.

Table III. Time Study of the Reaction of 6-Bromo-1-hexene with Magnesium[a]

expt	time (min)						
1	5	34.4	61.5 (92.5)	4.1 (74.4)	trace	trace	trace
2	10	11.4	78.6 (95.1)	5.0 (82.5)	1.0	0.7	0.8
3	15	3.5	85.2 (95.6)	5.9 (81.2)	1.1	0.8	0.8
4	60	0.0	88.8 (95.1)	5.5 (83.0)	1.1	0.9	0.9
5	180	0.0	89.1 (98.6)	5.5 (82.7)	1.0	0.9	0.8

[a] Reaction carried out in THF at 22 °C with sonication. Numbers in parentheses indicate the percent deuterium incorporation.

Table IV. Effect of Magnesium Purity on Its Reaction with 6-Bromo-1-hexene[a]

expt	Mg						
1	99.98%	91.0 (98.5)	5.8 (87.0)	trace	0.9	0.8	0.0
2	99.98% (+2.24% $FeCl_3$)	38.2 (13.1)	22.5 (4.8)	2.6	1.4	2.7	25.9
3	Grignard Grade	90.7 (91.7)	2.4 (80.8)	0.8	1.9	0.7	0.0
4	99.98[b]	65.1	5.5	<1	<1	<1	28.5

[a] Reaction time was 3 h in THF at 22 °C with sonication. Numbers in parentheses indicate the percent deuterium incorporation. [b] 2.0% $FeCl_3$ added to the Grignard reagent of expt 1 after its completion.

the distance d^+ and are trapped by hydrogen atom abstraction at the higher temperatures. Thus, preactivation of the magnesium with bromoethane and sonication of the reaction mixture at 22 °C were chosen as the standard conditions for carrying out the study of other variables.

The reaction of 6-bromo-1-hexene with magnesium was monitored in order to determine the constancy of the product ratio and the stability of the products under the reaction conditions. Table III shows that the ratio of straight-chain to cyclic products (**2**:**3** and **2′**:**3′**) remained constant (15/1) during the reaction and after the reaction was complete. The initially low percentage of Grignard reagent in both the straight-chain and cyclic products is a reflection of the lower concentration of radicals at the beginning of the reaction, thus the chance of dimerization is reduced and the probability of hydrogen atom abstraction by the radicals is increased.

According to Kharasch's theory, impurities in the magnesium should have a significant effect on the formation of Grignard reagents. These impurities on the magnesium surface would be possible candidates as sites of electron transfer. In work by Lawler with iron chloride,[18] it was suggested that iron catalyzes subsequent reactions of Grignard reagents. The results of reaction of **1** with magnesium of different purities are consistent with an iron-catalyzed cyclization (Table IV). Using 99.98% pure magnesium (Reade) doped with 2.24% anhydrous $FeCl_3$ produced a dramatic change in the relative amounts of **2**, **3** and **2′**, **3′** (expt 1, 2). When the solution of **1** was added to the reaction flask already containing the magnesium and iron chloride, it quickly turned black presumably due to the reduction of $FeCl_3$ to Fe^0. The yields of the straight-chain and cyclized Grignard reagents were drastically reduced while the yields of the hydrocarbon and dimer products were increased and a substantial amount of 1,5-hexadiene was produced. This change in the amount of product (**2**, **3** and **2′**, **3′**) is attributed to the iron-catalyzed reaction of magnesium with the alkyl halide.[19] On the other hand, the substantial amount of 1,5-hexadiene was shown to be due to the reaction of the straight-chain Grignard (**2′**) after it was formed, with $FeCl_3$ (expt 4). Grignard grade magnesium, which has 0.033% transition metal impurities,[19] produced a similar effect to that observed in (expt 2), but on a much smaller scale (expt 3). Grignard grade magnesium (expt 3) produced less **3** than the Reade magnesium (expt 1), yet more **3** was produced when $FeCl_3$ was added (expt 2). These opposing trends suggest that not all transition metals act similarly to iron in their catalytic activities (note effect of other impurities in Grignard grade magnesium).[19]

The formation of Grignard reagent does not occur over the entire magnesium surface but at individual reaction sites as suggested earlier. Scheme IV is a reasonable depiction of the possible paths that an alkyl radical can take once it has diffused from the magnesium surface. The 5-hexen-1-yl radical, when initially produced on the magnesium surface, can react immediately with ·MgX on or near the surface or diffuse a significant distance from the surface. At any time after the reaction has started, some percentage of the 5-hexen-1-yl radicals have diffused to distance d from the surface of the magnesium where also some cyclization to the cyclopentylmethyl radical can take place. At this distance the radicals are still able to return to the magnesium surface to form Grignard reagent. In addition, the 5-hexen-1-yl and cyclopentylmethyl radicals can dimerize due to the reasonably high concentration of radicals a short distance (d) from the surface of the magnesium. When the radicals diffuse to distance d^+ from the magnesium surface, the radicals are less likely to return to the magnesium surface. Therefore, most of the 5-hexen-1-yl radical is converted to the cyclopentylmethyl radical, which subsequently abstracts a hydrogen atom from the solvent to produce methylcyclopentane.

The concentration of 6-bromo-1-hexene (**1**) in its reaction with magnesium was determined to affect the product ratio. The data reported in Table V show that increasing the concentration of **1** (0.001–1.0 M) increased the percentage of dimer products and decreased the yield of **2′** and **3′**. The lack of dimer formation was expected at lower concentrations, indicating dimer is formed only a short distance from the surface of the magnesium. The fact that formation of **2′** and **3′** did not decrease at the lower concentrations indicates that Grignard formation is taking place closer to the magnesium surface than dimer formation. The fact that cyclized hydrocarbon **3** is always produced in greater yield than the straight-chain hydro-

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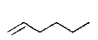
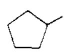
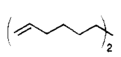
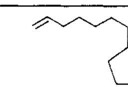
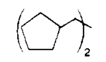
[18] (a) Lawler, R. G.; Livant, P. *J. Am. Chem. Soc.* **1976**, *98*, 3711. (b) Also see: Schaart, B. J.; Bodewitz, H. W. H. J.; Blomberg, C.; Bickelpaupt, F. *Ibid.* **1976**, *98*, 3713.

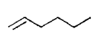
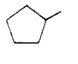
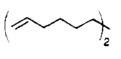
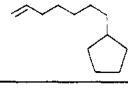
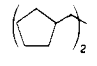
[19] Ashby, E. C. Buhler, J. D. Lopp, I. G.; Wiesemman, T. L.; Bowers, J. S., Jr.; Laemmle, J. T. *J. Am. Chem. Soc.* **1976**, *98*, 6561.

Table V. Effect of Concentration on the Reaction of 6-Bromo-1-hexene with Magnesium[a]

expt	M					
1	1.0	86.3 (96.7)	2.4 (85.9)	3.5	1.5	0.8
2	0.1	91.0 (98.5)	5.8 (87.0)	trace	0.9	0.8
3	0.01	94.6 (98.3)	5.4 (84.8)	0.0	0.0	0.0
4	0.001	94.4 (97.9)	5.6 (83.5)	0.0	0.0	0.0

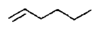
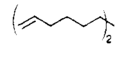
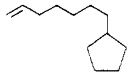
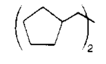
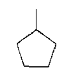
[a] Reaction time was 3 h in THF at 22 °C with sonication. Numbers in parentheses indicate the percent deuterium incorporation.

Table VI. Effect of Magnesium:RX Ratio in the Reaction of 6-Bromo-1-hexene with Magnesium[a]

expt	Mg:RX					
1	10:1	92.1 (98.1)	5.3 (84.7)	1.0	1.2	0.9
2	2:1	91.4 (97.4)	5.5 (81.8)	0.9	1.3	1.2
3	1:1	90.7 (98.0)	4.9 (83.3)	1.0	0.7	1.0
4[b]	0.6:1	84.9 (97.4)	4.0 (81.5)	2.2	1.5	1.7

[a] Reaction time was 3 h in THF at 22 °C with sonication. Numbers in parentheses indicate the percent deuterium incorporation. [b] Yields were based on the percent 6-bromo-1-hexene that reacted (~60%).

Table VII. Effect of the Halogen in the Reaction of 6-Halo-1-hexenes with Magnesium[a]

expt	X	solvent					
1	Cl	THF	95.1 (97.6)	4.9 (78.1)	0.0	0.0	0.0
2	Br	THF	91.0 (98.5)	5.8 (87.0)	trace	0.9	0.0
3	Br	ether	69.0 (97.0)	2.4 (67.2)	9.8	3.4	1.2
4	I	ether	38.8 (70.2)	1.7 (67.4)	21.3	6.2	2.0

[a] Reaction time was 3 h at 22 °C with sonication. Numbers in parentheses indicate the percent deuterium incorporation.

carbon **2** indicates that as the straight-chain radical distance from the magnesium surface increases, cyclization increases (expt 1, 2) and the amount of hydrogen atom abstraction from the solvent increases. At 0.1 M (expt 2) almost no straight-chain dimer was produced whereas at 1.0 M (expt 1), more than four times as much straight chain dimer was formed compared to cyclized dimer. All of these data tend to indicate that both Grignard and straight-chain dimer are formed on or near the surface of the magnesium. As the radical moves further from the surface, it tends to cyclize. At this point, it can return to the surface to form cyclize Grignard or continue to diffuse, abstract hydrogen from solvent, and form cyclized hydrocarbon.

Varying the magnesium to alkyl halide (RX) ratio should increase or decrease the number of sites at which RX can react. A high Mg:RX ratio should produce results similar to those obtained at a low concentration of 1 (Table V), where the reaction of the RX molecule on the magnesium surface is so spread out that the 5-hexen-1-yl radical that diffuses from the surface is less likely to dimerize. However, when the magnesium to alkyl halide ratio was 10:1, 2:1, and 1:1, the product ratios (**2**:**3** and **2′**:**3′**) were very similar (Table VI, expt 1–3). On the other hand, when the ratio of Mg:RX was decreased to 0.6:1, the yield of Grignard decreased as expected and the yield of dimer product increased as expected.

The nature of the halogen determines the mean distance at which the alkyl halide is able to react with the magnesium surface (via SET) to form an alkyl halide radical anion, which subsequently produces the corresponding alkyl radical. An alkyl halide with an unfavorable reduction potential (large negative number) would require close association with the magnesium surface for the initial electron transfer to take place while an alkyl halide with a more favorable reduction potential (smaller negative number) would not.[20] Thus, changing the halogen from Cl to Br to I lowers the reduction potential of the alkyl halide, which would increase the mean distance from the magnesium surface to the alkyl halide at which distance electron transfer could take place and thus the distance at which alkyl radicals can be produced. The radical's proximity to the magnesium surface and ·MgX determines its tendency to react at the surface to form the Grignard reagent.

Since radicals formed from 6-chloro-1-hexene are closer to the magnesium surface initially when formed than radicals formed from 6-bromo-1-hexene, it is not surprising that more straight-chain Grignard reagent, less cyclic Grignard reagent, and no dimer products were produced in THF (Table VII, expt 1, 2) when X = Cl compared to bromide. Also, since fewer radicals diffused from the magnesium surface, the radicals that did were unable to dimerize, but rather cyclized and abstracted hydrogen atoms, the result of which produced a lower d_1 value in the methylcyclopentane. On the other hand, when 6-bromo-1-hexene was allowed to react with magnesium and ether, diffusion of radicals from the surface into the ether (a solvent of significantly less viscosity than THF) was enhanced, resulting in less Grignard but more dimer formation at the expense of cyclized hydrocarbon. Radicals generated from 6-iodo-1-hexene are a greater distance from the magnesium surface than radicals generated from 6-bromo-1-hexene (ext 3, 4). This factor results in the formation of less straight-chain and cyclic Grignard reagents but more dimer products and 1-hexene.

The nature of the alkyl group of RX was determined to play an important role in the formation of Grignard

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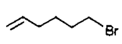
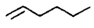
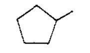
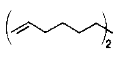
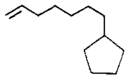
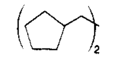
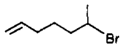
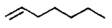
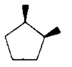
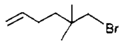
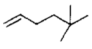
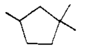
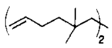
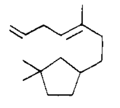
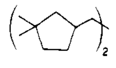
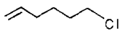
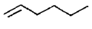
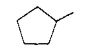
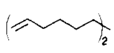
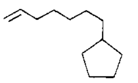
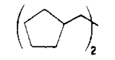
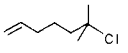
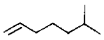
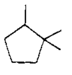
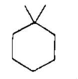
(20) It was assumed that the reactions of 6-hexen-1-yl chloride, bromide, and iodide proceed through an outer sphere mechanism although the question of inner versus outer sphere mechanism has not been resolved. See ref 11 and in particular ref 11e for a detailed discussion of the reduction of alkyl halides.

Table VIII. Effect of the Alkyl Group in the Formation of Grignard Reagents[a]

expt	reactants	products				
1						
		91.0 (98.5)	5.8 (87.0)	trace	0.9	0.8
2					dienes	dimers
		44.3 (73.7)	8.7 (62.1)	2.5 (48.7)	6.1	16.1
3						
		46.2 (98.5)	29.4 (90.8)	1.6	6.7	3.9
4						
		95.1 (97.6)	4.9 (87.0)	0.0	0.0	0.0
5					dienes	dimers
		68.0 (85.5)	11.8 (90.6)	7.3 (93.8)	5.1	9.1

[a] Reaction time was 3 h in THF at 22 °C with sonication. Numbers in parentheses indicate the percent deuterium incorporation.

reagents. The reduction potentials of the alkyl bromides used in this study were not expected to be very different; however, the relative stabilities and steric requirements of their incipient radicals are different and would be expected to influence the reactions to form Grignard reagents. The effect of changing the alkyl group from 5-hexen-1-yl to 6-hepten-2-yl to 2,2-dimethyl-5-hexen-1-yl in the reactions of the respective alkyl bromides to form the corresponding Grignard reagents is shown in Table VIII. Comparison of the 6-hepten-2-yl radical (expt 2), with the 5-hexen-1-yl radical (expt 1), shows the effect of the more stable secondary radical's longer life time.[21] The secondary straight-chain Grignard reagent, measured as the d_1 content in 1-heptene, decreased drastically (73.7% of 44.3%) compared to the primary straight-chain Grignard reagent (98.5% of 91.0%). This sharp decline in straight-chain Grignard reagent is the direct result of the 6-hepten-2-yl radicals greater stability and steric hindrance. The generation of both radicals is assumed to be at the same distance from the magnesium, yet once formed the heptenyl radical does not have as high a tendency to combine with $^{\bullet}$MgX as the 5-hexen-1-yl radical. This allows the heptenyl radical to diffuse from the magnesium surface to a greater extent, which results in an increased yield of dimers, dienes, and cyclized products. Note also that the amount of cyclized Grignard reagent (deuteriated *cis*- and *trans*-1,2-dimethylcyclopentane) has decreased relative to the methylcyclopentyl Grignard reagent (expt 1, 2). This fact indicates that the secondary heptenyl radical is able to diffuse farther from the magnesium surface, so that when the radicals do cyclize, they must travel farther back to the reaction site relative to the methylcyclopentyl radical. Thus the formation of dienes and the increased percentage of dimers in the reaction of the secondary bromide is expected because the heptenyl radical's greater stability affords it a greater chance of encountering other radicals. The cis/trans ratio of the cyclized secondary products (3.5:1) is consistent with a radical cyclization process.[22]

The reaction of the hindered primary probe, 5,5-dimethyl-6-bromo-1-hexene, with magnesium illustrates how steric requirement limits the combination of a radical with $^{\bullet}$MgX (expt 3). The faster rate of cyclization of the 2,2-dimethyl-5-hexene-1-yl radicals results in a reduction of straight-chain Grignard reagent and increase in cyclized Grignard reagent relative to the 5-hexenyl case (expt 1, 3). The fact that the deuterium incorporation remains so high in the straight-chain and cyclic product is characteristic of the reactivity of the 1° radical at the magnesium surface. The increase in dimer formation (expt 3) over the 5-hexenyl case was expected due to the increased steric hinderance in the return of the radical to the magnesium surface.

A comparison of the reactions of 6-chloro-6-methyl-1-heptene (tertiary chloride) and 6-chloro-1-hexene (primary chloride) with magnesium also exemplifies the effect of increasing the radical stability (expt 4, 5). Less straight-chain Grignard reagent is formed from the tertiary chloride than the primary since the tertiary radical has a longer life time that allows it to cyclize to a greater extent and form diene and dimer products which were not formed in the reaction of the primary chloride. The lower deuterium content of the tertiary straight-chain hydrocarbon compared to the primary indicates that return of the tertiary radical to the magnesium surface is retarded due to steric hinderance.

It has been known for some time that the nature of the solvent directly affects the formation of Grignard reagents.[13] For this reason basicity, viscosity, and polarity were examined in order to determine their respective effects on the reaction of alkyl halides with magnesium. Basic solvents, such as THF, assist in the process of forming Grignard reagents by helping to solvate the magnesious halide ($^{\bullet}$MgX) prior to its combination with the 5-hexen-1-yl radical. This enables a high yield in the reaction of 1 with magnesium to form the straight-chain Grignard reagent (2′) (Table IX, expt 1). Diethyl ether is a less basic solvent than THF and does not assist in the $^{\bullet}$MgX sol-

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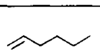
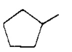
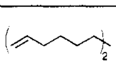
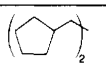
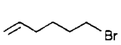
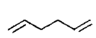
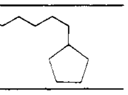
[21] (a) Beckwith, A. L. J.; Phillipou, G. J. *J. Am. Chem. Soc.* **1974**, 96, 613. (b) Brace, N. O. *J. Org. Chem.* **1967**, *32*, 2711. (c) Garst, J. F.; Hines, J. B. *J. Am. Chem. Soc.* **1984**, *106*, 6443. (d) Dowbenko R. *J. Am. Chem. Soc.* **1964**, *86*, 946.

[22] Aldercruetz, P.; Masnusson, C. *Acta. Chem. Scand., Ser. B* **1980**, *34*, 647.

Table IX. Effect of Solvent on the Reaction of 6-Bromo-1-hexene with Magnesium[a]

expt	solvent							
1	THF	91.0 (98.5)	5.8 (87.0)	trace	0.9	0.8		
2	ether	69.0 (97.0)	2.4 (67.2)	9.8	3.4	1.2		
3	toluene (2 equiv of THF)	62.0 (86.2)	6.8 (72.6)	9.5	4.3	1.8		
4	HMPA	37.8 (1.6)	3.0 (9.8)	17.3	1.4	0.4	3.95	17.6
5[b]	pentane	2.5 (87.1)	1.1 (77.1)	0.0	0.0	0.0	96.4	
6[b]	pentane (2 equiv of THF)	6.0 (89.3)	0.3 (72.7)	0.0	0.0	0.0	93.7	
7	pentane:THF (1:1)	80.4 (89.7)	2.8 (79.6)	4.7	2.5	1.2		
8	THF (10 equiv of DCPH)	95.3 (74.9)	4.7 (1.9)	0.0	0.0	0.0		

[a] Reaction time was 3 h at 22 °C with sonication unless noted. Numbers in parentheses indicate the percent deuterium incorporation. [b] Reaction time was 3 days.

vation process as well as THF and also because of the lesser viscosity of ether compared to THF, more of the 5-hexen-1-yl radical escapes immediate combination with •MgX which results in a decreased formation of **2′** (expt 2). The low yield of the (cyclopentylmethyl)magnesium bromide (**3′**) was caused by the lower viscosity of ether and this result will be discussed later. Pentane is completely nonbasic and affords no solvation assistance in the formation of Grignard reagent because of its lack of ability to coordinate with the magnesium in the transition state or after the Grignard reagent has formed. The low reaction yield in expt 5 is characteristic of previous attempts to generate Grignard reagents in hydrocarbon solvents at room temperature. From the results of these three reactions (expt 1, 2, and 5), it is concluded that as the basicity of the solvent decreases so does the tendency of the 5-hexen-1-yl radical to combine with •MgX to form 5-hexenylmagnesium bromide.

The effect of viscosity is usually hard to separate from the effect of basicity since the more basic solvents are usually more viscous. Bickelhaupt and co-workers[6] have done much to clarify these two factors; this study builds upon their earlier foundation. The relationship of the solvent's viscosity (THF > ether ≈ pentane) does not exactly follow the relationship of the solvent's basicity (THF > ether ≫ pentane); thus the different product ratios for the reaction of **1** with magnesium in these three solvents cannot entirely be attributed to viscosity. Basicity affects the reaction course by enhancing the combination of the 5-hexene-1-yl radical with •MgX. Viscosity, on the other hand, determines the rate of diffusion of the 5-hexen-1-yl radical from the magnesium surface, which ultimately results in cyclization, dimerization, and, at a greater distance from the magnesium surface, hydrogen atom abstraction.

As the viscosity is halved by switching from THF to ether, the ability of the 5-hexen-1-yl radical to diffuse from the magnesium surface increases. With this faster rate of diffusion, the concentration of radicals at distance *d* increases and hence an increase in the yield of dimers is observed (expt 1, 2). Cyclized as well as straight-chain radicals diffuse faster in the low viscosity diethyl ether medium than in THF. This results in higher yields of dimer and lower yields of Grignard reagent.

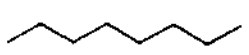
Changing the solvent from ether to pentane in the reaction of **1** with magnesium does not appreciably change the viscosity of the solvent system compared to ether (expt 2 and 5). The low ratio of straight-chain to cyclized product (expt 5) is indicative of the unfavorable combination of the 5-hexen-1-yl radical and •MgX caused by the inability of pentane to provide the needed assistance in solvation. Experiments 6 and 7 in conjunction with experiments 1 and 5 were designed to show that increasing the solvent basicity should increase the reactivity of the 5-hexen-1-yl radical with •MgX. When 2 molar equiv of THF (relative to **1**) were added to pentane (expt 6), slightly more reaction took place due to the slightly increased basicity of the solvent system imparted by the THF. The relative amount of cyclized product dropped substantially compared to that obtained in pure pentane because the combination of the 5-hexenyl-1-yl radical with •MgX is assisted more by solvation. When the molar ratio of THF to pentane was increased to 1:1 (expt 7), the reactivity of RX with the magnesium was increased substantially because of the solvent's overall increased basicity. The lower yield of **2** and **2′** (expt 1, 7) indicates that the basicity of the solvent system is not equal that of pure THF. The lower yield of **3** and **3′** and the elevated production of dimers relative to expt 1 is indicative of the viscosity effects explained previously.

Toluene is a solvent of approximately the same viscosity as THF. Toluene does exhibit some basic properties due to the presence of π-electrons in the aromatic ring—indeed there is growing evidence of the stabilization of radicals by aromatic solvents.[14] Toluene with 2 equiv of THF (expt 3) behaves similarly to pure ether (expt 2) and very differently from pentane with 2 equiv of THF (expt 6). These results are due to the increased stabilization of the radicals in toluene–THF compared to pentane–THF. The stabilized radicals are thus constrained to react immediately with •MgX, but rather react to form dimers thus lowering the yield of **2′** and **3′** (expt 1, 3). Toluene with 2 equiv of THF is more viscous than pure ether; however, since the formation of **2′**, **3′**, and dimers is nearly the same (expt 2, 3), it is concluded that basicity of the solvent is more important than viscosity in product formation.

The reaction of alkyl halides with magnesium in HMPA represents an extreme case of solvation and basicity. The very high polarity of HMPA stabilizes the 5-hexen-1-yl radical and •MgX to such an extent that their combination is negligible. Instead a large percentage of the 5-hexen-1-yl radical either was trapped by hydrogen atom donation, dimerized to the straight-chain hydrocarbon, or disproportionated to give the diene and **2**. The high viscosity of HMPA also slowed the cyclization of the 5-hexenyl radical to the extent that there was a decrease in yield of **3** and the dimers containing the cyclopentylmethyl moiety.

All of the reaction mixtures were analyzed by quenching with D_2O. The deuterium incorporation was then considered to be a measure of the Grignard reagent formed from the straight-chain and cyclized alkyl radical. The sum of the cyclized, dimerized, and hydrogen-atom-trapped

Table X. Time Study of the Reaction of Bromooctane with Magnesium in the Presence of 2 Equiv of DCPH[a]

	time, h			% deuterium incorporation
1[b]	0.5	97.6	0	
2	0.5	7.8	84.9	80.5
3	1.0	0	96.1	74.8
4	16.0	0	92.0	74.0
5	60.0	0	92.0	74.3

[a] Reaction in THF at 22 °C with sonication. [b] The bromooctane/DCPH solution was monitored for a half hour in order to determine its stability apart from the magnesium.

products were assumed to represent the minimum amount of radical present in the reaction since these products are the result of radical processes. With this in mind, it was thought that the addition of a radical trapping agent would give an even better measure of the percent of the reaction that proceeded through a radical that had escaped the surface of the magnesium and then returned to form Grignard reagent. Dicyclohexylphosphine (DCPH), which donates a hydrogen atom much more readily than THF, was employed as the trapping agent. It was necessary, however, to first determine the stability of DCPH in the presence of an alkyl halide and Grignard reagent, so that the protium incorporated products could be definitely linked to a radical process and not a side reaction. Table X shows the results of the reaction of bromooctane with magnesium in THF when 2 equiv of DCPH were added. Entry 1 shows that DCPH was nonreactive with bromooctane and entries 2 thru 5 show that DCPH also does not react with the Grignard reagent during the reaction or after the reaction is completed. This information should substantiate the premise that DCPH trapping is a better estimate of the portion of radicals **2$^\bullet$** and **3$^\bullet$** that diffuse to distance d (where trapping takes place). It is important now to return to Table IX, expt 8. The lowered d_1 in **2**, the almost nil d_1 in **3**, and the complete lack of dimer products all point to the conclusion that the radicals that diffuse from the surface of the magnesium are effectively trapped by DCPH before they can dimerize or return to the surface to form Grignard reagent. Interestingly, the formation of 4.7% cyclized hydrocarbon indicates that cyclization is taking place on or very near the surface of the magnesium since the cyclized radical is so effectively trapped in solution. Without this assumption, the straight-chain radical leaving the surface should be trapped before it can cyclize (compare expt 1 and 8, Table IX). Thus, in the reaction of 6-bromo-1-hexene with magnesium, the data (Table IX, expt 8) indicate that the radicals that escaped the magnesium surface are trapped by DCPH. Thus in this case it appears that, of the Grignard formed in this reaction, a minimum of ~25% is a result of radicals that diffuse into the solution and then return to the magnesium surface.

Experimental Section

Materials and Apparatus. Anhydrous tetrahydrofuran (THF) from Fisher was distilled from sodium aluminum hydride ($NaAlH_4$) under dried and deoxygenated nitrogen. Anhydrous diethyl ether from Fisher, HPLC grade pentane from Aldrich, and anhydrous toluene from Fisher were distilled under nitrogen from deep blue solutions of sodium benzophenone ketyl. Hexamethylphosphoramide (HMPA) from Fisher was distilled from sodium at reduced pressure. Dicyclohexylphosphine (DCPH) was distilled from calcium hydride (CaH_2) at reduced pressure. Samples of 1-heptene, heptane, 1-hexene, and methylcyclopentane were obtained from Aldrich and distilled over CaH_2. Authentic samples of 1,5-hexadiene (99.9%), *cis*- and *trans*-1,5-heptadiene (99+%), 1,6-heptadiene (99+%), and *cis*- and *trans*-1,2-dimethylcyclopentane (99+%) were obtained from Wiley and used as received. 5-Hexen-1-ol (98%), 5-bromo-1-pentene (98%), and 6-bromo-1-hexene (98%) were obtained from Wiley and distilled under nitrogen from CaH_2. An authentic sample of 5,5-dimethyl-1-hexene was obtained as previously described.[22] A sample of 1,1,3-trimethylcyclopentane was obtained by preparative GLC using a 6 ft Carbowax $^1/_4$ in. column and gave spectra identical with those previously reported.[23] Deuterium oxide (D_2O) was obtained from Aldrich (99.8%) and used as received. Acetaldehyde and acetone were obtained from Aldrich and distilled from CaH_2 and P_2O_5, respectively, under nitrogen. Samples of 1,11-dodecadiene, 7-cyclopentyl-1-heptene, and 1,2-dicyclopentylethane were prepared as previously reported.[6d] A sample of 6-bromo-5,5-dimethyl-1-hexene was prepared as previously reported.[23]

General Procedures and Analytical Methods. Reactions were performed under an atmosphere of nitrogen that was deoxygenated with R3-11 catalyst and dried by using molecular sieves. Calibrated syringes equipped with stainless steel needles and stainless steel cannulas were used to transfer reagents. Glassware was assembled hot and flamed under a high vacuum and then flushed with nitrogen. This vacuum and flush procedure was repeated at least twice more and the glassware was then allowed to cool under nitrogen.

Reactions were carried out in round-bottom flasks equipped with stopcocks attached with 14/20 standard taper joints to allow a nitrogen flush while reagents were being added or removed. Reactions were sonicated by immersing the reaction flask in a Bransonic 1200 sonicator or were stirred with a magnetic stirring bar in the reaction flask. The reactions were quenched by the slow addition of D_2O, washed with either saturated NH_4Cl or dilute HCl and saturated NaCl, and then analyzed by GLC.

Analyses were conducted with either of the following: column A, Varian 3700 equipped with a FID using a 30-m DB-1 capillary column with a programmed temperature (30 °C for 5 min, rising 10° per min to 250 °C for 5 min) and He flow pressure of 40 psi; column B, F&M 700 equipped with a FID using a 10 ft × $^1/_8$ in. column packed with 10% Na_2SO_4 on alumina at a temperature of 150 °C and a N_2 flow pressure of 40 psi. Quantitative GC analyses were obtained with response corrected peak areas by using heptane as an internal standard.

Proton NMR were recorded on a Varian T-60 with shifts reported relative to TMS. Mass spectra were obtained on a Varian MAT 112 S spectrometer coupled with a Varian 3700 GC. Deuterium incorporation analyses were obtained on a VG Analytical 70-Se mass spectrometer coupled with a HP 5890 GC.

1-Hexene, 1,5-hexadiene, methylcyclopentane, 1,11-dodecadiene, 7-cyclopentyl-1-heptene, 1,2-dicyclopentylethane, 1-heptene, *cis*- and *trans*-1,2-dimethylcyclopentane, 6-methyl-1-heptene, 1,1,2-trimethylcyclopentane, 5,5-dimethyl-1-hexene, 1,1,3-trimethylcyclopentane, 6-chloro-1-hexene, 6-bromo-1-hexene, 6-iodo-1-hexene, 6-bromo-1-heptene, 6-chloro-6-methyl-1-heptene, and 5,5-dimethyl-1-hexene were analyzed on column A. 1,6-Heptadiene and *cis*- and *trans*-1,5-heptadiene were analyzed and 1-hexene, 1,5-hexadiene, methylcyclopentane, 1-heptene, *cis*- and *trans*-1,2-dimethylcyclopentane, 6-methyl-1-heptene, 1,1,2-trimethylcyclopentane, 5,5-dimethyl-1-hexene, and 1,1,3-trimethylcyclopentane were reanalyzed on Column B.

Preparations. *p*-Toluenesulfonate of 1-Hexen-6-ol. To 50 mL of pyridine at 0 °C was added 32.6 g of *p*-toluenesulfonyl chloride (previously recrystallized from hexane) and to 25 mL of pyridine at 0 °C was added 10.0 g of 1-hexen-6-ol. The two solutions were then mixed and kept at 0 °C for 4 h to give complete conversion to the *p*-toluenesulfonate. The solution was added to a 100-mL mixture of dilute HCl and ice and then extracted with pentane. The organic layer was washed with dilute HCl until acidic, washed with saturated $NaHCO_3$ and saturated NaCl, and dried over $MgSO_4$, and the pentane was removed under vacuum to leave 20.2 g of a yellow oil upon which no further purification was performed.

5-Chloro-1-hexene. Ten grams of the *p*-toluenesulfonate of 1-hexen-6-ol and 2.0 g of LiCl were added to 75 mL of acetone in a 100-mL round-bottom flask fitted with a reflux condenser

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[23] Ashby, E. C.; DePriest, R. N.; Goel, A. B. Wenderoth, B.; Pham, T. N. *J. Org. Chem.* 1984, *49*, 3545.

and allowed to stir at 50 °C under nitrogen for 48 h. The mixture was then cooled and added to 150 mL of pentane, washed with water and saturated NaCl, and dried over $MgSO_4$, and the pentane was removed under vacuum to yield 3.5 g of the title compound. This liquid was distilled from CaH_2 at 127–128.5 °C and atmospheric pressure to give 99+% pure 6-chloro-1-hexene, which exhibited the following spectra: ^{1}H NMR δ 0.8–2.7 (m, 6 H), 3.5 (t, 2 H), 4.8–6.1 (m, 3 H); MS, m/e (relative intensity) 120 (6.25), 118 (26.7), 106 (13.6), 92 (16.5), 91 (25.6), 90 (51.7), 83 (40.3), 82 (100), 67 (17.7), 55 (68.8), 41 (69.9).

5-Iodo-1-hexene. To 120 mL of acetone were added 2 mL of 6-bromo-1-hexene and 10 g of NaI, and then the solution was stirred at 60 °C for 3 h. The solution was cooled and filtered, and the filtrate was washed twice with 50 mL of ether, which was added to the supernatant liquid in addition to 100 mL more of ether. This solution was subjected to a workup similar to that used for the chloro compound and yielded 1.8 g of the title compound in 99% purity. The product exhibited the following characteristics: bp 58.9–60 °C at 18 mmHg; ^{1}H NMR δ 1.2–2.3 (m, 6 H), 3.15 (t, 2 H), 4.8–6.1 (m, 3 H); MS, m/e (relative intensity) 210 (0.69), 155 (0.43), 128 (0.52), 127 (1.44), 83 (20.6), 55 (62.4), 41 (100).

1-Hepten-6-ol. Ten grams of 5-bromo-1-pentene was converted to its respective Grignard reagent by the slow addition of a solution of the bromide in 100 mL of THF to 2.5 g of magnesium turnings. The magnesium was previously activated by adding to it 5 mL of THF and 0.5 mL of bromoethane and sonicating this mixture for 1 h. This solution was then removed from the activated magnesium under nitrogen pressure via a cannula and then the solution of the pentenyl bromide was added slowly over an hour while sonicating and maintaining the temperature at roughly 25 °C. After the addition was complete, the reaction flask was sonicated for an additional 3 h. Ten milliliters of acetaldehyde in 10 mL of THF was added slowly while the temperature was kept low by adding ice to the sonicator's water bath. The reaction mixture was quenched with 100 mL of saturated NH_4Cl and then diluted with 400 mL of ether. The liquid was decanted from the remaining magnesium and the organic layer was subjected to a workup similar to that previously described and then dried over $MgSO_4$. The ether and most of the THF was removed under vacuum and the residual liquid was distilled at 74–76 °C and 23 mmHg to give 7.2 g of the title compound, which exhibited the following spectral data: ^{1}H NMR δ 0.97–2.4 (m, 10 H), 3.8 (br, 1 H), 4.8–6.2 (m, 3 H).

***p*-Toluenesulfonate of 1-Hepten-6-ol.** To 50 mL of pyridine were added 10 g of 1-hepten-6-ol and 19 g of tosyl chloride in a procedure analogous to that described for the *p*-toluenesulfonate of 1-hexen-6-ol. This procedure yielded 23 g of the title compound, which exhibited the following spectral data: ^{1}H NMR δ 0.97–2.2 (m, 10 H) 2.4 (s, 3 H), 4.5–6.2 (m, 3 H), 7.25–7.8 (m, 4 H); MS (CI), m/e (relative intensity) 269 (100), 213 (5.89), 193 (17.05) 187 (1.00), 173 (18.43), 157 (2.55), 153 (14.76).

6-Bromo-1-heptene. In a procedure analogous to that described for 5-chloro-1-hexene, 8.0 g of the tosylate of 1-heptene-6-ol and 20.4 g of LiBr in 50 mL of acetone produced the title compound. The 4.5 g that resulted from its distillation at 59–61 °C and 17 mmHg exhibited the following characteristics: ^{1}H NMR δ 1.2–2.3 (m, 9 H), 3.8–4.2 (m, 1 H), 4.8–6.3 (m, 3 H); MS, m/e (relative intensity) 178 (0.57), 176 (0.54), 97 (23.03), 96 (20.01), 81 (30.36), 55 (100).

2-Methyl-1-hepten-6-ol. Ten grams of 5-bromo-1-pentene was converted to its respective Grignard reagent with 2.5 g of magnesium turnings in 100 mL of THF, which was then allowed to react with excess acetone in a procedure similar to that described for 1-hepten-6-ol. This procedure yielded 6 g of the title compound, which exhibited the following characteristics: bp 48.9–50 °C at 11 mmHg: ^{1}H NMR δ 1.2 (s, 6 H), 1.4–1.8 (m, 6 H), 1.9–2.3 (br, 1 H), 4.7–6.1 (m, 3 H); MS, m/e (relative intensity) 113 (0.14), 95 (1.92), 81 (1.47), 69 (3.51), 59 (85.17), 55 (11.80), 43 (100).

6-Chloro-6-methyl-1-heptene. To 2 g of $ZnCl_2$ in 2 mL of concentrated HCl in a separatory flask was added 1 mL of 6-methyl-1-hepten-6-ol at 0 °C. The mixture was kept cold while shaking by rolling the flask in an ice bath intermittently. To the mixture were added 10 g of ice and 50 mL of hexane. The organic layer was subjected to a standard workup, dried over $MgSO_4$, and concentrated by removing the solvent under vacuum. Distillation of the crude product yielded 1 g of the title compound, which had the following characteristics: bp 55–56 °C at 21.5 mmHg; ^{1}H NMR δ 1.6 (s, 6 H), 1.62–2.4 (m, 6 H), 4.8–6.1 (m, 3 H).

General Experimental Procedures. All reactions were performed under completely identical conditions unless otherwise stated. The requisite amount of each alkyl halide was transferred by syringe into a dry, nitrogen-filled, preweighed volumetric flask. The appropriate amount of internal standard was then transferred by syringe into the flask, which was then filled to the mark with the desired solvent and additive. The magnesium was weighed on an analytical balance and then placed into the hot reaction flask immediately before it was assembled. The flask was then flamed while under vacuum and then refilled with oxygen-free, dry nitrogen. This procedure of evacuation and flushing was repeated at least twice. After the reaction flask had cooled, 1.0 mL of THF was added to the magnesium and 0.1 mL of bromoethane was added via syringe in order to activate the magnesium. The reaction flask was then immersed into the sonicator's water bath and sonicated for a half hour. The activated solution was then removed from the flask by using positive nitrogen pressure and a cannula.

The solution of the appropriate alkyl halide was then transferred with the use of positive nitrogen pressure and a cannula from the volumetric flask to the reaction vessel. For experiments above room temperature, the reaction flask was fitted with a reflux condenser and maintained under a positive pressure with the use of an oil bubbler. For experiments conducted at room temperature, the reaction flask was sealed at the stopcock and maintained at the stated temperature. All experiments were carried out at 22 °C with sonication for 3 h unless otherwise stated.

Quenching the reaction mixtures at various times entailed either the direct slow addition of D_2O to the reaction flask or the removal of an aliquot of the supernatant liquor via a syringe and slowly adding it to a vile of D_2O under dry nitrogen.

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