thoroughly extracted with benzene. The combined extracts were washed twice with water and once with saturated brine, and dried over anhydrous magnesium sulfate. Removal of the solvent under reduced pressure afforded a quantitative yield of (±)-seychellene (1). An analytical sample was obtained by preparative glc (column D, 225°, 200), and exhibited spectral data (ir, pmr) and glc retention time (column E, 180°, 90) identical with those of authentic (−)-seychellene: ir (film) 3.26, 6.11, 11.42 μ; pmr τ 5.23, 5.41 (d, d, 2, J = 1.5 Hz, =CH_2), 7.78 (m, 1, -CHC=CH_2), 9.06, 9.19 (s, s, 6, tertiary methyls), 9.27 (d, 3, J = 6.5 Hz, secondary CH_3).

Mol Wt: Calcd for $C_{15}H_{24}$: 204.188. Found (high-resolution mass spectrometry): 204.188.

Acknowledgments. Financial support from the National Research Council of Canada and the University of British Columbia Committee on Research is gratefully acknowledged. W. de W. is indebted to the National Research Council of Canada for a studentship.

Organometallic Reaction Mechanisms.
V. The Mechanism of Dialkylmagnesium Addition to Ketones[1]

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Contribution from the School of Chemistry, Georgia Institute of Technology, Atlanta, Georgia 30332. *Received September 26, 1970*

Abstract: The kinetics of the reaction of $(CH_3)_2Mg$ with excess 2-methylbenzophenone was followed spectroscopically by observing the disappearance of absorption bands attributed to complexes of organomagnesium compounds with the ketone and by directly observing the appearance of the product. By using a large excess of ketone, the kinetic order of the organomagnesium species was determined unambiguously to be first order. The reaction of $(CH_3)_2Mg$ with excess ketone was found to consist of a series of pseudo-first-order reactions involving the formation of two intermediate products prior to the formation of the final product

$$\text{reactants} \longrightarrow P_1 \xrightarrow{\text{ketone}} P_2 \xrightarrow{\text{ketone}} P_3 \text{ (final product)}$$

Quenching studies at definite intervals during the reaction have established the formulas of P_1, P_2, and P_3 to be $[CH_3MgOR]_2$, $[CH_3MgOR \cdot Mg(OR)_2]$, and $[Mg(OR)_2]$, respectively (where R = $C(C_7H_7)(C_6H_5)CH_3$). Complexes between the ketone and P_1 and P_2 were observed spectroscopically. The kinetic data can be interpreted in terms of the reaction proceeding through complex formation between the ketone and the organomagnesium species, or in terms of a bimolecular collision not involving the complex. An abbreviated description of the proposed mechanism proceeding through complex can be found below and a more detailed description can be found in the main body of this paper (eq 22–28). The mechanism is as follows: (1) $(CH_3)_2Mg + K \rightleftarrows C \rightarrow P_1$, (2) $P_1 + K \rightleftarrows C_1 \rightarrow P_2$, (3) $P_2 + K \rightleftarrows C_2 \rightarrow P_3$, where K = ketone (2-methylbenzophenone), C = complex between $(CH_3)_2Mg$ and K, $P_1 = (CH_3MgOR)_2$, C_1 = complex between P_1 and K, $P_2 = CH_3MgOR \cdot Mg(OR)_2$, C_2 = complex between P_2 and K, and $P_3 = [Mg(OR)_2]_2$.

The mechanisms of organomagnesium alkylation reactions have been the subject of intensive study for the past decade. In spite of considerable efforts on the part of several groups, there is still no general agreement concerning the manner in which these reactions occur. The principle areas of dispute basically involve the kinetic order of these reactions in organomagnesium reagent, the nature of the reactive species in those cases where several species exist in equilibrium, the exact nature of the alkyl transfer steps, whether they take place by complex formation or by direct bimolecular collision, and finally it is not clear at this time whether the reaction proceeds by a single electron transfer or polar mechanism.

The mechanism receiving the most attention in recent years has been the alkylation of ketones by Grignard reagents. Several mechanisms have been proposed for this reaction. The mechanism proposed by Swain[3] and others[4-6] envisions the rapid formation of a complex between Grignard reagent and ketone followed by a rate-determining attack of a second molecule of Grignard reagent to form product. The dimer mechanism proposed by Bikales and Becker[7] suggests that ketone is attacked by $R_2Mg \cdot MgX_2$ in a bimolecular reaction. This mechanism was supported by the finding that the reaction was initially second order, although rate constants were consistent within each run for only 30% reaction of one alkyl group. Smith and coworkers[8] have offered evidence that Grignard reagents and ketones react immediately to form a complex which then rearranges intramolecularly to give product. The position of Smith and coworkers is supported by a plot of the pseudo-first-order rate constants *vs.* Grignard concentration which is linear for low complex concentrations and extrapolates through the origin. The fact that pseudo-first-order rate constants increase with Grignard concentration is not consistent with the proposed mechanism; however, this observation in regions where all ketone is complexed is justified by Smith by invoking a linear medium effect in order to obtain an empirical fit to the data. It was also not possible for Smith and

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[1] We are indebted to the National Science Foundation (Grant No. SP-14795) for partial support of this work.

[2] To whom all inquiries should be sent.

[3] C. G. Swain and H. B. Boyles, *J. Amer. Chem. Soc.*, 73, 870 (1951).

[4] M. Anteunis, *J. Org. Chem.*, 26, 4214 (1961).

[5] E. C. Ashby, R. B. Duke, and H. M. Neumann, *J. Amer. Chem. Soc.*, 89, 1964 (1967).

[6] (a) I. Koppel, L. Margua, and A. Tuulmets, *Reakts. Sposobnost. Org. Soedin.*, 5, 1041 (1968); (b) A. Tuulmets, *ibid.*, 6, 854 (1969).

[7] N. M. Bikales and E. J. Becker, *Can. J. Chem.*, 41, 1329 (1963).

[8] (a) S. C. Smith and G. Su, *J. Amer. Chem. Soc.*, 88, 3995 (1966); (b) J. Billet and S. C. Smith, *ibid.*, 90, 4108 (1968).

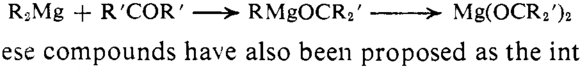
coworkers to determine from their data the reactive species ($RMgX$, R_2Mg, $R_2Mg \cdot MgX_2$) or the exact nature of alkyl transfer. Holm[9] agreed with the earlier proposal by Smith that Grignard reagents and ketones form complexes; however, he further proposed that product formation occurs by bimolecular collision of either ether-solvated Grignard reagent or ketone-solvated Grignard reagent with free ketone. Holm's proposal is based primarily on the fact that the reaction of butylmagnesium bromide with excess acetone leads to extremely high and continuously increasing rates, implying that acetone-solvated butylmagnesium bromide is approximately as reactive toward free acetone as is ether-solvated butylmagnesium bromide.[10]

All workers in the area of Grignard ketone mechanisms have recognized the importance of understanding the mechanism of dialkylmagnesium addition to ketones since dialkylmagnesium is a reactive species in Grignard reagents. Several workers have investigated

$$2RMgX \rightleftharpoons R_2Mg + MgX_2 \qquad (1)$$

the kinetics of the reaction of dimethylmagnesium with ketones and suggested mechanisms as diverse as those proposed for the Grignard ketone mechanism.[7,9,11] It is interesting and somewhat amusing to note that the mechanism suggested for the addition of dimethylmagnesium to ketones by each worker coincides with his proposed mechanism for the addition of methyl Grignard reagents to ketones. For example, Anteunis[4,11a] reported that both the addition of methyl Grignard reagents and dimethylmagnesium are overall third-order kinetic processes (second order in organomagnesium reagent). Bikales and Becker[7] found that the reaction of dimethylmagnesium and benzophenone gave a second-order fit for the first 30% of the first methyl group. Smith[11b] offers evidence that dimethylmagnesium and ketone form a complex which rearranges intramolecularly to form product, whereas Holm[9] cites evidence by House and Oliver[11c] against a rearrangement mechanism for the reaction of benzophenone with dimethylmagnesium. Perhaps the most convincing evidence regarding the order of the reaction of dimethylmagnesium with benzophenone is provided by House and Oliver.[11c] Several one-point kinetic runs were made at various concentrations of each substance and at various initial ratios of dimethylmagnesium to benzophenone greater than or equal to two. The extent of reaction at quenching varied from 14 to 63% and several integral order fits were attempted. Although rate constants for a second-order fit varied by as much as 30%, they were much superior in agreement to all other fits attempted.

An interesting and important aspect of the reaction of dialkylmagnesium compounds with ketones concerns the nature and role of the intermediate $RMgOR'$ compound formed in the reaction



$$R_2Mg + R'COR' \longrightarrow RMgO\overset{R}{C}R_2' \xrightarrow{R'COR'} Mg(O\overset{R}{C}R_2')_2 \qquad (2)$$

These compounds have also been proposed as the intermediate formed in reactions of Grignard compounds with ketones.[12,13] For the reasons suggested and because of our interest in $RMgOR'$ compounds as stereoselective alkylating agents, the elucidation of the mechanism of $RMgOR'$ addition to ketones was also considered to be important.

House and coworkers[14] have prepared CH_3MgOR compounds by three methods: the reaction of $(CH_3)_2Mg$ with alcohols; the reaction of $(CH_3)_2Mg$ with ketones; and the redistribution of $(CH_3)_2Mg$ with $Mg(OR)_2$. The association of several $RMgOR'$ compounds in various solvents has been examined by Coates and coworkers.[15] They report these compounds to be tetramers in diethyl ether when R′ is small (C_2H_5–, *tert*-C_4H_9–) and dimers when R′ is large [$(C_2H_5)_3C$–, $CH_3(C_2H_5)_2C$–].

The mechanism of the reaction of alkylmagnesium alkoxides with ketones has received little attention. Early workers reported that the second methyl group of dimethylmagnesium did not react with ketones even after prolonged reaction times.[11a,16] House and Respess[17] in an investigation of the reaction of $(CH_3)_2Mg$ and $CH_3MgOC(C_2H_5)_2CH_3$ with 4-*tert*-butylcyclohexanone found that the ratio of cis:trans carbinol products differed depending on the methylating agent. From this they concluded that $(CH_3)_2Mg$ is not the reactive species in the methylation of ketones by $CH_3MgOC(C_2H_5)_2CH_3$.

In view of the importance of understanding the mechanism by which Grignard reagents, R_2Mg and $RMgOR$ compounds, alkylate ketones, we undertook a detailed study of the reaction of $(CH_3)_2Mg$ with excess 2-methylbenzophenone. Although kinetic studies involving excess ketone in organomagnesium reactions have not been reported previously, this method made it possible to eliminate the kinetic dependence on ketone thereby allowing the determination of the kinetic order of $(CH_3)_2Mg$ in ketone alkylation reactions. In addition we were also able to determine the kinetics of CH_3MgOR alkylation of 2-methylbenzophenone.

The ketone 2-methylbenzophenone was chosen for these studies because it reacts with $(CH_3)_2Mg$ at a rate convenient for kinetic measurements and because it cannot enolize. Dimethylmagnesium and methylmagnesium alkoxide have been shown to alkylate 2-methylbenzophenone in quantitative yield.

Experimental Section

Materials. Single-crystal magnesium from Ventron Corporation was milled with a carbide tool. The turnings were washed several times with diethyl ether prior to use. Dimethylmagnesium was prepared by allowing an excess of magnesium turnings to stir slowly overnight with dimethylmercury (Strem Chemicals, Inc.). The resulting dimethylmagnesium was extracted with diethyl ether and stored in a glass flask equipped with a three-way Teflon stopcock.[18] Magnesium analysis of $(CH_3)_2Mg$ was carried out by both the Gilman and EDTA methods and gave a C–Mg:Mg ratio of 2.02:1.00. Thioacetamide tests for ionic Hg on hydrolyzed samples of $(CH_3)_2Mg$ were negative.

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[9] T. Holm, *Acta Chem. Scand.*, **23**, 579 (1969).

[10] T. Holm, *ibid.*, **20**, 1139 (1966).

[11] (a) M. Anteunis, *J. Org. Chem.*, **27**, 596 (1962); (b) S. G. Smith and J. Billet, *J. Amer. Chem. Soc.*, **89**, 6948 (1967); (c) H. O. House and J. E. Oliver, *J. Org. Chem.*, **33**, 929 (1968).

[12] H. O. House and D. D. Traficante, *ibid.*, **28**, 355 (1963).

[13] E. C. Ashby, F. Walker, and H. M. Neumann, *Chem. Commun.*, 330 (1970).

[14] H. O. House, R. A. Latham, and G. M. Whitesides, *J. Org. Chem.*, **32**, 2481 (1967).

[15] G. E. Coates, J. A. Heslop, M. E. Redwood, and D. Redley, *J. Chem. Soc. A*, 1118 (1968).

[16] J. G. Aston and S. A. Bernhard, *Nature (London)*, **165**, 485 (1950).

[17] H. O. House and W. L. Respess, *J. Org. Chem.*, **30**, 301 (1965).

[18] E. C. Ashby and R. Arnott, *J. Organometal. Chem.*, **14**, 1 (1968).

Eastman highest purity 2-methylbenzophenone was distilled under vacuum from Linde 4A Molecular Sieve. The middle fraction (bp 130° (0.03 mm)) was used in the kinetic studies. Glpc analysis of the distilled material showed it to be better than 99.9% pure. Diethyl ether solutions of 2-methylbenzophenone were stored in a glove box and carefully shielded from light.

Eastman reagent grade 9-fluorenone was used as a glpc standard without further purification.

Fisher reagent grade anhydrous diethyl ether was distilled under nitrogen from $LiAlH_4$ prior to use.

Apparatus and Procedure. A Cary Model 14 recording spectrophotometer was used for recording visible spectra over a number of wavelengths. In the kinetic studies, a Zeiss PMQII single-beam spectrophotometer was used for making absorbance measurements at a single wavelength. A Pyrex 10-mm sample cell was used in conjunction with a quartz 10-mm reference cell for obtaining visible spectra.

An F & M Model 700 flame ionization gas chromatograph equipped with dual 6-ft $^{1}/_{8}$-in. stainless steel 10% Carbowax 20M columns was used to identify products.

All transfers of materials used in this study were performed in a glove box equipped with a recirculating system described elsewhere.[19] As an added precaution, a special line for prepurified nitrogen was added to the glove box and all materials were transferred in Schlenk tubes under a blanket of prepurified nitrogen.[20]

Calibrated syringes equipped with stainless steel needles were used for transfers of reagents. Deliveries could be reproduced to better than ±0.5%.

Solutions of 2-methylbenzophenone were prepared by adding a known amount of ketone from a calibrated syringe to a calibrated volumetric flask and diluting to the mark with diethyl ether. The concentration of 2-methylbenzophenone could then be easily determined from its density, 1.079, and the total volume of solution.

For obtaining visible spectra of reacting mixtures and for kinetic studies, accurate amounts of standard $(CH_3)_2Mg$ solutions were injected into known volumes of ketone solution with a Hamilton 100-μl syringe. The concentration of $(CH_3)_2Mg$ in the reacting solutions was determined by the dilution factor. For the product study, larger amounts of standard $(CH_3)_2Mg$ solution were injected with a 1-ml syringe.

Visible Spectra and Kinetics. Diethyl ether solutions of 2-methylbenzophenone show negligible absorbance in the 400–600-mμ region of the visible spectrum, although concentrated solutions of ketone absorb strongly at wavelengths shorter than 390 mμ. Diethyl ether solutions of $(CH_3)_2Mg$ show no absorbance in the visible spectrum.

Visible spectra of mixtures of $(CH_3)_2Mg$ with excess 2-methylbenzophenone were obtained in the following fashion. A Pyrex visible spectrum cell equipped with a 1-mm bore two-way Kimax micro-Teflon stopcock was filled with a known volume of standard ketone solution in the glove box. The stopcock was closed and the cell was placed in the chamber of the Cary 14 spectrophotometer along with a reference quartz cell filled with diethyl ether. The spectrum of the ketone solution was then scanned between 400 and 600 mμ. The wavelength was then set at 400 mμ, the cell stopcock opened, and a small amount (10–80 μl) of standard $(CH_3)_2Mg$ injected. The cell was shaken rapidly to ensure mixing, and the spectrum was rapidly scanned between 400 and 600 mμ. When $(CH_3)_2Mg$ is mixed with solutions of excess 2-methylbenzophenone, the intensity of the initially observed absorbance band is low, but rapidly increases with time in the 400–550-mμ region. No distinct peak occurs in the spectrum although the intensity of the absorbance decreased sharply with increasing wavelength. The absorbance at each wavelength rises with time to a maximum, and thereafter the absorbance declines very slowly. The reacting solutions appear yellow to the unaided eye and the yellow color fades with time.

The procedure for initiating reaction for the kinetic studies was similar to that for obtaining visible spectra. The reference and sample cells were placed in the jacketed cell holder of the Zeiss spectrophotometer. The cell chamber and cell holder were maintained at 20 ± 0.1° by means of a Haake constant-temperature recirculator. The temperature was monitored in the water reservoir of the recirculator.

After a suitable amount of time was allowed for the cells to come to temperature equilibrium, the sample cell was removed and a known small amount of standard $(CH_3)_2Mg$ solution was injected. The cell was rapidly shaken and placed in the chamber. The instrument was maintained in such a fashion that readings could be taken immediately. The total time between the initial injection and the first reading was generally 10 sec. Measurements were made at 410 mμ.

Product Analysis. An authentic sample of 1-(2-methylphenyl)-1-phenylethylene was prepared in the following manner. Two milliliters (2.16 g, 0.011 mol) of 2-methylbenzophenone was added slowly to a solution of 2.38 g (0.033 mol) of $(CH_3)_3Al$ in about 75 ml of benzene. The solution was allowed to reflux for 8 hr. The solution was slowly hydrolyzed with distilled water and then just enough 20% HCl was added to dissolve the aluminum salts. The solution was washed twice with saturated aqueous Na_2CO_3 and then twice with distilled water. The organic layer was then dried over anhydrous $MgSO_4$ and filtered. Glpc analysis of the filtrate showed two peaks at 195° on 6-ft Carbowax 20M columns, 1-(2-methylphenyl)-1-phenylethylene (8.2 min) and 1-(2-methylphenyl)-1-phenylethanol (38.7 min). Mixtures of the above sample with 2-methylbenzophenone (24 min) and 9-fluorenone (52.5 min) showed that the retention time of each was such that a mixture of all components could be easily separated.

To the remainder of the organic layer was added a few crystals of *p*-toluenesulfonic acid and the solution allowed to reflux for 18 hr over a Dean–Stark trap. The solution was then washed twice with saturated aqueous Na_2CO_3 and twice with distilled water, dried over anhydrous $MgSO_4$, and filtered. The benzene was removed under vacuum (0.02 mm) leaving a pale yellow, viscous liquid. Glpc analysis showed only a single peak at 8.2 min (1-(2-methylphenyl)-1-phenylethylene). The product was characterized by nmr and mass spectroscopy. The nmr spectrum showed a singlet peak at τ 8.03 (3.0), doublets at 4.90 (1.0) and 4.33 (1.0), and a complex aromatic multiplet centered at 2.86 (9). The mass spectrum showed a parent peak at mass 194, a small peak due to isotopic contributions at mass 195, and no peaks at higher masses.

Standard mixtures of 1-(2-methylphenyl)-1-phenylethylene and 9-fluorenone were prepared and subjected to gas chromatography to give the relationship, (area olefin)/(area 9-fluorenone) = 1.59(mol of olefin)/(mol of 9-fluorenone).

Two reactions were run in which samples were withdrawn and quenched at appropriate intervals and after 36 hr. The concentrations of ketone and $(CH_3)_2Mg$ in these two runs were the same as those employed in two selected kinetic runs which were followed spectroscopically. The purpose of these runs was to determine if the amount of product found at specific times during the course of the reaction would agree with the intermediates proposed on the basis of the kinetic experiments followed spectroscopically. The reactions were set up in the following way.

To a calibrated 50-ml volumetric flask, whose only entry was *via* a three-way Teflon stopcock, was added an appropriate amount of 2-methylbenzophenone, followed by dilution to the mark with diethyl ether. The flask was placed in a Sargent constant-temperature bath at 20° and allowed to come to temperature equilibrium. An appropriate amount of $(CH_3)_2Mg$ was rapidly injected under nitrogen flow to bring the amount of each component to the desired concentration and the flask was rapidly shaken to ensure mixing. Samples were withdrawn under nitrogen flow at appropriate times and quenched in ether-saturated 10% H_2SO_4. The diethyl ether layer of each quenched sample was transferred to a quartz uv cell and about 20 μl of saturated solution of 9-fluorenone in diethyl ether added. The concentration of 9-fluorenone in each sample was determined by visible spectroscopy (λ 410 mμ, $\epsilon = 144$, slit < 0.02 mm) and the samples were transferred to tubes containing anhydrous $MgSO_4$. A crystal of *p*-toluenesulfonic acid was added to each tube and the samples were vigorously shaken. The samples were then subjected to gas chromatography and 1-(2-methylphenyl)-1-phenylethylene was identified by comparison of its retention time with the authentic sample and was found to be the only product. The final yields for each run were calculated to be 103% for 0.339 *M* ketone and 0.0127 *M* $(CH_3)_2Mg$ and 99.2% for 0.662 *M* ketone and 0.0127 *M* $(CH_3)_2Mg$.

Calculations. Eight visible spectrum kinetic experiments were carried out at constant $(CH_3)_2Mg$ concentration and a tenfold variation of ketone concentration. Four experiments were carried out at a constant ketone concentration and an eightfold variation of the $(CH_3)_2Mg$ concentration. Approximately 30 individual points were taken during the course of each run and an infinity reading was taken after 24 hr. Rate constants were extracted graphically in a manner to be described.

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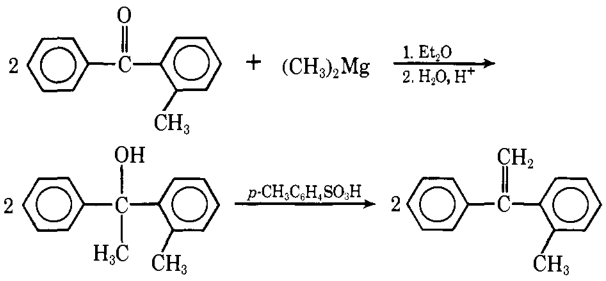
(19) T. L. Brown, D. W. Dickerhoof, D. A. Bafus, and G. L. Morgan, *Rev. Sci. Instrum.*, 33, 491 (1962).

(20) D. F. Shriver, "The Manipulation of Air Sensitive Compounds," McGraw-Hill, New York, N. Y., 1969.

In those experiments involving quenching of reaction mixtures, eight or nine points were taken as well as an infinity reading after 36 hr. The data are presented in Tables III and IV.

Results and Discussion

Dimethylmagnesium reacts with excess 2-methylbenzophenone to produce on hydrolysis the expected alcohol, 1-(2-methylphenyl)-1-phenylethanol, in quantitative yield based on the reaction of both methyl groups.



(3)

Kinetics. Solutions of $(CH_3)_2Mg$ in diethyl ether show no absorbance in the visible spectrum whereas concentrated solutions of 2-methylbenzophenone show a slight absorbance only in the 400–410-mμ region. Upon rapid mixing of solutions of $(CH_3)_2Mg$ and 2-methylbenzophenone, a strong absorbance appears in the 400–550-mμ region. The absorbance decreases with increasing wavelength with no maximum. The wavelength 410 mμ was suitable for kinetic studies since the intensity of the absorbance is sufficient to allow accurate measurements and the absorbance of concentrated solutions of 2-methylbenzophenone is negligible.

The reaction of $(CH_3)_2Mg$ with excess 2-methylbenzophenone in diethyl ether was studied by following directly the change in absorbance at 410 mμ with time. After mixing $(CH_3)_2Mg$ and ketone, the absorbance was low initially, increased rapidly to a maximum value, and then slowly decreased to a small infinite-time absorbance. The conclusion drawn is that the absorption is due to one or more intermediate products in the reaction, while the initial reactants and final product have relatively small absorption. The absorption is not attributed to the intermediate products themselves, but to colored complexes which they form with ketone. Plots of log abs *vs.* time for the early portion of the reaction showed that the absorbance just after the maximum absorbance (abs_{max}) gave a straight line for a long enough period of time that extrapolation of the line to zero reaction time could be carried out with confidence. Plots of log (extrapolated line − absorbance prior to abs_{max}) *vs.* time demonstrated that the initial fast reaction was resolvable into a first-order plot (Figure 1). The resolution of the fast reaction in this way demonstrates unequivocally the first-order kinetic dependence on dimethylmagnesium in its reactions with ketones. The reliability of the observed rate constant, k_1, was tested at constant excess ketone concentration over better than an eightfold range of dimethylmagnesium concentration and found to be independent of the concentration of $(CH_3)_2Mg$ (Table I).

Smith[11b] has shown in experiments using an excess of $(CH_3)_2Mg$ with 4-methylmercaptoacetophenone that the reaction is first order in ketone, and it was anticipated that the same dependence on ketone would be observed in these experiments using excess ketone. In order to verify the dependence on ketone concentration, the concentration of ketone was varied in several runs from 0.130 to 0.340 *M* at constant (0.0126 *M*) $(CH_3)_2Mg$ concentration. At ketone concentrations above 0.340 *M*, the reaction was so fast that k_1 could not be reliably determined. Thus if our interpretation of k_1 is correct, a first-order dependence on ketone can be demonstrated by a graph of k_1 *vs.* $[K]_0$ which should give a straight line which intersects the origin. Figure 2 shows that indeed the expected ketone dependence is observed.

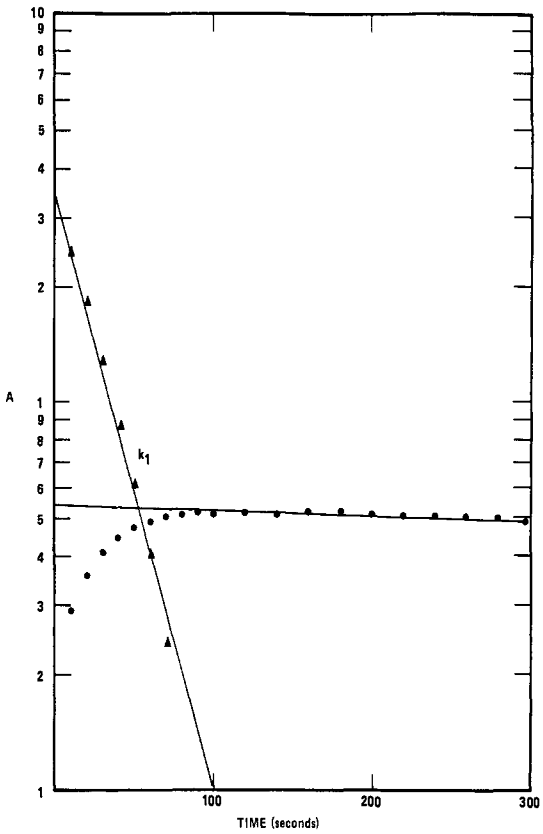


Figure 1. Graphical representation of the early portion of reactions showing abs_{max} and demonstrating the extraction of k_1, the first-order rate constant for the reaction of $(CH_3)_2Mg$ with 2-methylbenzophenone (data from run 1, Table IV).

Table I. Observed Rate Constants for the Various Organometallic Species Involved in the Reaction of Varying Amounts of $(CH_3)_2Mg$ with a Constant Excess of 0.309 *M* 2-Methylbenzophenone

Run	$[Me_2Mg]_0$	10^3k_1 sec^{-1}	10^3k_2 sec^{-1}	10^3k_3 sec^{-1}
1	0.00254	86.0	2.11	0.428
2	0.00634	86.4	1.89	0.468
3	0.0124	86.0	2.14	0.465
4	0.0203	75.3	1.99	0.447

The nature of the product formed in the initial fast reaction, *i.e.*, the product present at the time of the maximum absorbance (t_{max}), was investigated in independent experiments. Two reactions were carried out (Tables II and III) in which reaction samples were quenched as close to t_{max} as possible. These experiments show that at t_{max} one-half of the methylmagnesium groups have

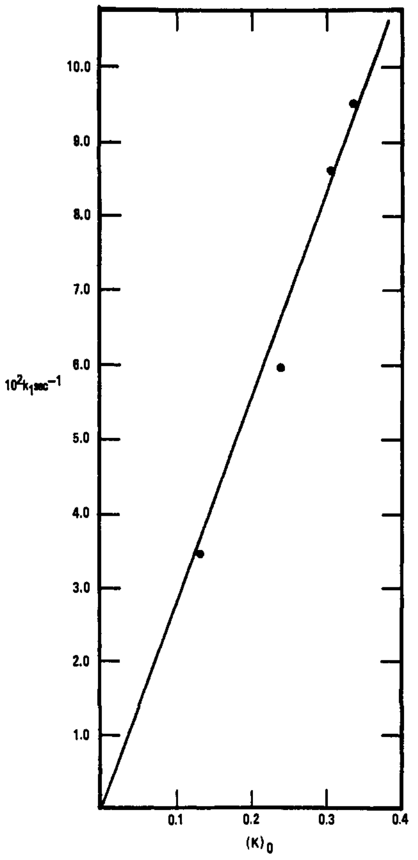
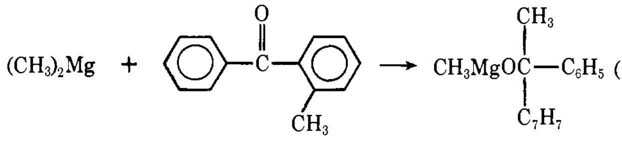


Figure 2. Plot of k_1 *vs.* initial ketone concentration for the reaction of 0.0126 *M* $(CH_3)_2Mg$ with 2-methylbenzophenone, demonstrating the reaction to be appropriately first order in ketone.

reacted. In addition to the above evidence, k_1 was found to be ten times greater than the initial rate constants for the reaction of methylmagnesium bromide



(4)

with excess 2-methylbenzophenone. This kind of rate difference between the reaction of $(CH_3)_2Mg$ and the methyl Grignard reagent with ketones is in good agreement with that observed by other workers.[9,11a,11b]

Table II. Comparison of the Rate of Product Formation for 0.339 *M* 2-Methylbenzophenone with 0.0127 *M* $(CH_3)_2Mg$[a] with Those Found by Glpc Analysis

	Olefin $M \times 10^2$	
Time, sec	Calcd	Found
0	0.00	0.00
50	1.33	1.36
209	1.51	1.48
403	1.67	1.67
599	1.79	1.79
2009	2.17	2.11
3000	2.32	2.24
3501	2.37	2.29
4002	2.40	2.32
∞(36 hr)	2.54	2.61

[a] As predicted by eq 6–9 and k_2 and k_3 from run 3, Table IV.

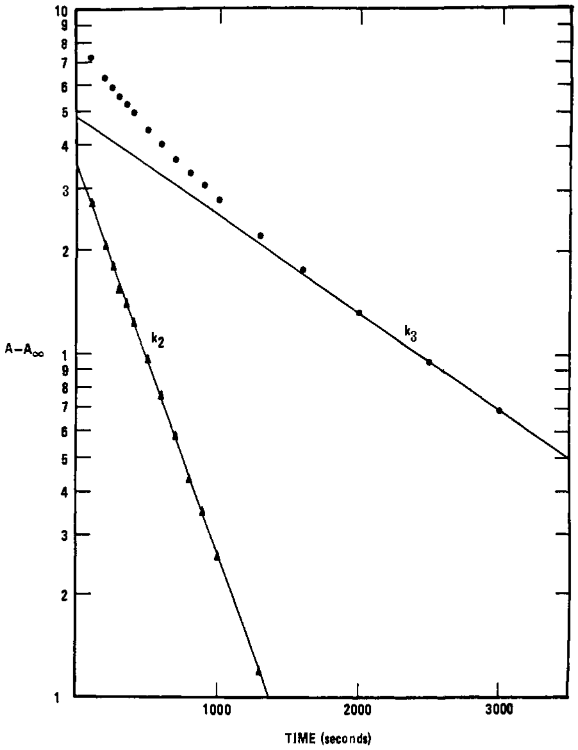


Figure 3. Plot of abs − abs$_\infty$ for the latter portion of the reaction of $(CH_3)_2Mg$ with excess 2-methylbenzophenone demonstrating the extraction of k_3 and the resolution of k_2 (data from run 6, Table IV).

For the slower portion of the reaction beyond abs$_{max}$, plots of log (abs − abs$_\infty$) *vs.* time were constructed. The curvature of these plots demonstrates that the reaction beyond abs$_{max}$ cannot be simply the reaction of CH$_3$MgOR [where R = 1-(2-methylphenyl)-1-phenylethyl], or any single organomagnesium species related to CH$_3$MgOR, reacting with ketone in a pseudo-first-order fashion. Instead, the plots suggest a series of pseudo-first-order reactions. In the very late stages of the reaction, plots of log (abs − abs$_\infty$) *vs.* time were linear for each run. An observed first-order rate constant, k_3, could then be extracted from the late portions of each reaction. The line defining k_3 was extrapolated to zero reaction time and its value at the appropriate time was subtracted from those absorbances which fell above the line defined by k_3. Plots of log [(abs −

Table III. Comparison of the Rate of Product Formation for 0.662 *M* 2-Methylbenzophenone with 0.0127 *M* $(CH_3)_2Mg$[a] with Those Found by Glpc Analysis

	Olefin $M \times 10^2$	
Time, sec	Calcd	Found
0	0.00	0.00
30	1.32	1.20
106	1.43	1.34
193	1.53	1.43
300	1.64	1.53
400	1.73	1.68
1505	2.21	2.12
2501	2.37	2.19
3004	2.42	2.29
∞(36 hr)	2.54	2.52

[a] As predicted by eq 6–9 and k_2 and k_3 from run 6, Table IV.

abs$_\infty$) − extrapolated line] *vs.* time resolved beautifully into a third first-order component, k_2. The resolution of k_2 and k_3 for a specific experiment is demonstrated in Figure 3.

A severe test of the validity of the pseudo-first-order series interpretation is whether or not the resolved k_2 and k_3 remain constant for experiments at constant ketone concentration but varying initial $(CH_3)_2Mg$ concentrations. Four experiments were carried out for $[K]_0 = 0.309$ and $0.00254\ M < [Me_2Mg]_0 < 0.0203\ M$ (Table I). The pseudo-first-order rate constant k_2 and k_3 are constant within experimental uncertainty.

In addition, k_2 and k_3 were determined for $[Me_2Mg]_0 = 0.0126\ M$ and $0.130\ M < [K]_0 < 1.084\ M$. These results are shown in Table IV.

Table IV. Observed Rate Constants for the Various Organometallic Species Involved in the Reaction of 0.0126 *M* $(CH_3)_2Mg$ with Varying Excess of 2-Methylbenzophenone

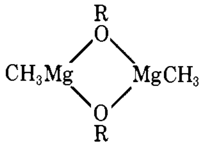
Run	$[K]_0$	10^3k_1 sec^{-1}	10^3k_2 sec^{-1}	10^3k_3 sec^{-1}
1	0.130	34.5	0.99	0.251
2	0.239	59.6	1.34	0.338
3	0.340	95.0	2.13	0.441
4	0.456		2.57	0.564
5	0.561		2.74	0.613
6	0.667		2.57	0.648
7	0.871		2.66	0.722
8	1.084		3.05	0.770

The resolution of the latter portion of the reaction into two well-behaved pseudo-first-order reactions shows that $(CH_3)_2Mg$ reacts with 2-methylbenzophenone to form two intermediate products. The fact

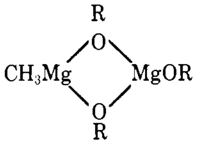
$$(CH_3)_2Mg \xrightarrow[k_1]{\text{ketone}} P_1 \xrightarrow[k_2]{\text{ketone}} P_2 \xrightarrow[k_3]{\text{ketone}} P_3 \tag{5}$$

that k_2 and k_3 are so well behaved over such a large portion of the reaction shows that the intermediate products P_1 and P_2 are two distinct organomagnesium species each of which has structural integrity. The simplest interpretation is that P_1 has two equivalent methylmagnesium groups and that one of these reacts with 2-methylbenzophenone at a rate k_2 to form P_2, which has one methylmagnesium group, and which further reacts with ketone at rate k_3 to form P_3, the final product.

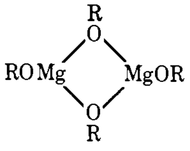
The structure assigned to P_1 has two equivalent CH_3Mg sites and the association (dimer) predicted by Coates[15,21] for RMgOR compounds with large alkoxy groups. P_2 is the product of the reaction of one methyl group of P_1 with ketone. The kinetic data presented do not demand that P_3 be represented by a dimer; however, it is reasonable to assume from the structures of P_1 and P_2 that P_3 is initially formed as a dimer although it may polymerize later.



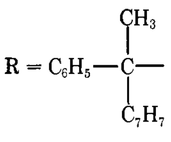
P_1



P_2



P_3



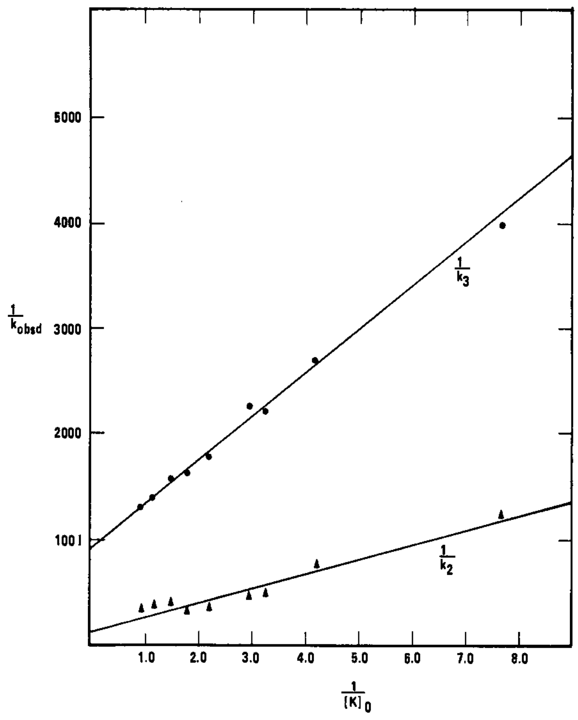


Figure 4. Plot of $1/k_2$ and $1/k_3$ *vs.* $1/[K]_0$.

Product Analysis. The reasonableness of the structure assignment of P_1 and P_2 can be readily checked. The amounts of P_1, P_2, and P_3 at any time during the course of the reaction are given by the following equations.[22]

$$[P_1] = {}^1\!/_2[(CH_3)_2Mg]_0e^{-k_2t} \tag{6}$$

$$[P_2] = \frac{[(CH_3)_2Mg]_0k_2}{2(k_3 - k_2)}(e^{-k_2t} - e^{-k_3t}) \tag{7}$$

$$[P_3] = {}^1\!/_2[(CH_3)_2Mg]_0 \times \left[1 + \frac{1}{k_2 - k_3}(k_3e^{-k_2t} - k_2e^{-k_3t})\right] \tag{8}$$

The yield of product alcohol at any time, assuming the proposed structures of P_1, P_2, and P_3 to be correct, is then given by eq 9.

$$[\text{product alcohol}] = 2[P_1] + 3[P_2] + 4[P_3] \tag{9}$$

Two experiments were carried out in which samples were withdrawn and quenched at approximate intervals and after 36 hr. The concentrations of 2-methylbenzophenone and $(CH_3)_2Mg$ in these two runs were as close as possible to the concentrations employed in kinetic runs 3 and 6, Table IV. To each of the quenched samples 9-fluorenone was added as an internal standard. The samples were then dehydrated with *p*-toluenesulfonic acid to the corresponding olefin and the concentration of olefin determined by glpc anal-

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[21] P. T. Moseley and H. M. M. Shearer, *Chem. Commun.*, 279 (1968).

[22] The equations are valid not only for the obvious case in which P_1 and P_2 represent single species in solution, but also for the case in which part of the product is complexed with ketone. In the latter case [P] represents the sum of the concentrations of free and complexed product.

ysis. The initial quenching was done to correspond as nearly as possible to $t_{\max}$. The other samples were quenched at time intervals early and late in the slow portion of the reaction to observe the maximum dependence on k_2 and k_3. The predicted values for the concentration of olefin at the time of quenching and the concentration of olefin experimentally found are given in Tables II and III. The concentrations of olefin found experimentally are in good agreement with the predicted concentrations throughout the reaction. In addition, the total yield of olefin is quantitative, indicating the absence of any interfering side reaction.

It should be noted that the scheme of reactions outlined implies that the CH_3MgOR monomer, formed in the initial reaction of $(CH_3)_2Mg$ with 2-methylbenzophenone, dimerizes very rapidly once formed. It was noticed that at the two highest ketone concentrations (runs 7 and 8, Table IV) points obtained within about 60 sec after $t_{\max}$ fell distinctly above the line defining k_2. This was also the case, but less distinctly, with run 6, Table IV, but did not occur at all at lower ketone concentrations. By subtracting the line defining k_2 from these points a fourth pseudo-first-order portion could be resolved. The rate constants for this reaction are shown in Table V.

Table V. Observed Rate Constants for the Reaction of CH_3MgOR Monomer with Excess 2-Methylbenzophenone

Run	$[K]_0$	10^3k_m sec^{-1}	$10^3k_m/[K]_0$ l. mol^{-1} sec^{-1}
6	0.667	19.8	30.0
7	0.871	21.3	24.4
8	1.084	29.1	26.9

We attribute this additional reaction observed at very high ketone concentrations to the reaction of CH_3MgOR monomer with ketone. At these high ketone concentrations the reaction of monomer with ketone can compete to some extent with dimerization. If our assignment of k_m is correct, then $(CH_3)_2Mg$ reacts with 2-methylbenzophenone at a rate about ten times that of $CH_3MgOC(C_7H_7)(C_6H_5)CH_3$ monomer, and the latter reacts at about the same rate as methylmagnesium bromide.

Mechanism of Product Formation. The conclusions that can be drawn from our results vary somewhat with the three different organomagnesium species. The linearity of Figure 2 is consistent with a bimolecular reaction between the ketone and $(CH_3)_2Mg$, or for reaction *via* complex formation. If a complex is formed, its amount is very small relative to the total amount of $(CH_3)_2Mg$.

More detailed analysis was possible for the reaction of P_1 and P_2 with ketone, and three general mechanistic schemes were considered. Each scheme predicts that the behavior of the system, in the presence of a large excess of ketone, is mathematically equivalent to consecutive first-order reactions with pseudo-first-order

$$P_1 \xrightarrow{k_2} P_2 \xrightarrow{k_3} P_3 \qquad (10)$$

rate constants k_2 and k_3. Detailed considerations are presented for the step in which P_2 forms P_3.

Case I. Case I is represented by eq 11 in which complex formation between P_2 and ketone is a nonproductive equilibrium, and alkylation occurs by a bimolecular reaction between the free organomagnesium reagent and ketone. C_2 represents the complex, and

$$C_2 \overset{K_2}{\rightleftharpoons} P_2 \xrightarrow{k_p[\text{ketone}]} P_3 \qquad (11)$$

$K_2 = [C_2]/[P_2][K]_0$. In this case k_3 is given by

$$k_3 = \frac{k_p[K]_0}{1 + K_2[K]_0} \qquad (12)$$

where k_p is the second-order rate constant. An equivalent form of eq 12 is

$$\frac{1}{k_3} = \frac{1}{k_p[K]_0} + \frac{K_2}{k_p} \qquad (13)$$

For the set of experiments in which the concentration of ketone is varied, a plot of $1/k_3$ *vs.* $1/[K]_0$ should be linear with an intercept equal to k_2/k_p and a slope equal to $1/k_p$. The linearity of such a plot (Figure 4) demonstrates the consistency of our data with this description. Values of K_2 and k_p, obtained by a fit of eq 12 to minimize the per cent error in k_3, are $K_2 = 2.0$ l./mol and $k_p = 0.00227$ l. mol^{-1} sec^{-1}.

Case II. Case II is represented by eq 14 in which product is formed directly by internal rearrangement of the complex. The assumption is that complex C_2

$$P_2 \overset{K_2}{\rightleftharpoons} C_2 \xrightarrow{k_c} P_3 \qquad (14)$$

reacts by a unimolecular process with rate constant k_c. In this case the pseudo-first-order rate constant is given by

$$k_3 = \frac{k_cK_2[K]_0}{1 + K_2[K]_0} \qquad (15)$$

Rearrangement of eq 15 to

$$\frac{1}{k_3} = \frac{1}{k_cK_2[K]_0} + \frac{1}{k_c} \qquad (16)$$

indicates that the linearity of the plot of Figure 4 is also consistent with this mechanism. Values obtained for K_2 and k_c by a fit of eq 15 are $K_2 = 2.0$ l./mol and $k_c = 0.00113$ sec^{-1}.

Thus, it is not possible to distinguish mathematically between case I and case II. It should be noted, however, that the value of K_2 is not dependent on distinguishing between case I and case II, since in each case K_2 is given by the intercept divided by the slope.

Case III. Holm[9] has suggested that alkyl Grignard reagents form complexes with ketone and that either Grignard reagents coordinated with diethyl ether or Grignard reagents coordinated by ketone can alkylate free ketone. Case III is based on this suggestion, and the recognition that in our system at very high ketone concentrations a large fraction of the organomagnesium species exists as organomagnesium–ketone complexes. Thus reaction of complex with free ketone to form products might be the principal mode of addition.

Case III is represented by eq 17. The assumption is

$$P_2 \overset{K_2}{\rightleftharpoons} C_2 \xrightarrow{k_{cK}[\text{ketone}]} P_3 \qquad (17)$$

that C_2 reacts with ketone in a bimolecular process to form products. In this case the pseudo-first-order rate constant k_3 is given by

$$k_3 = \frac{k_{cK}K_2[K]_0^2}{1 + K_2[K]_0} \qquad (18)$$

Rearrangement of eq 18 to the appropriate slope-intercept form gives

$$\frac{[K]_0}{k_3} = \frac{1}{k_{cK}K_2[K]_0} + \frac{1}{k_{cK}} \qquad (19)$$

The experimental fact is that $[K]_0/k_3$ decreases as $1/[K]_0$ increases, which is inconsistent with eq 19. The conclusion then is that product formation by reaction of the organomagnesium–ketone complex with free ketone does not occur in the system studied.

The behavior of k_2 with changing ketone concentration is less regular (see Figure 4), and a straight line does not provide a good fit to the data. This is not surprising, since the presence of two reactive Mg sites in the molecule doubles the number of constants needed to describe the dependence of k_2 on $[K]_0$, and this is so even when the reaction at a given site is of a single type (*i.e.*, either case I or case II). Two complexes will be present in the system (thus requiring two equilibrium constants), one with both magnesiums complexed, and one with one magnesium complexed. Similarly, two rate constants are required, the probability of reaction at the reacting Mg being dependent on whether the nonreacting Mg is complexed or not. With four parameters available in either case, the data for k_2 can be fit by schemes based on either case I or case II mechanisms, so the data cannot be used to distinguish between them.

Either case can be reduced to a system with two parameters, however, if one assumes that the two equilibrium constants differ only by the statistical factor caused by the presence of two sites, and similarly for the two rate constants. With these assumptions case I predicts

$$k_2 = \frac{2k_{\mathrm{I}}\{[K] + K[K]^2\}}{1 + 2K[K] + 2K^2[K]^2} \qquad (20)$$

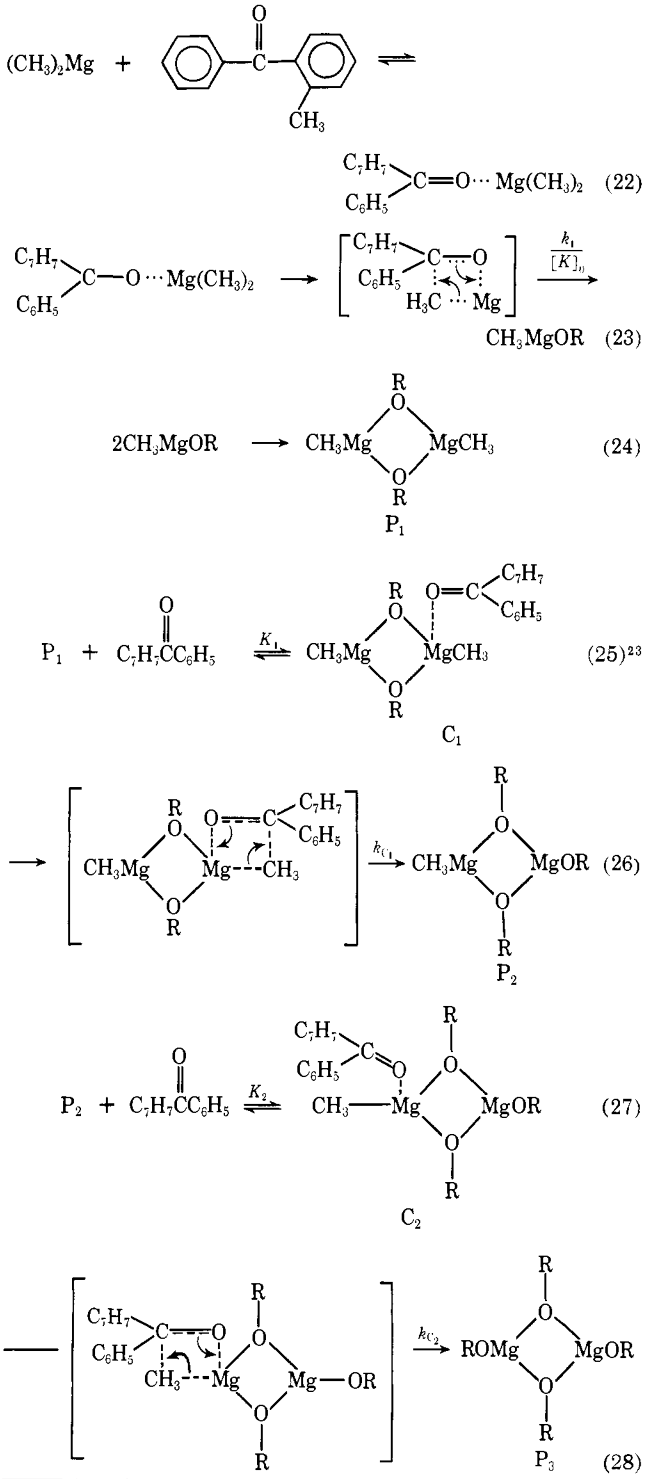
where k_{I} is the rate constant giving the inherent reactivity at a single $MgCH_3$ site, and K is the inherent equilibrium constant for complexing at one site. Case II predicts

$$k_2 = \frac{2k_{\mathrm{II}}\{K[K] + 2K^2[K]^2\}}{1 + 2K[K] + 2K^2[K]^2} \qquad (21)$$

These two functions are not mathematically equivalent, but are similar enough that it would take data of great accuracy to choose between them. Reasonably good fits of our data (calculated values of k_2 within 15% of k_{obsd} for all values) can be obtained with either function. Parameters yielding such a fit are for case I, $K = 1.0$, $k_{\mathrm{I}} = 0.0039$ l. mol^{-1} sec^{-1} and for case II, $K = 2.0$, $k_{\mathrm{II}} = 0.0039$ sec^{-1}.

It is worth noting that the ability to fit the data for k_2 and k_3 with self-consistent mechanisms and numerical parameters supports the proposed structures for P_1 and P_2. It should also be noted that, regardless of which mechanism is operative, a CH_3Mg site in P_1 is two or three times more reactive than the site in P_2.

Considering the reactions of all the organomagnesium species dealt with here, in no case do the kinetic data allow one to distinguish between case I and case II mechanisms. The case III mechanism can be eliminated as a possible mechanism in the reaction of P_2, and there is no evidence for it in the reaction of $(CH_3)_2Mg$. The only difference in the case I and case II mechanisms is whether reaction proceeds by a simple bimolecular collision or by rearrangement of a complex between the organomagnesium compound and ketone. Although the complexes P_1–ketone and P_2–ketone have been directly observed, the kinetic data do not demand that the reaction actually proceed through the complex. Inability to distinguish between case I and case II is relatively minor compared to the more essential features of the reaction path which have been clearly established. The detailed mechanism for case II is presented in eq 22–28.



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[23] The steps involving formation and reaction of a complex containing two ketone molecules are omitted for brevity.