investigated further. Tubes 3–7 (538 mg.) yielded a homogeneous single-spot crystalline material (thin layer chromatography). Recrystallization from methanol provided 356 mg. of IX: m.p. 160°; $\lambda_{\max}^{\mathrm{KBr}}$ 2.97, 4.43, and 5.95 μ; $\delta^{\mathrm{DMSO}} = 1.46$ (3H, s), 1.56 (3H, s), 3.89 (1H, d, $J = 7$ c.p.s.), 4.88 (1H, d, $J = 7$ c.p.s.), and 7.57 (2H, b) p.p.m.

Anal. Calcd. for $C_7H_{10}N_2O_2$: C, 54.53; H, 6.59; N, 18.17. Found: C, 54.40; H, 6.59; N, 18.26.

Hydrolysis of the *trans*-Oxetane in Methanolic Hydrogen Chloride.—A solution of 2 g. of I in 20 ml. of 1 *N* HCl in methanol was left at 25° for 20 min. and then evaporated to dryness *in vacuo*. The residue was taken up in 20 ml. of hot water. Crystallization gave 1.8 g. of X; m.p. 59–61°. A sample was recrystallized from ether for analysis: m.p. 64°; $\lambda_{\max}^{\mathrm{CHCl_3}}$ 2.88, 4.56, and 5.70 μ; $\delta^{\mathrm{DMSO}} = 1.46$ (3H, s), 1.57 (3H, s), 3.46 (3H, s), 4.17 (1H, d, $J = 7.5$ c.p.s.), and 5.17 (1H, d, $J = 7.5$ c.p.s.) p.p.m.

Anal. Calcd. for $C_8H_{11}NO_3$: C, 56.79; H, 6.55; N, 8.28. Found: C, 56.65; H, 6.51; N, 8.22.

Mass spectra of X showed the following peaks in descending order of intensity: *m/e* 43, 29, 82, 58, 41, 81, 29, 27, 28, 55, 52, 54, 59, 80, 31, 53, 83, 40, 44, 66, 45, 38, 33, 154, 60, 37, 110, 112, 64, 67, 65, and 56.

From the aqueous mother liquors of the crystallization above, there was obtained 200 mg. of a mixture (m.p. 152–195°) that was taken up in ethyl acetate and extracted several times with 5% sodium bicarbonate. Evaporation of the ethyl acetate provided 18 mg. of VI (mixture melting point and infrared spectra). Acidification and ethyl acetate extraction of the combined water layers gave 109 mg. of a mixture that contained III and VI (infrared spectra and thin layer chromatography.)

Conversion of X to IX.—To 60 mg. of X was added 1 ml. of methanol and 1 ml. of concentrated ammonium hydroxide. After standing at 25° for 2 hr., the solution was evaporated to dryness *in vacuo* and the residue was crystallized from ethyl acetate giving 18 mg. of IX (mixture melting point and infrared spectra), m.p. 152–154°.

Hydrolysis of the *cis*-Oxetane with Methanolic HCl.—A solution of II (1 g.) and 20 ml. of *N* HCl in methanol was left at 25° for 20 min. and then evaporated to dryness *in vacuo*. The residue was crystallized from 10 ml. of water to give 610 mg. of XI, m.p. 185–190°. Recrystallization from ethyl acetate gave a pure material: m.p. 207–208°; $\lambda_{\max}^{\mathrm{KBr}}$ 2.92, 3.15, 4.44, and 5.97 μ; $\delta^{\mathrm{DMSO}} = 1.53$ (6H, s), 4.22 (1H, d, $J = 9.5$ c.p.s.), 4.96 (1H, d, $= 9.5$ c.p.s.), and 7.59 (2H, b) p.p.m.

Anal. Calcd. for $C_7H_{10}N_2O_2$: C, 54.53; H, 6.59; N, 18.17. Found: C, 54.65; H, 6.36; N, 17.92.

Acknowledgment.—We are indebted to Professor G. Büchi for the mass spectra reported herein. We also thank Mr. L. Lackey for technical assistance.

Solvent Effects in the Reaction of Grignard Reagent with 1-Alkynes[1]

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The kinetics of the reaction between ethylmagnesium bromide and 1-alkynes in diethyl ether, *n*-dibutyl ether, diethylene glycol diethyl ether, and tetrahydrofuran have been studied in detail in the range of from 0–40° by measuring the rate of evolved ethane gas. It has been found that the reaction is second order in diethyl ether and in *n*-dibutyl ether, third order in tetrahydrofuran, and about 2.5 order in diethylene glycol diethyl ether. ΔE^* and ΔS^* for the reaction in each solvent were obtained. Possible mechanisms of the reaction are presented.

The constitution of the Grignard reagent has been reinvestigated with chemical and physical techniques by several groups of workers in recent years. Dessy and co-workers[2,3] demonstrated that an equimolar mixture of diethylmagnesium and magnesium bromide in diethyl ether yields the same species as that from ethylmagnesium bromide in diethyl ether, that is, the Grignard reagent prepared in the usual manner. This conclusion seems to have been confirmed by infrared spectral studies[4] and by n.m.r. studies[5] by other workers. From the experimental results that there was only a low percentage of magnesium exchange between diethylmagnesium and radioactive magnesium bromide in diethyl ether solvent, Dessy, *et al.*,[6] concluded that in diethyl ether the predominant species in the Grignard reagent was $R_2Mg \cdot MgX_2$ and that the Grignard reagent is best represented by the equilibrium shown in eq. 1. Recently the above Mg^{28} exchange reaction

$$R_2Mg \cdot MgX_2 \rightleftharpoons R_2Mg + MgX_2 \qquad (1)$$

was reinvestigated and both no exchange results and statistical exchange results have been found in two systems which differed only in magnesium sources.[7] The cause of this dichotomy is unknown at present. Ashby and Becker[8] proposed by the fractional crystallization method and by ebullioscopic measurements that in tetrahydrofuran (THF) monomeric species RMgX predominates in simple alkyl Grignard reagents in contrast to dimeric species existing in diethyl ether. Recently, Salinger and Mosher[4] concluded by infrared spectral studies that in THF the Grignard reagents can be interpreted in terms of the equilibrium of eq. 2.

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

Stucky and Rundle[9] showed by X-ray analysis that crystals of phenylmagnesium bromide contain $C_6H_5MgBr \cdot 2Et_2O$ units. These diverse and partially conflicting observations suggest that the nature or equilibria of the Grignard reagents may vary depending upon the variety of solvents as well as of organic radicals or halides. Therefore, it appeared of interest to investigate the solvent effects on the kinetics of a Grignard reaction in order to give an information concerning the precise nature of the Grignard reagents.

Lewis and Wright[10] studied solvent effects in the reaction between ethylmagnesium bromide and benzophenone and assumed that the difference of the yields of products was attributed to the difference of basicity

(1) A portion of this work was presented at the 17th Meeting of the Chemical Society of Japan, Tokyo, Japan, April 1964; Abstracts of Papers, p. 156.

(2) R. E. Dessy, *J. Org. Chem.*, **25**, 2260 (1960).

(3) J. H. Wotiz, C. A. Hollingsworth, and R. E. Dessy, *ibid.*, **21**, 1063 (1956).

(4) R. M. Salinger and H. S. Mosher, *J. Am. Chem. Soc.*, **86**, 1782 (1964).

(5) H. Roos and W. Zeil, *Ber. Bunsenges. Physik. Chem.*, **67**, 28 (1963).

(6) R. E. Dessy, G. S. Handler, J. H. Wotiz, and C. A. Hollingsworth, *J. Am. Chem. Soc.*, **79**, 3476 (1957).

(7) R. E. Dessy, S. E. I. Green, and R. M. Salinger, *Tetrahedron Letters*, 1369 (1964).

(8) E. C. Ashby and W. E. Becker, *J. Am. Chem. Soc.*, **85**, 118 (1963).

(9) G. D. Stucky and R. E. Rundle, *ibid.*, **85**, 1002 (1963).

(10) R. N. Lewis and J. R. Wright, *ibid.*, **74**, 1253 (1952).

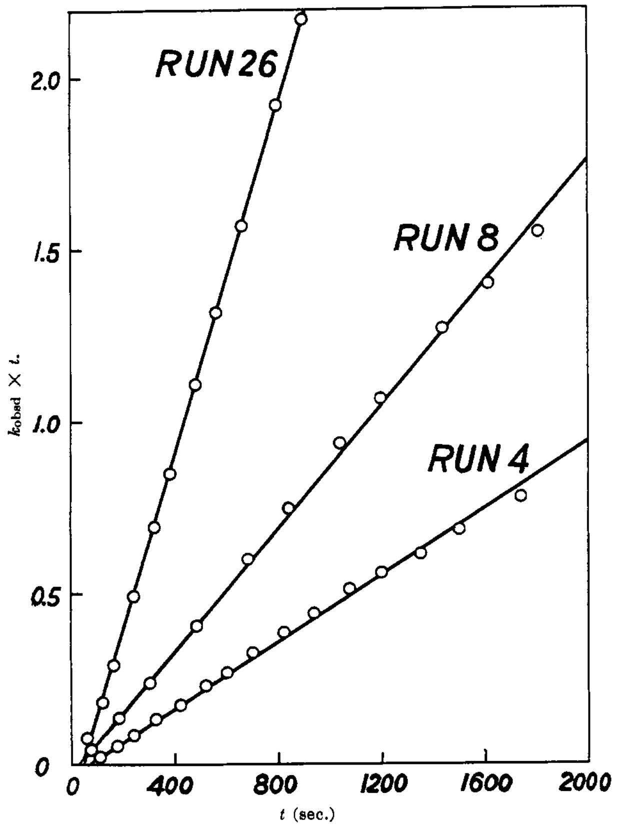

Figure 1.—Second-order rate plot for the reaction of EtMgBr with 1-alkynes in Et$_2$O and n-Bu$_2$O: $k_{obsd} \times t = 1/(a - b) \ln b(a - x)/a(b - x)$ for 1-hexyne; $k_{obsd} \times t = 2/(a - 2b) \ln 2b(a - x)/a(2b - x)$ for 1,7-octadiyne, where a and b are the initial concentrations (mole/l.) of EtMgBr and 1-alkynes, respectively. Run numbers are those given Table I and II.

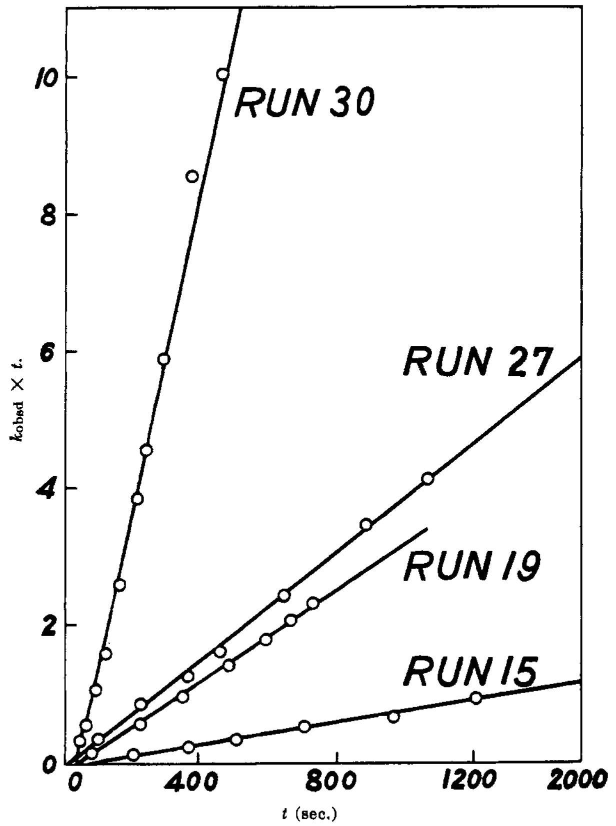

Figure 2.—Third-order rate plot for the reaction of EtMgBr with 1-alkynes in THF: $k_{obsd} \times t = 1/(a - b)^2 \ln b(a - x)/a(b - x) - x/a(a - b)(a - x)$ for 1-hexyne; $k_{obsd} \times t = 2/(a - 2b)^2 \ln 2b(a - x)/a(2b - x) - 2x/a(a - 2b)(a - x)$ for 1,7-octadiyne, where a and b are the initial concentrations (mole/l.) of EtMgBr and 1-alkynes, respectively.

of the solvents having influence on the formation of the ketone–Grignard reagent coordination complex, but not considering solvent effects on the nature of the Grignard reagent. Dessy, Wotiz, and co-workers[11-17] reported a series of studies concerning the reactions of the Grignard reagents or dialkylmagnesium with 1-alkynes, in which the effects of addition of THF,[12] dioxane,[13] or tertiary amines[16,17] were investigated. The greater part of the studies, however, had dealt with the reaction in diethyl ether. The present work was undertaken in order to reveal solvent effects in the reaction of ethylmagnesium bromide with 1-hexyne or 1,7-octadiyne by a kinetic method. The reaction kinetics were studied in detail in diethyl ether, n-dibutyl ether, THF, and diethylene glycol diethyl ether in the range of from 0 to 40° by measuring the rate of evolution of ethane. As the result, it has been found that the reaction order varies from second order to third order with the specific solvents used. In addition, some data on measuring of the molecular weight of ethylmagnesium bromide in diethyl ether and THF, and on analyses of the reaction products precipitated by the reaction between ethylmagnesium bromide and 1,7-octadiyne are presented.

Results and Discussion

Kinetics of the Reaction of Ethylmagnesium Bromide with 1-Hexyne.—The typical second-order rate plots for the reactions in diethyl ether and in n-dibutyl ether are shown in Figure 1, wherein run numbers are those given in Table I. The plots are linear up to 70% conversion or more when calculated from the amount of the evolution of ethane. Such a relationship fits all the temperatures investigated. As the results of experiments in which nonequimolar mixtures of ethylmagnesium bromide and 1-hexyne were used, it has been found that the reaction is second order in diethyl ether and is first order in the Grignard reagent and in 1-hexyne. Similarly, the reaction is second order in n-dibutyl ether and is probably first order in the Grignard reagent and in 1-hexyne.

For the reaction in THF, a linear relationship is not obtained by a second-order rate plot, but is obtained by a third-order rate plot of which some examples are shown in Figure 2 (run 15 and 19). In this case, the experimental data fitted the third-order rate plot of second order in the Grignard reagent and first order in 1-hexyne much better than that of first order in the former and second order in the latter. It has then been concluded that the reaction in THF is

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[11] J. H. Wotiz, C. A. Hollingsworth, and R. E. Dessy, *J. Am. Chem. Soc.*, **77**, 103 (1955).

[12] J. H. Wotiz, C. A. Hollingsworth, and R. E. Dessy, *J. Org. Chem.*, **20**, 1545 (1955).

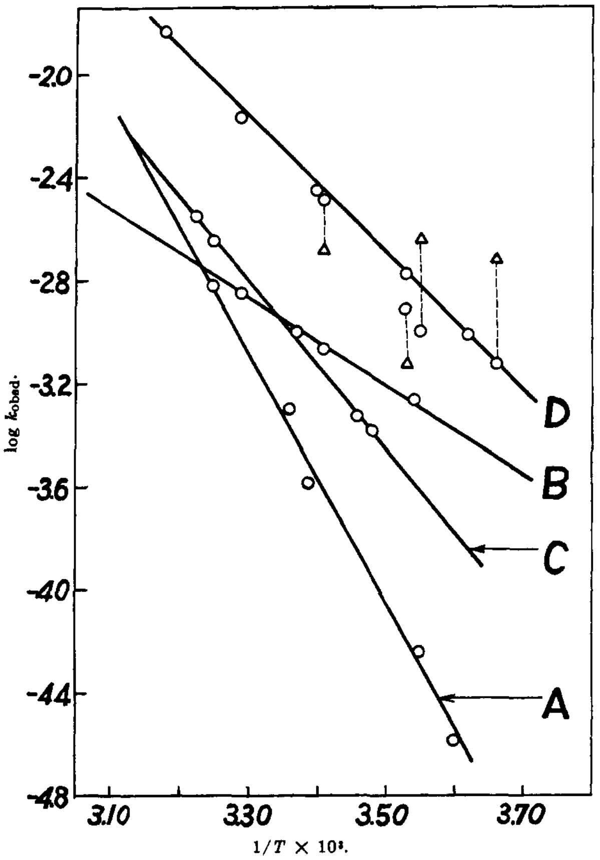
[13] J. H. Wotiz, C. A. Hollingsworth, and R. E. Dessy, *J. Am. Chem. Soc.*, **78**, 1221 (1956).

[14] J. H. Wotiz, C. A. Hollingsworth, and R. E. Dessy, *J. Org. Chem.*, **21**, 1063 (1956).

[15] R. E. Dessy, J. H. Wotiz, and C. A. Hollingsworth, *J. Am. Chem. Soc.*, **79**, 358 (1957).

[16] J. H. Wotiz, C. A. Hollingsworth, R. E. Dessy, and L. C. Lin, *J. Org. Chem.*, **23**, 228 (1958).

[17] J. H. Wotiz, C. A. Hollingsworth, and A. W. Simon, *ibid.*, **24**, 1202 (1959).



1/T × 10³.

Figure 3.—Plot of log k_{obsd} *vs.* $1/T$ for the reaction of EtMgBr with 1-hexyne in various solvents: A, in Et_2O; B, in $n\text{-}Bu_2O$; C, in diethylene glycol diethyl ether; D, in THF; △, rate constants obtained as first order in EtMgBr and second order in 1-hexyne.

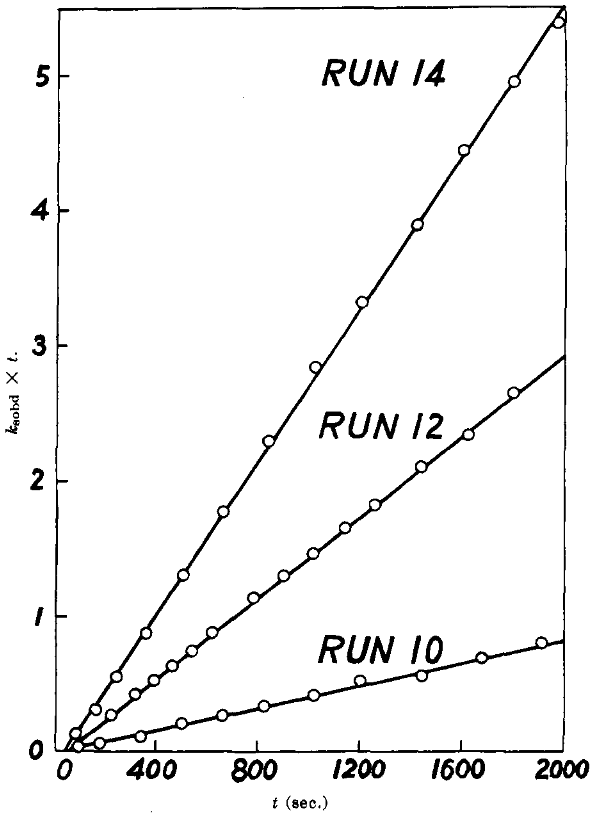


Figure 4.—2.5-Order rate plot for the reaction of EtMgBr with 1-hexyne in diethylene glycol diethyl ether: $k_{obsd} \times t = 1/(a - x)^{1.5} - 1/a^{1.5}$, where a is the initial concentration (mole/l.) of EtMgBr and 1-hexyne.

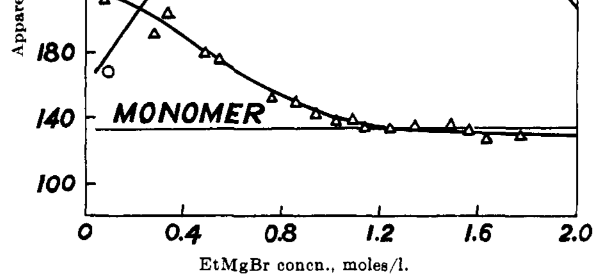


Figure 5.—Apparent molecular weight of EtMgBr in Et_2O and THF: ○, in Et_2O; △, in THF.

third order over-all: of second order in the Grignard reagent and first order in 1-hexyne. This conclusion is also ascertained by reference to the plot of logarithms of the reaction rates in THF against the inverse absolute temperatures in Figure 3. It is shown in Figure 3 that the rate constants calculated as first order in ethylmagnesium bromide and second order in 1-hexyne considerably deviate from the straight line.

On the other hand, for the reaction in diethylene glycol diethyl ether a linear relationship is obtained neither by a second-order rate plot, which showed downward curvature, nor by the third-order rate plot, which showed upward curvature. In this case, the 2.5-order rate plot gave a straight line at all the temperatures studied as shown in Figure 4. It may be concluded therefore that the reaction in diethylene glycol diethyl ether shows approximately 2.5-order kinetics.

Reaction of Ethylmagnesium Bromide with 1,7-Octadiyne.—It has been also found that the reaction of ethylmagnesium bromide with 1,7-octadiyne is second order in diethyl ether and third order in THF similar to that of 1-hexyne, if the terminal ethynyl groups of 1,7-octadiyne react independently. It may be concluded that in THF the reaction is second order in ethylmagnesium bromide and first order in 1,7-octadiyne. The examples of the second-order rate plot in diethyl ether and of the third-order rate plot in THF are shown in Figure 1 (run 26) and in Figure 2 (run 27 and 30). The third-order kinetics, therefore, seems to be general in the reaction between ethylmagnesium bromide and 1-alkynes. In these respects, it will be also noted that the reaction of ethylmagnesium bromide with benzophenone in THF did not obey second-order kinetics.[18]

As shown in Figure 3, the plots of log k_{obsd} *vs.* $1/T$ give a good linear relationship for the reaction in every solvent used. Activation energy for the reaction between ethylmagnesium bromide and 1-hexyne evaluated

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(18) S. J. Storfer and E. I. Becker, *J. Org. Chem.*, **27**, 1868 (1962).

TABLE I

REACTION OF ETHYLMAGNESIUM BROMIDE WITH 1-HEXYNE

		Initial concn., M						
Run	Solvent	EtMgBr	1-Hexyne	Temp., °C.	Reaction order	k_{obsd}[a]	ΔE^*, kcal./mole	ΔS^*, e.u.
1	Et_2O	1.00	1.00	5.4	2	2.63×10^{-5}	21.1	−3.12
2	Et_2O	1.00	1.00	9.1	2	5.88×10^{-5}		
3	Et_2O	1.00	1.00	21.9	2	2.61×10^{-4}		
4	Et_2O	1.00	2.00	24.8	2	5.06×10^{-4}		
5	Et_2O	1.00	2.00	35.0	2	1.50×10^{-3}		
6	Bu_2O	1.00	1.00	0.5	2	1.87×10^{-4}	7.15	−48.2
7	Bu_2O	1.00	1.00	9.2	2	5.49×10^{-4}		
8	Bu_2O	0.750	0.750	20.0	2	8.71×10^{-4}		
9	Bu_2O	0.500	0.500	31.2	2	1.46×10^{-3}		
10	DGE[b]	0.885	0.885	14.0	2.5	4.18×10^{-4}	14.6	−23.2
11	DGE[b]	0.936	0.936	16.2	2.5	4.76×10^{-4}		
12	DGE[b]	0.936	0.936	24.4	2.5	1.00×10^{-3}		
13	DGE[b]	0.936	0.936	34.6	2.5	2.24×10^{-3}		
14	DGE[b]	0.885	0.885	37.0	2.5	2.81×10^{-3}		
15	THF	0.721	0.380	0.4	3	7.59×10^{-4}	12.5	−27.2
16	THF	0.500	0.500	2.8	3	1.01×10^{-3}		
17	THF	0.892	0.543	8.4	3	1.06×10^{-3}		
18	THF	0.500	0.500	10.0	3	1.69×10^{-3}		
19	THF	1.12	1.43	20.0	3	3.29×10^{-3}		
20	THF	0.500	0.500	31.0	3	6.79×10^{-3}		
21	THF	0.500	0.500	41.3	3	1.57×10^{-2}		

[a] Given in $l.^{n-1}$ $mole^{n-1}$ sec., where n is reaction order. [b] Diethylene glycol diethyl ether.

TABLE II

REACTION OF ETHYLMAGNESIUM BROMIDE WITH 1,7-OCTADIYNE

		Initial concn., M						
Run	Solvent	EtMgBr	1,7-Octadiyne	Temp., °C.	Reaction order	k_{obsd}[a]	ΔE^*, kcal./mole	ΔS^*, e.u.
22	Et_2O	1.22	0.382	12.9	2	2.10×10^{-4}	20.3	−4.63
23	Et_2O	1.00	0.500	13.0	2	2.15×10^{-4}		
24	Et_2O	1.00	1.00	20.0	2	5.00×10^{-4}		
25	Et_2O	0.974	0.487	28.1	2	1.07×10^{-3}		
26	Et_2O	0.700	1.05	34.0	2	2.54×10^{-3}		
27	THF	0.547	0.274	7.0	3	4.44×10^{-3}	9.35	−35.9
28	THF	0.616	0.308	18.5	3	8.95×10^{-3}		
29	THF	0.695	1.20	21.0	3	1.47×10^{-2}		
30	THF	0.695	1.19	25.3	3	2.26×10^{-2}		

[a] Given in $l.^{n-1}$ $mole^{n-1}$ sec., where n is reaction order.

from the linear plot in Figure 4 is 21.1 kcal. in diethyl ether, 7.15 kcal. in n-dibutyl ether, 14.6 kcal. in diethylene glycol diethyl ether, and 12.5 kcal. in THF. Similarly, the activation energy for the reaction between ethylmagnesium bromide and 1,7-octadiyne is 20.3 kcal. in diethyl ether and 9.35 kcal. in THF. These experimental results and the calculated values of activation entropy are summarized in Table I and II. It has also been found that the plot of ΔE^* *vs.* ΔS^* gives a linear relationship.

Molecular Weight of Ethylmagnesium Bromide in Diethyl Ether and THF.—The molecular weight of ethylmagnesium bromide in diethyl ether and in THF prepared by the usual method was determined ebullioscopically at the normal boiling point of the solution. The results[19] are shown in Figure 5. It is seen that increasing of the concentration of the Grignard solution apparently decreased the degree of association of ethylmagnesium bromide in the concentration range of more than 1.0 mole/l. in diethyl ether and of more than about 0.2 mole/l. in THF. The above abnormal phenomena may probably be attributed to the failure of Raoult's law at such high concentrations, because increasing the concentration should generally increase the degree of association. Recently, Vreugdenhil and Blomberg[20] investigated the association number of diethylmagnesium, magnesium bromide, and ethylmagnesium bromide in diethyl ether or THF at concentrations from 10^{-3} to 10^{-2} M at 27.3° by the vapor pressure method in the complete absence of oxygen. It has been found that ethylmagnesium bromide in the highly pure state is monomeric in dilute ether or THF solutions. However, it may be concluded from the results shown in Figure 5 and those of previous workers[21] that ethylmagnesium bromide in diethyl ether prepared from Grignard-grade magnesium turnings by the usual method is present as at least the dimer at concentrations of more than 0.5 M under the condition measured. On the other hand, Ashby, *et al.*,[8] also proposed that ethylmagnesium bromide is monomeric in THF. It may be deduced from the present results that ethylmagnesium bromide in THF prepared by the usual method and used in the kinetic study is present as a mixture of monomer and dimer in such higher concentrations as measured.

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(19) The measurements were carried out in a nitrogen atmosphere but oxygen was not so perfectly excluded that some effect of a trace of remaining oxygen for association with EtMgBr may not have occurred.

(20) A. D. Vreugdenhil and C. Blomberg, *Rec. trav. chim.*, **82**, 453, 461 (1963).

(21) For example, J. Meisenheimer and W. Schlichenmaier, *Ber.*, **61**, 720 (1928).

Products Precipitated in the Reaction of Ethylmagnesium Bromide with 1,7-Octadiyne.—The reaction was always homogeneous between ethylmagnesium bromide and 1-hexyne independent of the reaction temperatures or solvents used. However, in the reaction with 1,7-octadiyne, precipitation sometimes occurred as the reaction proceeded. By isolating and analyzing these precipitated products, the results shown in Table III are obtained. The products precipitated in diethyl ether have a mole ratio of total magnesium to total bromide of about 1. Additionally, since the number of moles of total magnesium approximately equals the number of moles of univalent basic magnesium, it is assumed that these precipitations have $\equiv$CMgBr terminal groups. The products in THF seem to have coprecipitated with magnesium bromide. The compositions of the products in THF were not made certain merely by the analyses as described above.

TABLE III

ANALYSES OF REACTION PRODUCTS

	Basic Mg[a], mole	Total Mg, mole	Total Br, mole
Et_2O precipitation[b]	1.26×10^{-3}	1.31×10^{-3}	1.26×10^{-3}
THF precipitation[c]	1.11×10^{-2}	2.44×10^{-2}	3.42×10^{-2}
Filtrate	5.86×10^{-2}	4.78×10^{-2}	4.12×10^{-2}

[a] Calculated as univalent Mg. [b] EtMgBr, 0.0158 mole; 1,7-octadiyne, 0.0236 mole; reaction temperature, 34°; time, 20 min. [c] EtMgBr, 0.0725 mole; 1,7-octadiyne, 0.0202 mole; reaction temperature, 40°; time, 40 min.

Proposed Mechanism.—There are several mechanistic possibilities for the reaction of ethylmagnesium bromide with 1-alkynes which may satisfy the observed kinetics. It seems reasonable to assume that in the case of the reaction in THF the reactive species of ethylmagnesium bromide is its monomeric form, EtMgBr, which is in equilibrium with its dimeric form. It is then proposed for the reaction mechanism in THF that 1-hexyne first reacts with ethylmagnesium bromide monomer, EtMgBr, to form a complex, which is followed by the rate-determining attack of a second EtMgBr monomer upon the complex (eq. 3, 4, and 5).

$$Et_2Mg \cdot MgBr_2 \text{ or } (EtMgBr)_2 \rightleftharpoons 2EtMgBr \quad (3)$$

$$EtMgBr + BuC{\equiv}CH \underset{k_{-1}}{\overset{k_1}{\rightleftharpoons}} [EtMgBr \cdot BuC{\equiv}CH] \quad (4)$$

$$[EtMgBr \cdot BuC{\equiv}CH] + EtMgBr \xrightarrow{k_2} BuC{\equiv}CMgBr + C_2H_6 + EtMgBr \quad (5)$$

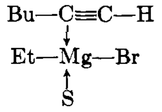
The over-all rate expression for the above process becomes that given by eq. 6 where a and b are the initial

$$\frac{dx}{dt} = \frac{k_1(a - x)^2(b - x)}{k_{-1}/k_2 + (a - x)} \quad (6)$$

concentrations of EtMgBr and 1-hexyne, respectively. Owing to $k_{-1}/k_2 \gg (a - x)$ in THF, the reaction obeys third-order kinetics of second order in ethylmagnesium bromide and first order in 1-hexyne. According to this mechanism, the observed rate constant k_{obsd} is k_1k_2/k_{-1}. From the integral form of eq. 6, eq. 7 is

$$Y = \frac{k_{-1}/k_2}{k_1} X - \frac{1}{k_1} \quad (7)$$

derived, where X and Y consist of concentration terms only and are calculated from the experimental data. If the plot of X vs. Y gives a straight line, then k_1 is obtained from the intercept. The obtained k_1 is the order of 10^{-2} l. mole^{-1} sec.$^{-1}$. ΔE_1^* of eq. 4, which is calculated from the plot of k_1 vs. $1/T$, is about 3 kcal. This value is a reasonable value for the activation energy for formation of the complex from ethylmagnesium bromide with 1-alkynes. Although this mechanism is somewhat similar to Swain's mechanism[22] for the addition of Grignard reagents to ketones with no kinetic evidence, the precise mechanism may be different. The complex may thus have structure I where a solvating solvent molecule in the



$$\begin{array}{c} Bu{-}C{\equiv}C{-}H \\ \downarrow \\ Et{-}Mg{-}Br \\ \uparrow \\ S \end{array}$$

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EtMgBr molecule is substituted by a 1-hexyne molecule. 1-Hexyne is activated by complex formation with EtMgBr, then attacked by a second EtMgBr. It is still unknown whether the second EtMgBr attacks the complex by a four-center mechanism, or by another mechanism.

In the case of the reaction in diethyl ether or n-dibutyl ether, the same mechanism as that of the reaction in THF may be applied, assuming that k_{-1}/k_2 is negligible compared with $(a - x)$. However, considering the association of ethylmagnesium bromide in these solvents and the activation energy of the first step (*i.e.*, eq. 4), the above assumption does not seem to be correct. In these cases, a simple second-order mechanism in which the dimeric Grignard reagent reacts with 1-hexyne in a rate-determining process as in eq. 8 and 9 will be proper. According to this mechanism, the observed rate constant k_{obsd} is $k_1/2$. ΔE^* in the reaction in diethyl ether is shown to be much greater than that in n-dibutyl ether. This can be attributed to the greater solvation of ethylmagnesium bromide in the ground state in diethyl ether. On the other hand, much of the negative ΔS^* in the reaction in n-dibutyl ether may be attributed to the greatly increased solvation in the transition state, although solvation in the ground state is smaller compared with that in diethyl ether.

$$Et_2Mg \cdot MgBr_2 \text{ or } (EtMgBr)_2 + BuC{\equiv}CH \xrightarrow{k_1} BuC{\equiv}CMgBr + C_2H_6 + EtMgBr \quad (8)$$

$$2EtMgBr \xrightarrow{\text{fast}} Et_2Mg \cdot MgBr_2 \text{ or } (EtMgBr)_2 \quad (9)$$

In the case of the reaction in diethylene glycol diethyl ether, both of the above mechanisms will occur competitively, owing to the intermediate basicity or solvating power of diethylene glycol diethyl ether.

Experimental

Solvents.—Diethyl ether and tetrahydrofuran (THF) were purified and dried by the usual method and redistilled with a small amount of previously prepared ethylmagnesium bromide diethyl ether or THF solution before use. Diethylene glycol diethyl ether was dried with calcium chloride and with metallic sodium and vacuum distilled; the fraction boiling at 74° (16 mm.) was collected on sodium metal. n-Dibutyl ether was treated with carbon disulfide and aqueous sodium hydroxide to remove any butyl alcohol present, dried, and vacuum distilled

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

with ethylmagnesium bromide *n*-dibutyl ether solution as described above.

Reagents.—1-Hexyne was prepared by the method given in the literature, dried, and distilled with a Widmer fractionating column; b.p. 71–72°, showing only one peak in the gas chromatogram. 1,7-Octadiyne was prepared from 1,4-dibromobutane and sodium acetylide in liquid ammonia and purified in a manner similar to that described above, b.p. 69–71.5° (62.5 mm.).

Grignard Reagents.—Ethylmagnesium bromide solutions were prepared by the general method from ethyl bromide and magnesium turnings[23] in each purified solvent. The resulting Grignard solutions were filtered through a glass filter under a nitrogen atmosphere to remove the remaining solid materials. The concentrations of ethylmagnesium bromide in the above solutions were determined by hydrolyzing aliquots in a known excess of 0.2 *N* sulfuric acid and back-titrating with 0.2 *N* sodium hydroxide (method A), or by hydrolyzing aliquots with distilled water and measuring the volume of the evolved ethane gas (method B). Measurements by the method A always tend to give several per cent lower analytical values than those by the method B. In calculation of reaction rates described herein, the analytical values obtained by method B were adopted as the concentration of ethylmagnesium bromide.

Reaction Rate Measurements.—The apparatus used in these studies consisted of a 100-ml. four-necked, flat-bottomed reaction flask, a long conduit in reversed U-shape for withdrawal of evolved ethane gas, a cooler, and a Mariotte bottle. The flask was equipped with a thermometer, a nitrogen gas inlet tube, and rubber serum cap for the introduction of alkynes, and was immersed into a thermostated water bath and agitated magnetically. The conduit was attached to the top of the flask at one end, inserted into the Mariotte bottle at the other end, and had a three-way stopcock at the middle part. The cooler had a capacity of about 2 l. and was attached just above the top of the flask, with the conduit passing through it. Where diethyl ether or THF was used as a solvent in reaction, a mixture of Dry Ice and methanol was used as a cooling medium and, in the case of *n*-dibutyl ether or diethylene glycol diethyl ether solvent, ice–water was used.

The general procedures of the kinetic studies were carried out as follows. The apparatus was flushed with dry nitrogen before starting a run. A measured volume of ethylmagnesium bromide solution (from about 15 ml. to 20 ml.) of known concentration was placed in the reaction vessel. When *n*-dibutyl ether, THF, or diethylene glycol diethyl ether was used as a solvent, said ethylmagnesium bromide solution in the reaction vessel was saturated at a temperature of 0° or lower with ethane gas which was being evolved at an average rate of about 5 ml./min. in a separate vessel by hydrolyzing ethylmagnesium bromide solution with water diluted with the solvent, because it had been found in preliminary experiments that the solubility of ethane in these solvents could not be neglected in precise kinetic measurements, especially in lower temperature reactions. The time required for saturation of ethane was about 1.5 to 2 hr. The reaction medium was then brought to the desired temperature for measurement of the reaction rate and maintained at that temperature by thermostatting the reaction flask. A required amount of 1-hexyne or 1,7-octadiyne was introduced into the flask through the serum cap with a syringe, followed by the rapid introduction of 0.5 ml. of purified solvent to wash the alkyne down into the flask. At zero time of the reaction the temperature of the reaction medium was sometimes raised about 1° or so by the heat of reaction. In that case, the reaction temperature was maintained and regulated at the resulting temperature by heatcontrolling the water bath. The reaction media could be kept at a constant temperature with fluctuations of ±0.1°, if any, during measurements. The evolved ethane gas was collected in the Mariotte bottle and the weight of aqueous sodium bisulfate solution[24] displaced by the ethane gas was measured at regular intervals of from 1 min. to 3 min. From the above measured values, the volumes of ethane gas in the standard state were determined. In each solvent, a series of reaction rates was measured by varying the initial concentrations of the reagents (from 0.5 to 1.0 mole/l.) and the reaction temperature (from about 0 to 40°). The reactions were followed up to a conversion of from 50 to 70% in all cases. Duplicate measurements were carried out at a given reaction temperature to give reproducible results.

The suitability of the method for measuring reaction rates as described above was examined as follows. It was found by gas chromatography that the gases evolved by the reaction of 1-hexyne with ethylmagnesium bromide in ether principally consisted of ethane and contained only a negligible amount of methane (less than about 0.4%). Similarly, the gases evolved by the reaction of the above reagents in THF only contained less than 1.0% methane as an impurity. Therefore, side reactions can be neglected in these reaction systems. Additionally, the material balance obtained by method B was as given in Table IV and shows that the above method for determining reaction rates is suitable.

Table IV

Material Balance in the Reaction of 1-Hexyne with Ethylmagnesium Bromide

Solvent	Temp., °C.	Time, min.	EtMgBr used, mole	Ethane evolved during reaction, mole	Ethane evolved by hydrolyzing after reaction, mole
Et_2O	35	25	0.0176	0.0142	0.0027
THF[a]	9.2	55	0.0176	0.0113	0.0057

[a] Ethylmagnesium bromide in THF was previously saturated with ethane gas.

Molecular Weight Measurements.—Ebullioscopic determination of the molecular weight of ethylmagnesium bromide in ethyl ether and THF was attempted in an inert atmosphere in order to know the association number of the Grignard reagent under the conditions used in the kinetic study. The apparatus used was a modification of that described by Uemura.[25] The molecular weight (M) of the solute was calculated according to eq. 10, where K is the molal boiling-point elevation constant,

$$M = K\frac{1000w_1}{\Delta T w_2} \qquad (10)$$

$$\Delta T = S(T_i - T_0) \qquad (11)$$

w_1 is grams of solute, w_2 is grams of solvent, and ΔT is the boiling-point elevation (°C.) corrected by eq. 11 wherein S is the correction coefficient for the part of the Beckmann thermometer exposed to air and T_i and T_0 are the readings of the Beckmann thermometer measured at i and zero of solute concentration, respectively. T_i and T_0 have been corrected to values at standard pressure. As the molal boiling point elevation constants of diethyl ether (M_{Et_2O}) and of THF (M_{THF}), 2.034 (M_{Et_2O}) and 2.176 (M_{THF}) were used. These values are average values which were determined using pure *m*-terphenyl and fluorenone as solutes. The measurements were carried out in the range 0.1–2.0 mole/l. of ethylmagnesium bromide, but in a concentration less than 0.1 mole/l. there may occur greater experimental error due to a small value of ΔT.

Analyses of Reaction Products Precipitated in the Reaction of 1,7-Octadiyne with Ethylmagnesium Bromide.—In the reaction of 1,7-octadiyne with ethylmagnesium bromide, the reaction products sometimes precipitated as the reaction proceeded. They were isolated in an inert atmosphere, washed with ether or THF, and vacuum dried on silica gel. The dried products were analyzed for basic magnesium by acid titration (method A), for total magnesium by gravimetric method using 8-hydroxyquinoline as a precipitating agent for magnesium ion, and for total bromide by the Volhard method.

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(23) Purity 99.96%, impurities: Zn, 200; Al, 50; Si, 50; Mn, 30; Fe, 10; and Cu, 5 p.p.m. All of the Grignard reagents used were prepared from the same lot of magnesium.

(24) The solution consisted of anhydrous sodium sulfate (200 g.), concentrated sulfuric acid (40 ml.), and distilled water (800 ml.). The solubility of ethane in this solution is 1.09 ml./100 ml. at 25° and therefore the dissolved ethane in the above solution can be neglected. Since crystals precipitated in the solution at lower temperatures, the following composition of the solution was used at a temperature below 16°: anhydrous sodium sulfate (170 g.), concentrated sulfuric acid (34 ml.), and distilled water (800 ml.) [*cf.* K. A. Kobe, *Ind. Eng. Chem. Anal. Ed.*, **10**, 77 (1938)].

(25) H. Uemura, *Nisseki Rev.*, **4**, 296 (1952)