

Kinetics of Formation of Alkyl Grignard Reagents. Evidence for Rate-Determining Electron Transfer¹

Summary: A technique for obtaining relative rates of reaction of organic halides with metallic magnesium has been developed, and rate data obtained using this technique have been interpreted to indicate that the rate-determining step for formation of alkyl Grignard reagents involves electron transfer from the metal to alkyl halide.

Sir: The mechanism of the reactions between alkyl halides and metallic magnesium in ethereal solvents has proved difficult to investigate, in part because in this, as in other surface processes, the influence of the structure of the organic reactant on the rate of the reaction is not easily characterized using absolute kinetics techniques.² Organic radicals have been implicated as intermediates in these reactions by stereochemical,³ CIDNP,⁴ and product⁵ studies, but the relevance of these radicals to the principal reaction path leading to Grignard reagent, the strength of their interaction with the magnesium surface, and the nature of the rate-determining step for the overall reaction remain unsolved problems. Here we report that reliable relative rate data for these reactions may be obtained using competition techniques and present evidence suggesting that electron transfer from magnesium to the alkyl halide occurs in the rate-limiting step.

The principal difficulty in studying the kinetics of the reaction of an alkyl halide, RX, with magnesium is that of accounting for the unknown and variable effective surface area of the metal (S_{Mg}). We have hypothesized that an expression having the form of eq 1 might prove adequate to describe this reaction. If this hypothesis is correct, it should be possible to write precisely analogous expressions (eq 1 and 2) containing the same value of S_{Mg} for two

$$-d(R_1X)/dt = k_1(R_1X)^\alpha S_{Mg} \quad (1)$$

$$-d(R_2X)/dt = k_2(R_2X)^\alpha S_{Mg} \quad (2)$$

$$\ln[(R_1X)_t/(R_1X)_0] = (k_1/k_2) \ln [(R_2X)_t/(R_2X)_0] \quad (3)$$

structurally similar organic halides competing in the same reaction mixture for a common magnesium surface. Assuming that $\alpha = 1$, a simple expression (eq 3) containing no term in magnesium is obtained by dividing eq 1 by eq 2 and integrating. We find experimentally that plots of eq 3 are linear to >65% consumption of alkyl halide,^{6,7} and that values of k_1/k_2 obtained from these plots are sensibly independent of the quantity and type of magnesium used, the starting concentration of alkyl halide, the presence of magnesium salts in the reacting solutions, and the presence of small quantities of water or oxygen intentionally added to the solutions; these values were reproducible within $\pm 10\%$. Thus, eq 3 appears to describe adequately the kinetic behavior of a mixture of two alkyl halides competing for a single magnesium surface.

Comparison of the rate-structure profile produced by the kinetic data generated using this procedure (Figure 1) with profiles for reactions proceeding by S_N2 and anionic mechanisms establishes that the rate of the Grignard reaction is much less sensitive to the structure of the organic moiety than are members of these classes of reactions⁸ and confirms that the transition state for the formation of alkyl Grignard reagents is not similar to transition states typical of these classes. The exceptionally

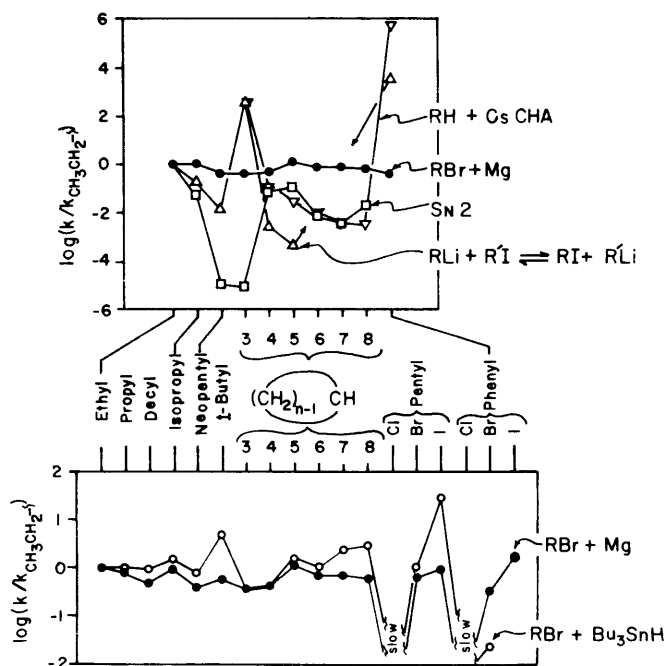
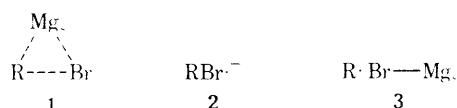


Figure 1. Rate-structure profiles for representative S_N2 and anionic reactions, and for the reactions (diethyl ether, 0°) of organic halides, RX, with metallic magnesium and with tri-*n*-butyltin hydride (*hν*, AIBN). Unless indicated otherwise, X = Br.

small influence of the structure of the organic moiety on the rate of reaction is compatible with a diffusion-controlled reaction; however the absolute rates of the Grignard reactions are less than diffusion controlled.⁶ Since these observations exclude heterolytic and diffusion-limited mechanisms for the reaction, and since the predominant loss of stereochemistry at carbon observed by others³ on reaction of diastereomeric alkyl halides with magnesium argues against concerted insertion of a surface magnesium atom (Mg_s) into a carbon-halogen bond (1), two basic types of transition states for the reaction remain to be considered. One (2) would resemble an alkyl halide radical anion, produced by one-electron reduction of the alkyl halide by the metal; a second (3) would approximate an alkyl radical, either free or surface-bound, and might be generated by abstraction of a halogen atom by the magnesium surface or by decomposition of 2.



Generalizable reaction-rate profiles for radical reactions are difficult to obtain, since many methods of generating radicals—including, in principle, the reaction considered here—impose polar character on their transition states.⁹ We have used the reduction of alkyl halides with tri-*n*-butyltin hydride¹⁰ to model 3 (Figures 1 and 2) and find that, although the rates of both the tin hydride and Grignard reactions are relatively insensitive to variations in structure, only a poor correlation exists between them: the latter are significantly *less* responsive to changes in structure than are the former, and, while the structure-rate profiles for the two reactions are similar in general form, they differ markedly at specific compounds. To estimate

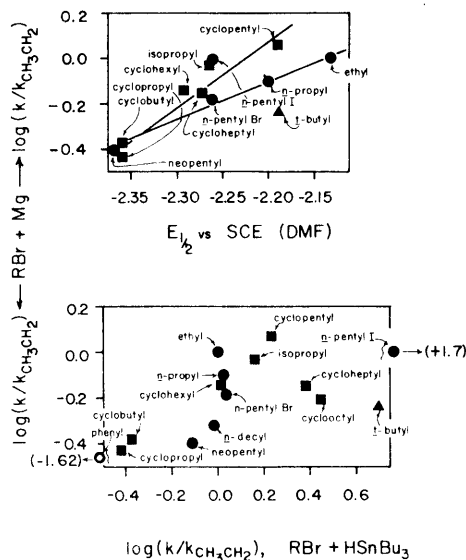


Figure 2. The relative rates of reactions of alkyl halides with magnesium correlate better with half-wave potentials for their reduction at a dropping mercury electrode than with their rates of reaction with tri-*n*-butyltin hydride. In this figure, primary halides are represented by ●, secondary by ■, the single tertiary halide by ▲, and phenyl, included on the plot for comparison, by ○.

the energy required to convert RX to RX^- (2), we have used half-wave potentials, $E_{1/2}$, for reduction of alkyl halides.¹¹ For a reaction generating 2, the log of the rate of electron transfer to RX at constant potential should be approximately proportional to $E_{1/2}$, provided, as we observe, that the rate is not diffusion limited. The correlation between $\log(k_{RX}/k_{EtBr})$ from the Grignard reactions and $E_{1/2}$ for the corresponding alkyl bromides is again not particularly close over the limited range of compounds for which consistent electrochemical data are available, but appears better than that characterizing the tri-*n*-butyltin hydride reductions.^{12,13}

These rate studies indicate that the rate-determining transition state in the formation of an alkyl Grignard reagent does not involve a heterolytic fission of the C-X bond, nor is it diffusion limited. The superiority of the correlation of $\log(k_{RX}/k_{EtBr})_{Mg}$ with $E_{1/2}$ to that with $\log(k_{RX}/k_{EtBr})_{TribuSnH}$ suggests, but does not prove, that 2 rather than 3 describes the transition state for the reaction. Evidence implicating 2 as an intermediate in the formation of Grignard reagents has been described by others,^{3,4} but these data have not been sufficient to characterize the rate-determining step, or, in the instance of CIDNP experiments, to establish that the 2 lies along the principal reaction path leading to product.

Acknowledgment. Preliminary work in this problem was carried out by E. V. Merry and C. H. Breckheimer.

Supplementary Material Available. Experimental procedures used to obtain the data summarized in Figure 1, and a representative plot of experimental data according to eq 3, will appear following this article in the microfilm addition of this journal. Photocopies of the supplementary material from this paper only or microfiche (105 × 148 mm, 24× reduction, negatives) containing all of the supplementary material for the papers in this issue may be obtained from the Journals Department, American Chemical Society, 1155 16th St., N.W., Washington, D. C. 20036. Remit check or money order for \$3.00 for photocopy or \$2.00 for microfiche, referring to code number JOC-74-857.

References and Notes

- (1) Supported by the National Science Foundation, Grant GP-28586X.
- (2) M. S. Kharasch and O. Reinmuth, "Grignard Reactions of Nonmetallic Compounds," Prentice Hall, New York, N. Y., 1954.
- (3) H. M. Walborsky and M. S. Aronoff, *J. Organometal. Chem.*, **51**, 31 (1973); H. L. Goering and F. H. McCarron, *J. Amer. Chem. Soc.*, **80**, 2287 (1958).
- (4) H. W. H. J. Bodewitz, C. Blomberg, and F. Bickelhaupt, *Tetrahedron*, **29**, 719 (1973).
- (5) W. C. Kossa, Jr., T. C. Rees, and H. G. Richey, Jr., *Tetrahedron Lett.*, 3455 (1971); C. Blomberg, *J. Organometal. Chem.*, **45**, 1 (1972); C. Rüchardt and H. Trautwein, *Ber.*, **95**, 1197 (1962).
- (6) This observation and the fact that crude noncompetitive kinetics carried out using magnesium surfaces sufficiently large that their effective surface area does not change during the course of a kinetic run indicate that the assumption that $\alpha = 1$ is at least approximately justified; Y. Fujiwara, unpublished results.
- (7) Supplementary material available. See paragraph at end of this communication.
- (8) Data for these rate profiles were obtained from the following sources: A. Streitwieser, Jr., "Solvolytic Displacement Reactions," McGraw-Hill, New York, N. Y., 1962; A. Streitwieser, Jr., and W. R. Young, *J. Amer. Chem. Soc.*, **91**, 529 (1969), and references cited therein; D. E. Applequist and P. F. O'Brien, *ibid.*, **85**, 743 (1963). Values for S_N2 reactions are Streitwieser's "average" values. The data for exchange of hydrocarbons with CsCHA have not been related to the rate of exchange of ethane. Since only the general forms of these profiles are important, the relative rate of exchange of cyclopropane has arbitrarily been given the same value as the equilibrium constant for metal-halogen exchange between ethyllithium and cyclopropyl iodide.
- (9) C. Rüchardt, *Angew. Chem., Int. Ed. Engl.*, **9**, 830 (1970).
- (10) H. G. Kuivila, *Accounts Chem. Res.*, **1**, 299 (1968).
- (11) Details of the mechanism of electrochemical reduction of alkyl halides are still unclear; however, the bulk of the available evidence suggests one-electron transfer from the electrode to the alkyl halide as the potential-determining step; cf. C. K. Mann, J. L. Webb, and H. M. Walborsky, *J. Amer. Chem. Soc.*, **92**, 2042 (1970), and A. J. Fry and R. G. Reed, *ibid.*, **94**, 8475 (1972), for discussion of this point.
- (12) All of the $E_{1/2}$ values included in Figure 2 are taken from a single source: F. L. Lambert and K. Kobayashi, *J. Amer. Chem. Soc.*, **82**, 5324 (1960). This study employed a dropping mercury electrode, DMF solvent, and $Bu_4N^+I^-$ as supporting electrolyte. Our efforts to obtain $E_{1/2}$ data in ethereal solvents have not been successful: C. L. Hill, unpublished work.
- (13) The origin of the differences in the slopes of the lines correlating $E_{1/2}$ with $\log(k_{RX}/k_{EtBr})$ for primary and secondary alkyl moieties is not obvious, but does not deserve speculation until it has been established that the difference persists in ethereal solvents.
- (14) National Institutes of Health Predoctoral Fellow, 1966-1969.

Department of Chemistry
Massachusetts Institute
of Technology
Cambridge, Massachusetts 02139

Randall J. Rogers
H. Lee Mitchell¹⁴
Yuzo Fujiwara
George M. Whitesides*

Received November 28, 1973