

Deuterium Isotope Effects in the Decomposition of Organometals by Proton Donors¹

Y. Pocker² and J. H. Exner³

Contribution from the Department of Chemistry, University of Washington, Seattle, Washington 98105. Received March 18, 1968

Abstract: Deuterium isotope effects associated with proton *vs.* deuteron transfer reactions from oxygen and carbon acids to the phenyl and benzyl derivatives of magnesium, lithium, and sodium in diethyl ether and in tetrahydrofuran (THF) have been determined by a competitive method. The isotope effects, k_H/k_D , observed with oxygen acids, phenol, water, methanol, and *t*-butyl alcohol are small, varying between 1.0 and 1.5, and suggest a reaction pathway involving the prior replacement of a metal-coordinated solvent molecule by the oxygen acid. On the other hand, proton transfers to organometals from the carbon acids, phenylacetylene, indene, fluorene, *p*-biphenyldiphenylmethane, and triphenylmethane in THF are associated with isotope effects, k_H/k_D , which vary between 1.4 and 10.8. The isotope effects in the reactions of each organometal with the series of carbon acids support the theoretical prediction of a maximum isotope effect and provide information about the transition states for these proton transfer processes as well as about the nature of these organometallic compounds.

The study of kinetic deuterium isotope effects has become a fruitful tool in the elucidation of reaction mechanisms involving proton transfer. For instance, enolate anions, when intermediates in kinetic concentrations, react five to six times faster with water than with deuterium oxide.^{4,5} Although the exact nature of the organometallic compounds which contain C-Mg, C-Li, and C-Na bonds is at present still uncertain, the carbanionic character of these bonds is well established. Consequently, the deuterium isotope effects associated with the reactions of these incipient carbanions with various proton donors are of considerable interest. Isotope effects for the reaction of deuterated⁶ and tritiated⁷ oxygen acids with some Grignard reagents were found to be close to unity by Wiberg⁶ and Assarsson.⁷

The present work reports on the deuterium isotope effects associated with proton transfer from oxygen and hydrocarbon acids to the phenyl and benzyl derivatives of magnesium, lithium, and sodium in diethyl ether and in tetrahydrofuran (THF). The oxygen acids used as proton donors are phenol, water, methanol, and *t*-butyl alcohol; the carbon acids are phenylacetylene, indene, fluorene, *p*-biphenyldiphenylmethane, and triphenylmethane.

Experimental Section

Instruments. In general, mass spectra were taken on a CEC 21-103B mass spectrometer, with the exception of deuterated mixtures of triphenylmethane and of *p*-biphenyldiphenylmethane which were analyzed on an AEI MS 9 double-focusing mass spectrometer with a direct insertion probe. Nmr spectra were obtained on a Varian Associates A-60 spectrometer. Infrared spectra were taken on a Perkin-Elmer 21 spectrophotometer equipped with sodium chloride prisms. Ultraviolet spectra were obtained on a Cary 11 recording spectrophotometer. Melting points, taken on a Thomas Hoover capillary melting-point apparatus, are uncorrected.

Reagents. Anhydrous diethyl ether was distilled from lithium aluminum hydride before use. Tetrahydrofuran, THF (J. T. Baker

Co.), was refluxed with lithium aluminum hydride for 2 days and distilled from it under nitrogen before use. *n*-Pentane, shaken with concentrated sulfuric acid for 3 hr, distilled through a 30-cm Vigreux column from anhydrous potassium carbonate, contained no aromatic impurities. Bromobenzene, chlorobenzene, and benzyl chloride were distilled before use. Deuterium oxide (99.85%, Bio-Rad Laboratories) was periodically checked for deuterium content by nmr.

Oxygen Acids. Phenol-O-*d*. Phenol (200 g, 2.12 mol, Mallinckrodt Analytical Reagent) was stirred at reflux with successive portions of 80, 40, 20, and 10 ml of deuterium oxide for 48 hr each. Vacuum distillation of the dried phenol layer yielded 181 g of phenol-O-*d* which contained 78.9% deuterium. The deuterium content of this material was determined by quenching aliquots of benzylmagnesium chloride solutions with the deuteriophenol and analyzing the resultant hydrocarbon mixtures as described in the determination of isotope effects. Equimolar mixtures of phenol and deuteriophenol were made up by weight.

Methanol-O-*d*. Deuteriomethanol, prepared by the method of Murray and Williams,⁸ was distilled through a 20-cm column filled with glass helices. Liquid distilling at 64.5–66.0° contained 96.1% deuterium as determined by quenching aliquots of benzylmagnesium chloride in diethyl ether with the methanol-O-*d*. In weighing out equimolar mixtures of methanol and deuteriomethanol, absolute methanol containing 0.1% water was used without further purification.

***t*-Butyl-O-*d* Alcohol.** A mixture of 93 g (0.83 mol) of potassium *t*-butoxide (Columbia Organic Chemicals) and 15 ml (0.83 mol) of deuterium oxide was refluxed for 20 hr. Volatile material was distilled through a 10-cm Vigreux column into a dry, 250-ml flask containing 25 g (0.22 mol) of potassium *t*-butoxide and 3.0 ml (0.16 mol) of deuterium oxide. Volatile material was slowly distilled and redistilled from 0.5 g of finely cut sodium. A final distillation through the Vigreux column yielded 30 g of a semisolid, bp 82–84°, which contained 87.9% deuterium as determined by reaction of the solid with aliquots of a 0.44 *M* solution of phenyllithium in diethyl ether. *t*-Butyl alcohol (Eastman Organic Chemicals), distilled twice from sodium, bp 82–83°, was used in weighing out equimolar mixtures of *t*-butyl alcohol and *t*-butyl-O-*d* alcohol.

Deuteriophenylacetylene. Phenylacetylene (Matheson Coleman and Bell) was distilled through a Vigreux column, bp 141–143°. Deuteriophenylacetylene was prepared by stirring 206 g (2 mol) of phenylacetylene, 26.8 g (0.48 mol) of potassium hydroxide, and 80 ml (4.4 mol) of deuterium oxide at reflux for 90 hr. Distillation of the dried phenylacetylene layer yielded 148 g of colorless liquid containing 69.3% deuterium as determined by mass spectral analysis at 10 eV.

Indene-1,1,3-*d*₃. Freshly distilled indene (Matheson Coleman and Bell), bp 67–68° (18 mm), was stirred four times with 3 *N* solutions of sodium hydroxide in deuterium oxide at ca. 65° for 24 hr. The deuterium incorporation, followed by nmr spectroscopy,

(1) Taken in part from the Ph.D. dissertation of J. H. Exner, University of Washington, 1968.

(2) Author to whom correspondence should be addressed.

(3) National Science Foundation Graduate Fellow, 1964–1967.

(4) F. A. Long and D. Watson, *J. Chem. Soc.*, 2019 (1958).

(5) Y. Pocker, *Chem. Ind. (London)*, 599 (1959).

(6) K. Wiberg, *J. Amer. Chem. Soc.*, 77, 5987 (1955).

(7) L. O. Assarsson, *Acta Chem. Scand.*, 12, 1545 (1958), and references therein.

(8) A. Murray, III, and D. L. Williams, "Organic Syntheses with Isotopes," Vol. II, Interscience Publishers, New York, N. Y., 1958, p 1335.

copy, was 89% in the 1 position and 78% in the 3 position. Mass spectral analysis at 7 eV showed a total deuterium content of 86.4%. Equimolar mixtures of indene and indene-1,1,3- d_3 were weighed out, and the deuterium content after distillation was verified by mass spectroscopy.

Fluorene-9- d . Fluorene (Matheson Coleman and Bell) was recrystallized from ethanol and treated with Norit, mp 115–117° (lit.⁹ 116°). Deuteriofluorene, prepared by an adaptation of the method of Scherf and Brown,⁹ was dried under vacuum for 48 hr, mp 115.0–116.5°, and contained 8.8% fluorene, 82.9% fluorene-9- d_1 , and 8.2% fluorene-9,9- d_2 by mass spectral analysis. The deuteriofluorene thus prepared was used in the determination of isotope effects without further change.

Deuteriotriphenylmethane. Phenyllithium was prepared at –70° from 87 g (0.77 mol) of chlorobenzene, 7 g (1 g-atom) of lithium, and 500 ml of dry THF in a dry, 1-l., three-necked flask cooled to –70° by a Dry Ice-acetone bath. To this cooled mixture was added a solution of 100 g (0.41 mol) of triphenylmethane (Aldrich Chemical Co.) in 125 ml of dry THF over 15 min. During the addition, the red color of triphenylmethyllithium appeared. The Dry Ice-acetone bath was removed, and the reaction mixture was stirred for 20 min. The mildly exothermic reaction was moderated by cooling the flask with an ice-water bath. After stirring for an additional 10 min, 40 ml (44 g, 2.2 mol) of deuterium oxide was introduced rapidly over 5 min to the ice-cooled, stirred mixture. The resulting light brown reaction mixture was stirred for 30 min at room temperature and allowed to stand overnight. It was then cautiously neutralized with 250 ml of dilute sulfuric acid and shaken with 200 ml of diethyl ether. The ether layer was separated, washed with two 500-ml portions of water, and dried over anhydrous calcium chloride. After removal of the drying agent, the solvent was evaporated. The yellow solid was recrystallized from benzene and twice from ethanol. The white powder, 57 g, mp 90–93°, was purified further by column chromatography. Deuteriotriphenylmethane (25–30 g), suspended on "Hiflo" Supercell, was placed on a column of acid-washed alumina (Merck, 70 × 4 cm) in petroleum ether (bp 30–60°). Deuteriotriphenylmethane was eluted with 1:20 v/v mixtures of benzene to petroleum ether. The combined solid was recrystallized from ethanol. The white crystals, dried 4 days at 2 mm, mp 93.0–94.5°, contained 93.0% deuterium. An equimolar mixture of triphenylmethane and deuteriotriphenylmethane was weighed out. After recrystallization and drying, the deuterium incorporation of the white crystals, mp 93.0–94.5°, was ascertained by mass spectrometry.

p -Biphenyldiphenylmethane. p -Biphenyldiphenylcarbinol was prepared by the method of Bachmann and Wiselogle,¹⁰ mp 133–136° (lit.¹⁰ 132.5–134.5°). The carbinol was reduced to the hydrocarbon by refluxing it in a 10-mol excess of formic acid for 1.5 hr according to the method of Bowden and coworkers.¹¹ p -Biphenyldiphenylmethane was obtained in 90% yield, mp 110.0–112.5° (lit.¹⁰ 112°). p -Biphenyldiphenylmethane- d was prepared in the same manner as deuteriotriphenylmethane. Solid, which eluted with a 6% v/v solution of benzene to petroleum ether from an alumina column, was recrystallized from ligroin until it showed no impurities on thin-layer-plate chromatography and in the uv. This procedure yielded white solid (41%), mp 110.5–111.5°, which contained 85 ± 1% deuterium. Equimolar mixtures for isotope effect determinations were weighed out.

Organometallic Compounds. All organometals were prepared under a positive pressure of purified nitrogen in a dry, three-necked, round-bottomed flask with standard taper joints. This flask was equipped in all cases with a nitrogen inlet and a ground-glass stirrer (Ace Glass Co.) with a Teflon paddle. For reactions which were run at or above 0° a reflux condenser was fitted to the flask. Pressure-equalizing dropping funnels were used in preparations involving the addition of solutions. Glassware was dried by heating in an oven at 120° for a minimum of 2 hr followed by flushing with dry, purified nitrogen while cooling. Transfer of the organometallic solutions was effected by forcing the solution under nitrogen pressure through a dry, glass U tube into a dry, nitrogen-filled vessel. The U tube was fitted with a plug of glass wool at the immersed tip to filter any particles of unreacted metal and other insoluble material. During the preparation of most of the organometallic compounds, the organometal reacts with traces of moisture or with

solvent to produce hydrocarbon. Since this interferes with the isotope effect determinations, the amount of decomposition was estimated by quenching an aliquot of each organometal with deuterium oxide. The percentage of undeuterated hydrocarbon from the mixture of deuterated hydrocarbons thus obtained corresponds to the amount of hydrocarbon formed during the preparation, an amount which estimates the decomposition of the organometallic compound. The concentration of Grignard reagents was determined by Gilman's method;¹² the concentration of chloride ions was determined by Volhard titration;¹³ and the concentration of benzylmagnesium and sodium compounds was determined by Gilman's double-titration method.¹⁴ The concentration of phenyllithium was approximated by titration of total base.¹⁵

Organomagnesium Compounds. All Grignard reagents and diarylmagnesium compounds used for the determination of isotope effects were prepared using magnesium turnings (99.99% pure) obtained from Gallard Schlesinger Chemical Manufacturing Corp. No chemical initiators such as iodine or mercuric chloride were used.

Phenylmagnesium Bromide or Benzylmagnesium Chloride in Diethyl Ether or THF. The following procedure is similar to the one described by Allen and Converse.¹⁶ In a dry, nitrogen-filled, 500-ml, three-necked flask equipped as described above was placed ca. 50 ml of ether and 1.6 g (0.067 g-atom) of magnesium turnings which had been washed with 25 ml of ether. About 10 ml of a solution of 5.2 ml (7.8 g, 0.05 mol) of distilled bromobenzene in ca. 150 ml of ether was added to the flask, and the reaction was initiated by either rapid stirring or heating with a hot water bath. As soon as a brown color appeared, the flask was immersed in an ice-water bath, and the remainder of the halide solution was added dropwise within 1 hr with rapid stirring. The brown Grignard mixture was then stirred for 1 hr with ice cooling and an additional hour without cooling. The reaction mixture was allowed to settle for 15 min leaving a supernatant brown solution which was determined to be 0.22 M by titration. Quenching of an aliquot of Grignard solutions prepared in this manner with deuterium oxide gave a hydrocarbon mixture which was 90–95% deuteriobenzene (deuteriotoluene) and 5–10% benzene (toluene), indicating a 5–10% decomposition of the Grignard reagent.

Dibenzylmagnesium by the Dioxane-Precipitation Method.^{17,18} Solutions of dibenzylmagnesium in diethyl ether or THF were prepared by adding the desired volumes of the ether solvent to the solid prepared by previous methods.^{17,18} When diethyl ether was used, the maximum concentration which was obtained was 0.14 M by titration. In THF, dibenzylmagnesium concentrations of 0.3 M were obtainable. In several preparations by this method, dibenzylmagnesium contained between 4 and 15 mol % of magnesium chloride.

Dibenzylmagnesium from Dibenzylmercury in THF. The following method was adapted from one described by Schlenk.¹⁹ In a dry, 500-ml, three-necked flask was placed 9.6 g (0.025 mol) of dibenzylmercury (prepared by Wolff's method²⁰), 5.6 g (0.43 g-atom) of magnesium, and 180 ml of dry THF. Vigorous stirring of the reaction mixture at 22° under nitrogen for 8 hr yielded a 0.13 M solution of dibenzylmagnesium free of any halide. Quenching of an aliquot of this solution gave a hydrocarbon mixture which was 8% toluene.

Dibenzylmagnesium from Dibenzylmercury in Diethyl Ether. For the preparation of halide-free dibenzylmagnesium in diethyl ether, 9.6 g (0.025 mol) of dibenzylmercury, 15 g (0.62 g-atom) of magnesium turnings, and 250 ml of dry diethyl ether in a 500-ml, three-necked flask were stirred vigorously for 26 hr. The yellow-green solution was 0.095 M in dibenzylmagnesium by titration and contained ca. 4% toluene.

(12) H. Gilman, E. A. Zoellner, and J. B. Dickey, *J. Amer. Chem. Soc.*, **51**, 1576 (1929).

(13) I. M. Kolthoff and E. B. Sandell, "Textbook of Quantitative Inorganic Analysis," 3rd ed, The Macmillan Co., New York, N. Y., 1952, p 546.

(14) H. Gilman and A. H. Haubein, *J. Amer. Chem. Soc.*, **66**, 1515 (1944).

(15) H. Gilman and F. K. Cartledge, *J. Organometal. Chem.*, **2**, 447 (1964).

(16) C. F. Allen and S. Converse, "Organic Syntheses," Coll. Vol. I, 2nd ed, John Wiley & Sons, Inc., New York, N. Y., 1941, p 226.

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

(18) W. Strohmeier and F. Seifert, *Chem. Ber.*, **94**, 2356 (1961).

(19) W. Schlenk, Jr., *ibid.*, **64**, 734 (1931).

(20) P. Wolff, *ibid.*, **46**, 64 (1913).

(9) G. W. H. Scherf and R. K. Brown, *Can. J. Chem.*, **39**, 856 (1961).

(10) W. E. Bachmann and F. Y. Wiselogle, *J. Org. Chem.*, **1**, 354 (1936).

(11) S. T. Bowden, W. E. Harris, and D. I. Roberts, *J. Chem. Soc.*, 302 (1939).

Diphenylmagnesium from Diphenylmercury in THF or Diethyl Ether. A mixture of 7.1 g (0.02 mol) of diphenylmercury (Eastman Organic Chemicals, mp 120–122°) and 8 g (0.33 g-atom) of magnesium turnings in 150 ml of dry ether was stirred rapidly for 11 hr in a 500-ml, three-necked flask under nitrogen at 22°. This preparation gave a dark solution of 0.12 *M* diphenylmagnesium by titration. These solutions contained *ca.* 4% benzene.

Organolithium Compounds. Lithium wire was flattened into a ribbon and washed with ether. It was then cut into small pieces which were allowed to fall directly into the reaction vessel in a stream of dry nitrogen.

Phenyllithium in Diethyl Ether. The following procedure was adapted from the one described by Walter.²¹ Into a dry, 500-ml, three-necked flask was placed 1.6 g (0.23 g-atom) of lithium particles and 50 ml of dry diethyl ether under nitrogen. To this mixture was added 15 ml of a solution of 10.5 g (7 ml, 0.067 mol) of bromobenzene in 200 ml of dry diethyl ether. After initiation of the reaction by stirring as evidenced by the appearance of a yellow color, the reaction vessel was cooled with an ice-water bath. The remainder of the halide solution was added dropwise during 1 hr. After stirring for an additional 1.5 hr, the red reaction mixture was allowed to settle for 0.5 hr yielding a 0.26 *M* phenyllithium solution by titration. Phenyllithium solutions prepared in the above manner contained *ca.* 6% benzene.

Phenyllithium in THF. To a dry, 500-ml, three-necked flask filled with nitrogen was added 2.0 g (0.29 g-atom) of lithium and 50 ml of dry THF. To this mixture was added 15 ml of a solution of 6.0 g (0.052 mol) of distilled chlorobenzene in 150 ml of dry THF. Upon stirring of the mixture a pink color developed, and the flask was immediately immersed in a wide-mouth dewar flask containing a Dry Ice-acetone mixture which was maintained at –70 to –78°. The remainder of the halide solution was then added dropwise under nitrogen in 2 hr while maintaining the external temperature at –70 to –78°. The red reaction mixture was stirred in the cold for 1 hr more and then allowed to settle for 15 min, yielding a 0.34 *M* solution of phenyllithium by titration. Freshly prepared solutions of this molarity contained 7–10% benzene. Solutions which were prepared in greater dilution, 0.1–0.2 *M*, contained from 14 to 24% benzene as determined by quenching of an aliquot with deuterium oxide.

Benzyllithium in Diethyl Ether from Dibenzylmercury. The method given was adapted from one by Wittig and coworkers.²² To a dry, 500-ml, three-necked flask containing 3.0 g (0.43 g-atom) of lithium and 130 ml of dry diethyl ether under nitrogen was rapidly added 5.5 g (0.014 mol) of dibenzylmercury. As the mercury compound dissolved, a yellow color developed immediately near the lithium particles and turned green within 10 min. The reaction mixture was stirred vigorously for 2 hr at room temperature and allowed to settle for 15 min yielding a 0.14 *M* solution by double titration. Benzyllithium prepared in this manner contained *ca.* 6% toluene.

Benzyllithium in THF. Into a dry, 500-ml flask was placed 4.9 g (0.70 g-atom) of lithium, 230 ml of dry THF, and 7.65 g (0.020 mol) of dibenzylmercury. The mixture was stirred, and as soon as a yellow color developed, the reaction vessel was immersed in a wide-mouth dewar flask containing a Dry Ice-acetone mixture which was maintained between –40 and 60° for the remainder of the reaction. The reaction mixture was stirred vigorously for 2 hr. External cooling was removed, and the reaction mixture was allowed to settle while warming to 0° during 30 min, yielding a yellow-green solution of 0.16 *M* by double titration. Freshly prepared solutions of benzyllithium in THF contained between 6 and 9% toluene as determined by quenching of an aliquot with deuterium oxide.

Benzylnatrium in THF. In a dry, nitrogen-filled, 500-ml flask was placed 10 g (0.44 g-atom) of finely cut sodium ribbon. To the metal was added 130 ml of dry THF and, after several minutes, 5.0 g (0.013 mol) of dibenzylmercury. After the appearance of a yellow color near the sodium particles, the reaction vessel was cooled to –70 to –78° by immersion in a Dry Ice-acetone bath and maintained at this temperature while being stirred vigorously for 4 hr under nitrogen. After a 15-min settling period, the cooling bath was removed yielding a red solution of 0.13 *M* benzylnatrium by titration. Solutions prepared in this manner contained from 5 to 25% toluene. The amount of decomposition appears to depend

greatly on the length of time that the solution was allowed to remain at temperatures greater than –70°.

Methods. Determination of Isotope Effects. Isotope effects derived from product analysis were determined in the following manner. The organometallic compound was prepared in an ether solvent in the desired concentration range. The mixture was allowed to settle, and approximately equal volumes of the solution were forced under nitrogen pressure through a glass U tube, fitted with a glass wool plug at the immersed tip, into dry, nitrogen-filled, 125-ml, pressure-equalizing addition funnels. These solutions generally contained from 0.005 to 0.010 mol of organometal and ranged in volume from 25 to 100 ml. The funnels were immediately fitted onto dry, 100-ml, three-necked, round-bottomed flasks equipped with a nitrogen inlet, a thermometer, and a magnetic stirring bar. The reaction vessel was cooled by a water bath maintained at the desired neutralization temperature. Heating mantles were used for reactions at elevated temperatures. In a control hydrolysis, one of the aliquots of the organometallic solution was always added dropwise and with stirring to 2 ml of deuterium oxide in 10–25 ml of the ether. This control showed the amount of hydrocarbon present due to proton abstraction by the organometal in a side reaction prior to the isotope effect determination. Concurrently, the other aliquots were added dropwise and with stirring to at least a 10-mol excess of an equimolar mixture of the hydrogen- and deuterium-containing acid. The addition time was generally 5–30 min which was followed by additional stirring over a sufficiently long period so that the reaction could go to completion. After an extraction-distillation work-up, the hydrocarbon mixture was analyzed by mass spectrometry and the isotope effect was determined as follows.

$$[\text{RH}]/[\text{RD}] = \frac{[I_{92}/(I_{93} + I_{92})] - [I_{92}^0/(I_{93}^0 + I_{92}^0)]f}{[I_{93}/(I_{93} + I_{92})]}$$

where I_{92} = intensity of the *m/e* 92 peak; I_{93} = intensity of the *m/e* 93 peak, corrected for isotopic contribution from the 92 peak; I^0 = intensity of peaks from control hydrolysis with D₂O; f = moles of AD/mole of AH.

Work-up Procedures. Reactions of Phenyl- and Benzyllithium Compounds with Oxygen Acids or Phenylacetylene in Diethyl Ether. A reaction mixture containing 50–100 ml of diethyl ether and 0.01 mol of a deuterated hydrocarbon mixture was washed with 50 ml of a 2% aqueous sulfuric acid solution, followed by washing with two 75-ml portions of water. The ether solution was dried (anhydrous sodium sulfate) and decanted into a pear-shaped distillation flask. The volume was reduced to *ca.* 10 ml by distilling most of the ether through a Claisen distillation head, 9 cm of which had Vigreux indentations. The remainder of the liquid was then transferred to a 20-ml, one-piece distillation apparatus, and the hydrocarbon mixture was distilled and collected.

When the acid was phenol, the washing step with dilute acid was followed by an extraction step which consisted of washing the ether layer with three 50-ml portions of 5% aqueous sodium hydroxide solution to remove the phenol.

For the case of phenylacetylene, the hydrocarbon mixture was distilled directly through the described short column from a pear-shaped flask after the extraction procedure.

Reactions of Organometals with Oxygen Acids, Phenylacetylene, and Indene in THF. To a reaction mixture containing 0.005–0.01 mol of hydrocarbon in 50–100 ml of THF was added 10–15 ml of purified pentane. A large part of the THF was then washed out during extraction with 50 ml of dilute sulfuric acid and three 10-ml portions of water. The remaining pentane layer was dried over anhydrous sodium sulfate, decanted, and distilled as above.

When triphenylmethane was the reaction product, benzene was substituted for pentane and the extracted solid chromatographed.

When phenylacetylene or indene was used as the proton donor, the reaction mixture was extracted and dried as described. The pentane was then distilled off through a short column. Material distilling in a bath temperature range of 100–170° was collected. This material was again extracted to wash out any remaining THF. The dried pentane layer was distilled in a one-piece distillation outfit, and the deuterated hydrocarbon mixture was collected.

Reactions of Phenyl- and Benzyllithium Compounds with Solid Hydrocarbon Acids. Reactions in which solids (fluorene, *p*-biphenyldiphenylmethane, or triphenylmethane) were used as proton donors were worked up in the following manner. The reaction was hydrolyzed with 1 ml of deuterium oxide. All volatile material was then distilled at water pump pressure through a Hopkins distillation head into a 200-ml, round-bottomed flask immersed

(21) L. A. Walter, "Organic Syntheses," Coll. Vol. III, John Wiley & Sons, Inc., New York, N. Y., 1955, p 757.

(22) G. Wittig, F. J. Meyer, and G. Lange, *Ann. Chem.*, **571**, 167 (1951).

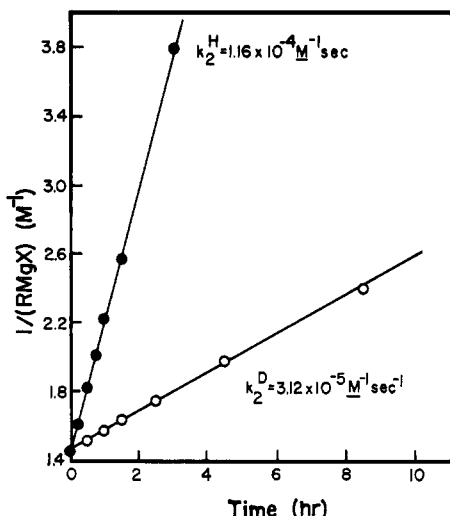


Figure 1. Second-order plots for the reaction of phenylmagnesium bromide with phenylacetylene, ●, and deuteriophenylacetylene, ○, in diethyl ether at 37°.

in a Dry Ice-acetone bath maintained at -78° . In this process the distilling flask was gradually heated up to $90-100^{\circ}$ by the end of the distillation (ca. 1 hr). The distillate was then extracted and dried, and the pentane layer was distilled.

Kinetic Measurements. Phenylmagnesium Bromide and Phenylacetylene in Refluxing Diethyl Ether. A typical kinetic run is described for the reaction of phenylmagnesium bromide with phenylacetylene in diethyl ether. Phenylmagnesium bromide was prepared in diethyl ether as a 0.746 *M* solution. Two 50-ml aliquots were drawn successively into a dry, nitrogen-flushed, 50-ml pipet and were immediately added to a dry, nitrogen-filled, 200-ml, three-necked flask equipped with reflux condenser, nitrogen inlet, thermometer, serum cap, and a magnetic stirring bar. To this aliquot was then added 8.20 ml (7.63 g, 0.0746 mol) of freshly distilled phenylacetylene through the serum cap by means of a 10-ml syringe. A 1.00-ml aliquot was withdrawn, hydrolyzed with water, and set aside. Titration at a later time showed the concentration of the Grignard reagent to be the anticipated value of 0.692 *M*. Concurrently with the removal of that aliquot, a 10–15-ml aliquot was drawn into a dry, nitrogen-flushed, 20-ml syringe. This portion of the reaction mixture was quenched immediately by addition to 1.5 ml of deuterium oxide in a dry, nitrogen-flushed, 125-ml erlenmeyer flask. During these manipulations the reaction vessel was being heated by means of a heating mantle and stirred magnetically. After quenching of the first aliquot, which marked the beginning of the kinetic run, the reaction mixture was very rapidly brought to reflux. The temperature of the solution at reflux was 37° . Aliquots containing ca. 0.006–0.010 mol (10–15 ml) of Grignard reagent were then withdrawn with a dry syringe and quenched at selected time intervals. The hydrocarbon mixture was obtained by the extraction-distillation work-up and analyzed mass spectrometrically. Observed second-order rate constants were obtained graphically from the equation $1/(a-x) - (1/a) = kt$, where *a* is the mean initial concentration of Grignard reagent and phenylacetylene, and *x* is the concentration of hydrocarbon produced (Figure 1).

Stability of Phenylmagnesium Bromide in Diethyl Ether. A 20-ml aliquot of a 0.53 *M* solution of freshly prepared phenylmagnesium bromide in diethyl ether was quenched with 2 ml of deuterium oxide. The isolated hydrocarbon mixture contained 7% benzene and 93% deuteriobenzene. Another 20-ml aliquot to the phenyl Grignard solution was refluxed for 24 hr and quenched with 2 ml of deuterium oxide. The hydrocarbon mixture from this reaction contained 12% benzene and 88% deuteriobenzene.

Stability of Benzylmagnesium Chloride in Diethyl Ether. A 20-ml aliquot of a freshly prepared 0.32 *M* solution of benzylmagnesium chloride in diethyl ether contained 4.5% toluene as determined by quenching with 2 ml of deuterium oxide and mass spectral analysis of the hydrocarbon mixture. Another 20-ml aliquot of the organometallic solution was refluxed under nitrogen for 71 hr and then quenched with 2 ml of deuterium oxide. The isolated hydrocarbon mixture contained 14.3% toluene, an increase of ca. 10% over 71 hr.

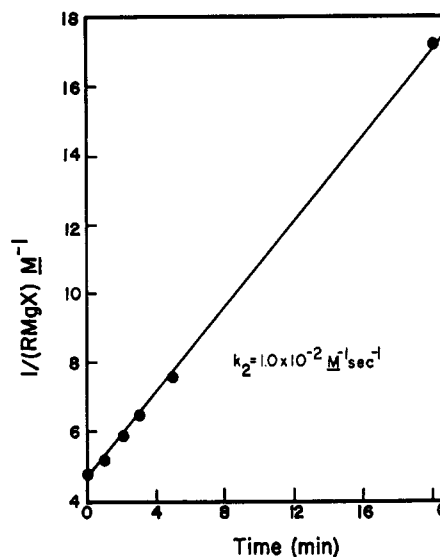


Figure 2. Second-order plot for the reaction of benzylmagnesium chloride with phenylacetylene in THF at 0° ; $[RMgX] = [PhC\equiv CH] = 0.205 M$.

Reactions of Grignard Reagents with Carbon Acids in THF. Benzylmagnesium Chloride and Phenylacetylene. The reactions of Grignard reagents with phenylacetylene in THF are much more rapid than those in diethyl ether; therefore, the aliquot method described for diethyl ether reactions was modified as follows. Depending on the number of desired points for the kinetic run, four to ten aliquots of a freshly prepared Grignard solution in a concentration range from 0.2 to 0.8 *M* were pipetted into dry, nitrogen-filled, 100-ml, three-necked flasks and cooled to 0° by means of external ice-water baths. Each flask contained between 0.005 and 0.010 mol of Grignard reagent. Equimolar amounts of freshly distilled phenylacetylene were then added *via* syringe to the magnetically stirred Grignard solutions, and each reaction mixture was quenched with 1.5 ml of deuterium oxide at given time intervals. The work-up and mass spectral analysis were as described. A sample run is shown in Figure 2.

Competition Rates. The Reaction of Phenyl- and Benzyl lithium with Carbon Acids. The relative reactivity of phenyl- and benzyl lithium toward carbon acids was determined by allowing equimolar mixtures of the organolithium compounds to compete for an insufficient amount of carbon acid.

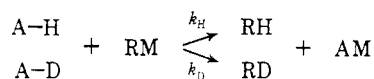
A 0.186 *M* solution of benzyl lithium in THF was prepared from dibenzylmercury. Simultaneously, a 0.224 *M* solution of phenyl lithium in THF was prepared. Using a dry, nitrogen-flushed, 25-ml pipet, five filtered, 25-ml aliquots of the benzyl lithium solution were transferred to five dry, nitrogen-filled, 100-ml, three-necked flasks equipped each with a nitrogen inlet, thermometer, and a magnetic stirring bar. Similarly, five 20-ml aliquots of the phenyl lithium solution were transferred to the benzyl lithium-containing flasks. The reaction vessels, maintained at 10° by external water baths, contained 0.00465 mol of benzyl lithium and 0.00448 mol of phenyl lithium as 0.10 *M* solutions in each component. The following materials were introduced with vigorous stirring to these solutions: to one flask, a solution of 0.41 ml (0.38 g, 0.00375 mol) of phenylacetylene in 10 ml of dry THF; to a second flask, a solution of 0.43 ml (0.44 g, 0.00375 mol) of indene in 10 ml of THF; to a third, a solution of 0.62 g (0.00375 mol) of fluorene in 10 ml of THF; to a fourth, a solution of 0.92 g (0.00375 mol) of triphenylmethane in 10 ml of THF; and to the fifth flask, 2 ml of deuterium oxide. After 2 min, each of the first four mixtures was quenched with 1 ml of deuterium oxide, the hydrocarbon mixtures were isolated, and the deuterium incorporation was determined by mass spectrometry. The relative reactivity ratios were calculated from the data by the method described for the determination of isotope effects.

Results and Discussion

Nuclear magnetic resonance spectroscopy is one of many tools which have been applied to examine the ionic character of organometallic compounds. The

general upfield shift of the proton absorptions of organomagnesium²³⁻²⁶ and organolithium compounds^{27, 28} has been attributed to the ionic charge inherent in the carbon-metal bond. Benzyl lithium in THF, for example, shows proton absorptions²⁷ at τ 3.70 for the *meta*, 3.91 for the *ortho*, and 4.50 for the *para* protons, compared to 2.9 for the aromatic protons in toluene. The above and related nmr data have been used to support the contention that benzyl lithium in THF exists as tight ion pairs.^{27, 28} The spectrum of benzylmagnesium chloride in THF obtained in the present work also exhibits an upfield shift of the aromatic proton absorptions. This spectrum shows proton absorptions at τ 3.31 (area 4) assigned to the *meta* and *ortho* protons of the Grignard reagent, at 3.68 (area 1) assigned to the *para* proton, and at 8.68 (area 2) assigned to the benzylic protons. It is interesting to note that the absorptions of the *para* and benzylic protons of benzylmagnesium chloride appear to be slightly solvent dependent, shifting upfield by about 0.1 ppm with increasing solvent polarity from diethyl ether to THF to hexamethylphosphoramide. A small solvent dependence is also observed for phenylmagnesium bromide, the absorption of the *meta* and *para* protons increasing from τ 3.01 in diethyl ether to 3.11 for THF, with the *ortho* proton absorptions remaining constant at 2.41. It is therefore attractive to consider the magnitude of the upfield shift of the aromatic proton absorptions to be an indication of the increasing ionic nature of the carbon-metal bond.

Determination of Isotope Effects. Most of the isotope effects in this work have been determined by a competitive method. In this procedure, an insufficient amount of a freshly prepared organometallic solution was added to a large excess (at least 10 mol excess) of an equimolar mixture of a proton and deuterium donor, $[HA] = [DA]$. After an extraction-distillation work-up, the isolated deuterated hydrocarbon mixture was mass spectrometrically analyzed using low ionizing voltages to avoid hydrocarbon fragmentation. For irreversible processes, the ratio of the product composition, $[RH]/[RD]$, is equivalent to the isotope effect, k_H/k_D .



The $P + 1$ peak was corrected for the isotopic contribution of the parent peak. The great sensitivity of these organometallic compounds to air, moisture, and solvent necessitated a second correction to account for the adventitious formation of RH accompanying the preparation of the organometal. The magnitude of the second correction was minimized by preparing the organometals under an atmosphere of dry nitrogen and by scrupulous drying of reagents and equipment. The attack of solvent, particularly on THF, could often be reduced by preparing the organometallic compounds

at low temperatures. The extent of RH formation was estimated in each isotope effect determination by quenching an aliquot of the organometallic solution with deuterium oxide. The percentage of RH present in the deuterated hydrocarbon mixture was then taken as a measure of the amount of decomposition of the organometal during preparation. The reported isotope effects were calculated by dividing the intensity of the $P + 1$ peak, corrected for ^{13}C contribution, by the intensity of the parent peak, corrected for the amount of hydrocarbon formed in side reactions. Inspection of all the parent peak areas of the mass spectra of the deuterated hydrocarbon mixtures excluded any dideuteration.²⁹ Random samples of toluene isolated from reaction mixtures were examined by infrared and showed no ring deuteration³⁰ within the limits of the infrared analysis.

When strictly irreversible processes are considered, the competitive method offers three advantages over the kinetic method in the determination of isotope effects. Relative velocities may be determined for very fast reactions, and precise temperature control and accurate knowledge of the reaction kinetics are not required. On the other hand, the competitive method may give spurious results in very fast reactions in which it may be difficult to obtain a homogeneous mixture prior to reaction.³¹ Nonkinetic factors like rate of stirring and concentration of solution appear to influence the product ratios in some competitive nitrations.³² Consequently, care was taken in the present work to show that isotope effects are indeed unaffected by variables in the method. The absence of systematic errors in the very fast reactions with oxygen acids was confirmed (a) by varying the rate of stirring up to 3000 rpm using a vibromixer; (b) by the use of a rapid stopped-flow type mixing; (c) by diluting the addendum; (d) by varying the concentrations of organometal tenfold; and (e) by varying the $[\text{ROH}]$ to $[\text{ROD}]$ ratio from $1/3$ to 3 (see footnotes to Table I). Following these findings, in all subsequent isotope effect determinations the organometallic solution was slowly added to a large excess of a proton and deuterium donor solution with vigorous magnetic stirring. Another difficulty in using a competitive method for the determination of isotope effects arises in multistep reactions in which competitive and kinetic measurements may not give the same result.³³ In three cases in which it was possible to determine the isotope effects in both manners, the product isotope effect was slightly larger but similar to the kinetically determined isotope effects. A larger discrepancy exists between our value for the isotope effect associated with reaction of benzyl lithium with triphenylmethane and the one determined kinetically by Waack and coworkers.³⁴ At present we have no explanation for this discrepancy.

Isotope Effects on Reactions of Organometals with Oxygen Acids. The isotope effects on the reactions

- (23) D. F. Evans and J. P. Maher, *J. Chem. Soc.*, 5125 (1962).
 (24) H. Roos and W. Zeil, *Z. Elektrochem.*, **67**, 28 (1963).
 (25) G. Fraenkel, D. G. Adams, and J. Williams, *Tetrahedron Lett.*, 767 (1963).
 (26) H. O. House, R. A. Latham, and G. M. Whitesides, *J. Org. Chem.*, **32**, 2481 (1967).
 (27) V. R. Sandel and H. H. Freedman, *J. Amer. Chem. Soc.*, **85**, 2328 (1963).
 (28) R. Waack, M. A. Doran, E. B. Baker, and G. A. Olah, *ibid.*, **88**, 1272 (1966).

- (29) G. A. Russell, *ibid.*, **81**, 2017 (1959).
 (30) L. J. Bellamy, "The Infra-Red Spectra of Complex Molecules," 2nd ed, Methuen & Co., Ltd., London, 1958, pp 67-69.
 (31) A. W. Francis, *J. Amer. Chem. Soc.*, **48**, 655 (1926).
 (32) W. S. Tolgyesi, *Can. J. Chem.*, **43**, 343 (1965).
 (33) L. Melander, "Isotope Effects on Reaction Rates," The Ronald Press Co., New York, N. Y., 1960, p 104.
 (34) R. Waack, P. West, and M. A. Doran, Abstracts, 152nd National Meeting of the American Chemical Society, New York, N. Y., Sept 1966, Abstract No. V41, private communication. We are grateful to Dr. R. Waack for sending us his isotope effect data prior to publication.

of organometallic compounds with oxygen acids determined in the present work are similar to those reported earlier.^{6,7} Wiberg⁶ found that deuterium isotope effects associated with proton transfer from deuterated methanol mixtures to *ca.* 1 *M* solutions of the organometallic compounds in dibutyl ether varied between 0.84 and 1.00. Similar work by Assarsson,⁷ using tritiated oxygen acids, suggested that the isotope effects for these reactions are close to unity. A summary of all the isotope effect data is given in Table I.

Table I. Deuterium Isotope Effects on the Reaction of Organometallic Compounds with Oxygen Acids in Ether Solvents^a

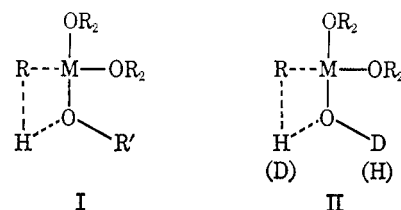
Organometal (solvent)	Phenol	Water	Methanol	<i>t</i> -Butyl alcohol
MeMgI (Bu ₂ O)	1.03 ^{b,c}	1.05 ^{b,d}	1.00 ^b	
<i>n</i> -BuMgBr (Bu ₂ O)			1.00 ^b 1.14 ^{b,d} 0.84 ^e	
PhMgBr (Et ₂ O)		1.37	1.00	
PhMgBr (Bu ₂ O)		1.45 ^{b,d}	1.12 ^b 0.97 ^e	
PhMgBr (THF)		1.56	1.08	
Ph ₂ Mg (THF)		1.37		
PhCH ₂ MgCl (Et ₂ O)		1.42	1.11 0.96 ^e	1.15
PhCH ₂ MgCl (THF)	1.08 ^f	1.52 ^{g,h}	1.15	1.26
(PhCH ₂) ₂ Mg (THF)		1.29		
PhLi (Et ₂ O)		1.06		
PhLi (THF)		1.06		
PhCH ₂ Li (THF)		1.06		
PhCH ₂ Na (THF)		1.15		
Ph ₃ CNa (THF)		1.29		
Ph ₃ CNa (Et ₂ O)		1.14		

^a This work at 15°, reproducibility $\pm 2\%$. ^b Assarsson's⁷ work, calculated from k_T/k_H . ^c With 2,6-di-*t*-butyl-4-methylphenol as the proton donor, 2.2. ^d THF-anisole solvent. ^e Wiberg's work. ^f With [PhOD]/[PhOH] = 1.01 the product ratio [RH]/[RD] was 1.08; with [PhOD]/[PhOH] = 1.77 the product ratio was 0.62. In both cases ([PhOD]/[PhOH])([RH]/[RD]) $\approx$ 1.08. ^g Addition to 20 mol excess of HOD gave [RH]/[RD] = 1.52; addition to 50 mol excess of HOD gave [RH]/[RD] = 1.50; addition to 50 mol excess of HOD and using a vibromixer (3000 rpm) gave [RH]/[RD] = 1.46; addition to 20 mol excess of HOD and using a vibromixer gave [RH]/[RD] = 1.52; changing the concentration of benzylmagnesium chloride from 0.05 to 0.5 *M* and addition to 20 mol excess of HOD gave [RH]/[RD] = 1.52; dilution of HOD with THF gave [RH]/[RD] = 1.54. ^h With [D₂O]/[H₂O] = $\frac{2}{3}$, the product ratio of [RH]/[RD] was 0.51; with [D₂O]/[H₂O] = $\frac{1}{3}$ the product ratio was 4.5. In both cases ([D₂O]/[H₂O])([RH]/[RD]) $\approx$ 1.5 at 15°.

The present work shows that isotope effects on the reaction of organometals with oxygen acids in diethyl ether and in THF are slightly greater than one. Generally, isotope effects are a little smaller in diethyl ether than in THF. Isotope effects are larger in transfer to organomagnesium compounds than to organoalkali-metal compounds, with the largest isotope effects occurring in the reactions of the Grignard reagents with water in THF. Changing the acid strength of the proton donor from $pK_a \sim 10$ (phenol)³⁵ to $pK \sim 19$ (*t*-butyl alcohol)³⁵ leaves the isotope effect for abstraction from these oxygen acids apparently unaffected. The largest isotope effect for these types of reactions was obtained by Assarsson.⁷ Although the isotope effect for the reaction of methylmagnesium iodide with phenol in dibutyl ether was 1.03,⁷ the effect

for the corresponding reaction with the sterically hindered 2,6-di-*t*-butyl-4-methylphenol was 2.2.⁷ The small deuterium isotope effects established in the present work for reactions of organometals with oxygen acids suggest that such reactions are either diffusion controlled or that they proceed *via* a prior ligand exchange between the oxygen acid and one of the ether molecules coordinated to the metal, followed by a proton transfer as visualized in transition state I.

The coordination of oxygen-containing compounds such as ethers,^{36,37} ketones,^{38,39} and esters³⁹ to organometallic compounds of magnesium and lithium is well established. Recent nmr work²⁶ has confirmed that tertiary alcohols like 3-methyl-3-pentanol complex with dimethylmagnesium in diethyl ether. Characteristic rate constants for the dissociation of water and methanol molecules from the inner coordination sphere of Mg²⁺, although fast, are significantly slower than diffusion-controlled processes: $k \sim 10^4$ sec⁻¹, and the estimated activation energy, E_a , is around 12 kcal/mol.⁴⁰ Butylmagnesium bromide complexes with acetone within 5 msec.³⁹ Thus, the ligand exchange between the oxygen acid and the ether molecule coordinated to the metal ("the coordination step") or the subsequent proton-transfer step could be rate determining. If the latter is indeed rate determining, or occurs concurrently with the former, one might anticipate that the coordination step would be associated with a small inverse isotope effect which may partially cancel the relatively small isotope effect resulting from proton transfer of the type visualized in transition state I. These considerations allow us to understand why the isotope effects for proton transfer from water to organomagnesium compounds are relatively larger than those from other oxygen acids. Since water and deuterium oxide form a species, HOD, in accord with eq 3, H₂O + D₂O = 2HOD, $K = 4$,⁴ to a first approximation there would be no inverse isotope effect arising from the coordination of HOD to the magnesium atom. The observed isotope effect would then arise primarily from the proton-transfer step (transition state II).



Reactivity of Organometals. In the course of the work on deuterium isotope effects associated with proton transfer from carbon acids to organometallic compounds, it became desirable to obtain some information about the relative speed of these processes. The reactions between Grignard reagents and the hydrocarbon acids phenylacetylene, indene, and fluorene were followed by withdrawing aliquots from the reaction mixture and quenching these with deuterium oxide

(36) G. D. Stucky and R. E. Rundle, *J. Amer. Chem. Soc.*, **85**, 1002 (1963); **86**, 4825 (1964).

(37) L. J. Guggenberger and R. E. Rundle, *ibid.*, **86**, 5344 (1964).

(38) S. G. Smith and G. Su, *ibid.*, **88**, 3995 (1966).

(39) T. Holm, *Acta Chem. Scand.*, **19**, 1819 (1965); **20**, 1139 (1966).

(40) S. Nakamura and S. Meiboom, *J. Amer. Chem. Soc.*, **89**, 1765 (1967).

(35) D. J. Cram, "Fundamentals of Carbanion Chemistry," Academic Press, New York, N. Y., 1965, pp 4, 19, 41.

at selected time intervals. After isolating the hydrocarbon mixture produced, mass spectral analysis of the deuterium content of the hydrocarbon fixed the concentration of the remaining organometallic compound. During the first half-life, all these reactions were found to be first order in organometal and first order in hydrocarbon acid, *i.e.*, second order over-all. Rate constants determined by the above method appear to be in good agreement with rate data pertaining to related reactions studied by other workers.⁴¹⁻⁴³ Thus we find that the rate constant for the reaction of phenylmagnesium bromide with phenylacetylene in ether is $1.2 \times 10^{-4} \text{ M sec}^{-1}$ at 37° ; Dessy and Salinger⁴³ report a second-order rate constant of $2.0 \times 10^{-4} \text{ M sec}^{-1}$ for the reaction of phenylmagnesium bromide with 1-hexyne in diethyl ether at 31.5° . We find the reactions of phenylacetylene with diphenyl- and dibenzylmagnesium in diethyl ether to be about twice as fast as the corresponding reactions with the arylmagnesium halides, and Dessy and Salinger report that the proton transfer from 1-hexyne to diethylmagnesium is three times faster than to ethylmagnesium bromide.⁴² It is interesting to note that the reaction of phenylmagnesium bromide with 1-octyne in ether at 37° is four times faster than the corresponding reaction with phenylacetylene, although octyne is apparently a weaker acid than phenylacetylene.⁴⁴ Table II summarizes the rate data obtained for reactions of Grignard reagents with carbon acids.

Table II. Rate Constants for the Reactions of Grignard Reagents with Proton Donors

Organo-metal	Proton donor	Solvent	Temp, °C	$k_2 \times 10^5, \text{ M}^{-1} \text{ sec}^{-1}$
PhMgBr	1-Octyne	Et ₂ O	37	50 ^a
PhMgBr	PhC≡CH	Et ₂ O	37	12
PhMgBr	PhC≡CH	THF	0	100 ^b
PhMgBr	Indene	THF	0	0.5
		THF	15	8
PhCH ₂ MgCl	PhC≡CH	Et ₂ O	0	0.03
		Et ₂ O	37	1.2
		THF	0	840
PhCH ₂ MgCl	Indene	THF	15	40
	Fluorene	THF	20	30

^a Followed by nmr. ^b Approximated from half-life of the reaction.

Proton abstraction from phenylacetylene by phenyl and benzyl Grignard reagents is much faster in THF than in diethyl ether. Thus, the reaction of phenylacetylene with benzylmagnesium chloride is about 30,000 times faster in THF than in ether. The large rate enhancement in THF, a more polar solvent than diethyl ether, is not unexpected since the transition states for this type of reaction exhibit a large degree of charge separation.⁴³ Proton transfer to organomagnesium compounds from fluorene, the weakest acid of the three hydrocarbons, is slowest. Indene, a stronger acid than fluorene by about 3 pK_a units,^{45,46}

reacts about five times faster than fluorene, phenylacetylene about 300 times faster than fluorene. This reactivity would mark phenylacetylene with a "kinetic" acidity of about 17-18 relative to 20 for indene and 23 for fluorene.^{45,46}

Information about relative rates was more difficult to obtain with the organoalkali-metal compounds. By the method of Waack and West⁴⁷ it was possible to estimate that benzylsodium abstracts a proton from triphenylmethane in THF at least four times faster than benzyl lithium in THF. Phenyllithium in THF abstracts a proton about three times faster from *p*-biphenyldiphenylmethane (Ar_3CH) than from triphenylmethane. In accordance with previous data⁴⁷ the reaction of benzyl lithium with triphenylmethane in THF is about 45 times faster than the corresponding reaction of phenyllithium. The relative rate of reaction between phenyl- and benzyl lithium and carbon acids in THF was estimated by competition experiments in which a small excess of an equimolar mixture of phenyl- and benzyl lithium was allowed to react with an insufficient amount of the carbon acid. The reaction mixture was quenched with deuterium oxide and the relative rate of reaction of the two organometals estimated from the ratio of toluene to benzene in the deuterated hydrocarbon mixtures (Table III). It is interesting to note that proton abstraction appears to become more selective in favor of benzyl lithium as the carbon acids become weaker in the order phenylacetylene ($pK_a \sim 18$), indene ($pK_a \sim 20$), fluorene ($pK_a \sim 23$), and triphenylmethane ($pK_a \sim 31.5$).^{45,46}

Table III. Relative Reactivity of Phenyl- and Benzyl lithium toward Proton Donors in THF

Proton donor	$k_{\text{PhCH}_2\text{Li}}/k_{\text{PhLi}}^a$
Phenylacetylene	0.8-1.0
Indene	4.0
Fluorene	5.0
Triphenylmethane	30-50

^a Estimated.

Isotope Effects on the Reactions of Organometals with Carbon Acids. Deuterium isotope effects arise primarily from the zero-point, ground-state energy difference between the C-H and the C-D bond.⁴⁸ A large portion of this difference is attributed to the differences in the stretching frequencies of the two bonds. From the infrared spectra of the hydrocarbon acids we estimate that the stretching vibrations would give rise to a maximum isotope effect of about 7 at 15° for all the carbon acids. An additional contribution from bending-mode differences could raise this estimate to approximately 10.

Isotope effects for the reaction of organometals with phenylacetylene vary from 2.2 to 6.2 in diethyl ether, and from 1.4 to 3.6 in THF (Table IV). The isotope effect is largest in the reactions of organomagnesium compounds and decreases for reactions involving organo-alkali metal compounds. Generally, $[\text{RH}]/$

(41) J. H. Wotiz, C. A. Hollingsworth, and R. E. Dessy, *J. Amer. Chem. Soc.*, **78**, 1221 (1956).

(42) R. E. Dessy, J. H. Wotiz, and C. A. Hollingsworth, *ibid.*, **79**, 358 (1957).

(43) R. E. Dessy and R. M. Salinger, *J. Org. Chem.*, **26**, 3519 (1961).

(44) R. E. Dessy, Y. Okuzumi, and A. Chen, *J. Amer. Chem. Soc.*, **84**, 2899 (1962).

(45) A. Streitwieser, Jr., J. H. Hammons, E. Ciuffarin, and J. I. Brauman, *ibid.*, **89**, 59 (1967).

(46) A. Streitwieser, Jr., E. Ciuffarin, and J. H. Hammons, *ibid.*, **89**, 63 (1967).

(47) R. Waack and P. West, *ibid.*, **86**, 4494 (1964).

(48) K. B. Wiberg, *Chem. Rev.*, **55**, 713 (1955).

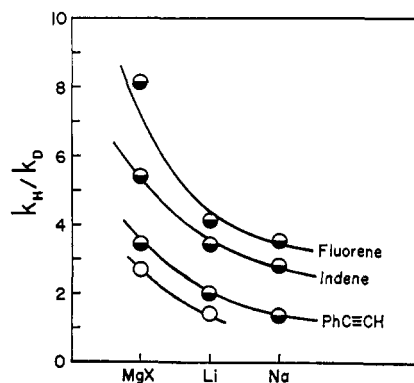


Figure 3. Kinetic deuterium isotope effects, k_H/k_D , for the reaction of proton *vs.* deuterium donors with benzylmetallic compounds, $\bullet$, and with phenylmetallic compounds, $\circ$. The horizontal scale is arbitrary.

[RD] decreases as the rate of the reaction increases. In THF, for example, the isotope effect is 3.4 for the reaction of benzylmagnesium chloride with phenylacetylene, 1.4 for the much faster reaction of benzylsodium. Waack and West³⁴ have noted that the variances in isotope effects for proton transfer from triphenylmethane to various organolithium compounds are difficult to interpret. Thus, different steric factors or different reactive species may affect the transition state of a reaction in such a way as to induce differences in the isotope effects in reactions involving different organometals. Consequently, comparisons of isotope effects associated with different organometallic compounds must be made with caution, even when comparisons are made in the same solvent. Isotope effects on the reactions of organometallic compounds with a series of carbon acids in THF are shown in Table V. In the reaction of benzylmetallic compounds, the isotope effect decreases in the series MgX, Li, and Na for the reaction of these compounds with the three strongest acids of the series, phenylacetylene, indene, and fluorene (Figure 3). For example, the isotope effect on the reaction of indene with benzylmagnesium chloride is 5.4, with benzyl lithium 3.4, and with benzyl sodium 2.9. In the reaction of phenylacetylene with phenylmagnesium bromide ($[RH]/[RD] = 3.0$) and with phenyllithium ($[RH]/[RD] = 1.4$) the same trend is observed, $MgX > Li$.

Table IV. Isotope Effects on the Reactions of Organometals with Phenylacetylene at 15°

Organometal	$[RH]/[RD]$ (Et ₂ O)	$[RH]/[RD]$ (THF)
Benzylmagnesium chloride	6.2 ± 0.2	3.4 ± 0.2
Dibenzylmagnesium	5.4 ± 0.2	3.6 ± 0.2
Phenylmagnesium bromide	5.2 ± 0.2	3.0 ± 0.2
Diphenylmagnesium	4.6 ± 0.2	3.4 ± 0.2
Benzyllithium	2.2 ± 0.1	2.0 ± 0.2
Phenyllithium	2.4 ± 0.1	1.4 ± 0.1
Benzylsodium		1.4 ± 0.1

It is perhaps more valid to compare isotope effects associated with transfer from a series of proton donors to the same organometallic compound in the same solvent. In the absence of concentration effects, the

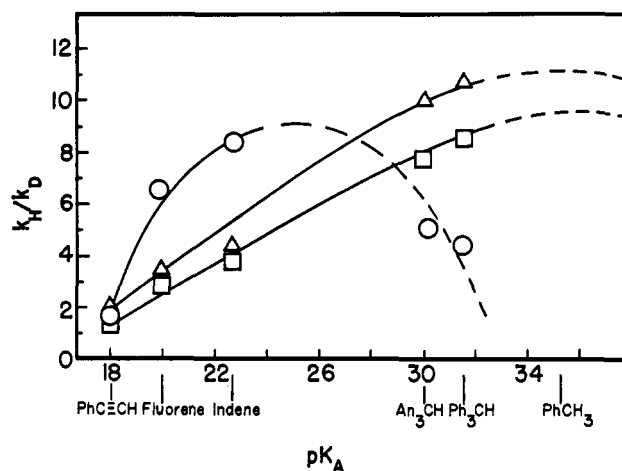


Figure 4. A plot of kinetic deuterium isotope effects, k_H/k_D , for the reaction of organometals with carbon acids *vs.* the pK_A of the hydrocarbon: $\circ$, phenyllithium; Δ , benzyllithium; $\square$, benzylsodium.

reactive organometallic species remains the same for reactions in which only the proton donor is varied. Thus, degree of association of the organometal in solution as well as its spacial requirements become secondary in any comparison of processes involving one and the same organometallic compound. Barring the existence of special steric factors in the carbon acids, the ground states for such a series of reactions should be relatively unimportant in considerations of isotope effects. The isotope effect on the reactions of benzylmagnesium chloride with the proton donors increases from 3.4 for phenylacetylene to 5.4 for indene and to 8.2 for fluorene. An increase of the isotope effect with decreasing rate of reaction of the organometal with the hydrocarbon is also observed for the reactions of benzyllithium and benzylsodium. For reactions of phenyllithium with proton donors, however, the isotope effects change from 1.4 to 6.5 to 8.1 with the three strongest hydrocarbon acids of the series, but decrease again to 4.7 and 4.6 for Ar_3CH and triphenylmethane, respectively. In acid-base reactions, the rate of the reaction is often related to the acidity constant of the acid. Figure 4 shows a plot of the isotope effect on the reactions of benzyllithium, benzylsodium, and phenyllithium with the hydrocarbons *vs.* the acidity of the hydrocarbon, the acidity constant being taken as a measure of the relative reactivity of these carbon acids. The acidity constants used in this work were determined by Streitwieser and co-workers^{45,46} in cyclohexylamine solvent. The actual pK_A 's may be different in THF; however, in view of the excellent agreement between the acidity scales in cyclohexylamine and in dimethyl sulfoxide,^{49,50} the *relative acidity differences* in THF might be expected to parallel those in cyclohexylamine. Inspection of Figure 4 suggests that the isotope effect for reactions of phenyllithium with the carbon acids reaches a maximum in going from phenylacetylene to fluorene and then decreases with the more weakly acidic hydrocarbons. The isotope effects for the reactions of benzyllithium and benzylsodium also appear to change with changes in

(49) E. C. Steiner and J. D. Starkey, *J. Amer. Chem. Soc.*, **89**, 2751 (1967).

(50) C. D. Ritchie and R. E. Uschold, *ibid.*, **89**, 2752 (1967).

Table V. Isotope Effects on the Reactions of Organometals with Proton Donors in THF at 15°

Organometal	Phenylacetylene	Indene	Fluorene	<i>p</i> -Biphenyl- diphenylmethane	Triphenyl- methane
Benzylmagnesium chloride	3.4 ± 0.2	5.4 ± 0.2	8.2 ± 0.4		
Phenylmagnesium bromide	3.0 ± 0.2				
Benzyllithium	2.0 ± 0.2	3.4 ± 0.2 ^a	4.0 ± 0.1	9.7 ± 1 ^a	10.8 ± 1
Phenyllithium	1.4 ± 0.1	6.5 ± 0.5	8.1 ± 0.4	4.7 ± 0.5 ^a	4.6 ± 0.5
Benzylsodium	1.4 ± 0.1	2.9 ± 0.2	3.6 ± 0.2	7.4 ± 0.7 ^a	8.4 ± 0.8

^a One determination.

acidity of the proton donors, and appear to reach a maximum value of 10–11 for the case of triphenylmethane.

The possibility of the existence of a maximum in isotope effects in proton transfer reactions has aroused a great deal of interest in recent years. It has been proposed by Westheimer,⁵¹ Swain,⁵² Bigeleisen,⁵³ and Bell⁵⁴ that the ratio k_H/k_D should be a function of the position of the hydrogen atom in the transition state. Experimental support of these theoretical predictions has come from isotope effect studies by Bell and coworkers^{55,56} on hydrogen transfer from acetone, β -carbonyl compounds, and nitroalkanes to various bases. For these related reactions, the isotope effects ranged from 7 at ΔpK ($pK_{\text{acceptor}} - pK_{\text{donor}}$) = 8, to a maximum at about 10 for ΔpK of -5 to +3, to 3.8 for a ΔpK of 14. Also, isotope ratios for the protonation of aromatic bases have varied with changes in pK .⁵⁷ Long and coworkers^{58,59} have observed isotope effects changing from 6 to a maximum at 9.6 and decreasing to 6 with ΔpK changes from +3 to -6. The maximum isotope effects for the above systems occur when ΔpK is near zero, in agreement with isotope effect theory which predicts a maximum for symmetrical transition states in a series of closely related processes. In such a series of reactions, maximum isotope effect theory predicts that isotope effects should be lower when the hydrogen atom in the transition state is closer to one of the reactants.

Similarly, the constants α and β of the Brønsted relationship have been taken as a measure of the extent of the reaction, with a value near unity indicating a transition state resembling products, and a value near zero close resemblance to reactants.⁶⁰ Recently, the development of techniques for studying fast reactions⁶¹ has made it possible to extend the Brønsted relation to a wide range of acid-base reactions. By plotting $\log k$ vs. ΔpK for proton-transfer reactions from an acid or its anion to a series of bases or acids, Eigen⁶¹ has shown that in the limiting case of a diffusion-controlled reaction, $k_2 \approx 10^{11} M^{-1} \text{sec}^{-1}$, $\Delta pK \sim 20$, the slopes of curves α and β tend to zero, suggesting a transition

state resembling reactants. At the other extreme, $k_2 \approx 10^{-7} M^{-1} \text{sec}^{-1}$, α and β tend to 1, suggesting a transition state resembling products for a series of related reactions. At $\Delta pK = 0$, the slope of α and β in an ideal case is 0.5, suggesting a symmetric transition state.⁶¹ However, this center of symmetry need not be at $\Delta pK = 0$, since the curves α and β depend on the limiting values of k .⁶¹ It has been suggested that isotope studies might be of considerable interest in correlating the degree of proton transfer in the transition state with the rates of these reactions.^{55,62}

The data in the present work support the existence of a maximum in the isotope effects for a series of closely related reactions. Thus, following the concept that the stronger base is the less neutralized of the two bases between which the proton is being transferred,⁶⁰ it is possible to speculate on the nature of the transition state for the reaction of organometals with the series of hydrocarbon acids. Thus, the reactions of benzyl-lithium and benzylsodium with phenylacetylene would proceed *via* an activated complex resembling the ground states. As the reactions become slower, *i.e.*, in reactions with the weakly acidic hydrocarbons, the transition state tends toward a symmetrical proton transfer. Similarly, the reaction of phenyllithium would tend from a transition state resembling reactants with phenylacetylene to a symmetrical activated complex with fluorene. The transition states for the reaction of phenyllithium with Ar_3CH and triphenylmethane would resemble the products.

Assuming a linear, triatomic transition state, isotope-effect theory predicts a maximum in the isotope effect for a symmetrical proton transfer in the transition state. Thus, the maximum isotope effect for reactions of benzyl-lithium and benzylsodium would be expected in proton transfer from toluene, at a pK_a of about 34–35.³⁵ Although the extrapolation from triphenylmethane is difficult to make, Figure 4 suggests that this is indeed the area in which the maximum occurs. In the reactions of phenyllithium, however, the maximum occurs at a pK_a of about 25–26, about 10 pK_a units removed from the expected pK of 36–37, corresponding to transfer from benzene. One explanation for this displacement of the maximum may be that the transition state for proton abstraction from the parent hydrocarbon would resemble an ion pair such as $[\text{R} \cdots \text{H} \cdots \text{R}]^-, \text{M}^+$. This activated complex is difficult to attain when the carbon-metal bond in the ground state is fairly strong and the ionizing capacity of the solvent relatively low. Thus, benzylmetallic compounds would be better able to generate this charge separation because

(51) F. H. Westheimer, *Chem. Rev.*, **61**, 265 (1961).(52) C. G. Swain, *J. Amer. Chem. Soc.*, **83**, 2154 (1961).(53) J. Bigeleisen, *Pure Appl. Chem.*, **8**, 217 (1964).(54) R. P. Bell, *Disc. Faraday Soc.*, **39**, 16 (1965).(55) R. P. Bell and J. E. Crooks, *Proc. Roy. Soc., Ser. A*, **286**, 285 (1965).(56) R. P. Bell and D. M. Goodall, *ibid.*, **294**, 273 (1966).(57) A. J. Kresge and Y. Chiang, *J. Amer. Chem. Soc.*, **84**, 3976 (1962).(58) J. C. Gruen and F. A. Long, *ibid.*, **89**, 1287 (1967).(59) J. L. Longridge and F. A. Long, *ibid.*, **89**, 1292 (1967).

(60) J. E. Leffler and E. Grunwald, "Rates and Equilibria of Organic Reactions," John Wiley & Sons, Inc., New York, N. Y., 1963, pp 156–159, 241.

(61) M. Eigen, *Angew. Chem. Int. Ed. Engl.*, **3**, 1 (1964).(62) M. Eigen, *Disc. Faraday Soc.*, **39**, 7 (1965).

of the favorable resonance distribution. The ability to develop ionic charge in the transition state varies with the cation and with the solvent as well as with the organic group. Thus, organometals undergo proton abstraction and nucleophilic substitution reactions much more easily in polar solvents like dimethyl sulfide⁶³ and hexamethylphosphoramide⁶⁴ than in THF or ether. Benzyl lithium appears to react faster than phenyllithium^{47,65} in processes requiring large charge separation, whereas the opposite may be the case⁶⁶

(63) J. T. Brauman, D. F. McMillen, and Y. Kanazawa, *J. Amer. Chem. Soc.*, **89**, 1728 (1967).

(64) H. Normant and T. Cuvigny, *Bull. Soc. Chim. Fr.*, 1881 (1965).

(65) E. Grovenstein, Jr. and G. Wentworth, *J. Amer. Chem. Soc.*, **89**, 1852 (1967).

(66) H. Gilman and H. A. McNinch, *J. Org. Chem.*, **27**, 1889 (1962).

when the activated complex for a reaction requires relatively little charge separation, such as in a transition state resembling reactants.

In summary, it has been demonstrated that isotope effects in reactions of an organometallic compound with hydrocarbon acids in THF change with the rate of the reaction. The variation of the isotope effect for proton transfer from weakly acidic hydrocarbons to a given organometal supports the theoretical prediction of a maximum in isotope effects for a series of closely related reactions. The position of the maximum in the isotope effect and the shape of the curve may be an indication of the effect of the cation or the organic group on the ionic nature of these organometallic compounds.

Radiation-Induced Oxidation of 2-Propanol by Dialkyl Peroxide^{1a}

Warren V. Sherman^{1b}

Contribution from the Radiation Laboratory,² University of Notre Dame, Notre Dame, Indiana 46556. Received May 20, 1968

Abstract: Solutions of di-*t*-butyl peroxide in 2-propanol have been subjected to ⁶⁰Co γ irradiation. Under alkaline conditions di-*t*-butyl peroxide was reduced to *t*-butyl alcohol and the solvent oxidized to acetone according to the stoichiometry $(t\text{-BuO})_2 + \text{Me}_2\text{CHOH} \rightarrow 2t\text{-BuOH} + \text{Me}_2\text{CO}$. Yields were independent of alkali concentration when the latter exceeded about $2 \times 10^{-2} M$, but were first order in peroxide concentration. The magnitudes of the yields indicate a chain reaction. It is proposed that the chain is initiated by radiolytic intermediates that undergo hydrogen abstraction reactions with the solvent to produce dimethylhydroxymethyl radicals (I). The latter ionize, and the resulting radical anions (II) undergo a redox reaction with di-*t*-butyl peroxide, decomposing it to *t*-butoxide and a free radical (*t*-butoxy) that can regenerate I from the solvent. The chain reaction exhibits a dose-rate dependence that is consistent with termination being second order in chain carrier. Retardation and inhibition were observed in the presence of compounds that may be expected to undergo nondissociative electron transfer with II (nitrobenzene, benzophenone, oxygen, sulfur hexafluoride, perfluorocyclobutane) but were not observed in the presence of neutral free radical scavengers (1-hexene, benzene) or compounds that may be expected to dissociate on electron capture (methyl bromide, bromobenzene, carbon tetrachloride, nitrous oxide).

In a recent study of the base-catalyzed chain decomposition of nitrous oxide in alcoholic solution, the photolysis of dissolved di-*t*-butyl peroxide (DTBP) was used as a source of initiating free radicals.³ Incidental to this study was the observation that, in the absence of nitrous oxide, decomposition of DTBP and the concomitant oxidation of the solvent were increased by the presence of alkali. The suggested cause of this increase was that DTBP itself enters into a chain reaction in which propagation involves a redox reaction with the ionized form of the solvent α-hydroxyalkyl radical (the latter being oxidized to the ketone, while DTBP is reduced to a *t*-butoxy radical and a *t*-butoxide ion). This type of reaction is an interesting extension of the chemistry of dialkyl peroxides,⁴ and therefore worthy of more detailed study. Toward this end the present communication reports further experiments on

the chain decomposition of DTBP in alkaline 2-propanol in which the chain-initiating species are generated by the absorption of ⁶⁰Co γ rays in the solution.

Experimental Section

Materials. 2-Propanol (Baker reagent) was used as received. Acetone ($\sim 10^{-5} M$) was the only detectable impurity in the sample used. Potassium hydroxide (Baker) and DTBP (K & K Laboratories) were similarly used as received. Nitrous oxide, sulfur hexafluoride, perfluorocyclobutane, and methyl bromide (Matheson) were purified from air by trap-to-trap distillation on a vacuum line. All other materials were of reagent grade and used without further purification.

Procedure. All solutions were freshly prepared directly before radiolysis to minimize any decomposition of the peroxide. Aliquots (5 ml) were placed in 13-mm o.d. Pyrex tubes fitted with standard-taper joints. These were attached to a vacuum line and thoroughly degassed by successive freeze-pump-thaw cycles. When a gaseous solute was to be added this was admitted into an evacuated bulb of known volume to a measured pressure, and then the gas was condensed into the reaction tube cooled in liquid nitrogen. The reaction tube was then sealed and allowed to warm to room temperature before irradiation. When a gaseous additive was present, the tube was vigorously shaken for at least 10 min to ensure equilibration.

Samples were irradiated at room temperature in a 4-kc ⁶⁰Co source. Dose rates received by Fricke dosimeter solutions, based on $G(\text{Fe}^{3+}) = 15.6$, were $1.57 \times 10^{18} \text{ eV ml}^{-1} \text{ min}^{-1}$. The dose received by a particular solution was calculated by correction for the

(1) (a) Part IV: The γ Radiolysis of 2-Propanol. Part III: W. V. Sherman, *J. Phys. Chem.*, **71**, 1695 (1967); (b) address inquiries to Chicago State College, Chicago, Ill. 60621.

(2) The Radiation Laboratory is operated by the University of Notre Dame under contract with the U.S. Atomic Energy Commission. This is AEC Document No. COO-38-608.

(3) W. V. Sherman, *J. Am. Chem. Soc.*, **89**, 1302 (1967).

(4) For reviews see A. G. Davies, "Organic Peroxides," Butterworth and Co., Ltd., London, 1961, and A. V. Tobolsky and R. B. Mesrobian, "Organic Peroxides," Interscience Publishers, New York, N. Y., 1954.