was collected on the same column for mass spectral analysis. The "benzene" contained 60% C_6H_6 and 40% C_6H_5D. Two other reactions gave "benzene" (56% C_6H_6 and 44% C_6H_5D) in 34% yield and "benzene" (53% C_6H_6 and 47% C_6H_5D) in 36% yield. The "methylenecyclohexane" yields were 62 and 66%, respectively. Samples of the "methylenecyclohexane" were collected by g.l.c. and their mass spectra obtained (cf. Table I).

Mass Spectrum Calculations. Mass spectra were determined with a Consolidated Electrodynamics Corp. Model 21-130 mass spectrometer. Since the mass spectra were used only for determining the per cent isotopic composition of mixtures of deuterated species, the spectra were run at reduced voltage, under which conditions all peaks lower than the molecular ion were eliminated. Operating conditions were a sample pressure of 20 or 40 μ, filament current of 40 μa., and voltage settings of 250–370. Several traces of each spectrum were obtained, and the results are based on averaged intensities. Examples of the type of calculations used in determining per cent isotopic composition are given in ref. 14.

Reaction of Triphenylphosphineethylidene with Methyltriphenylphosphonium Bromide. An ethereal solution of triphenylphosphineethylidene was prepared by treating a suspension of 11 mmoles of ethyltriphenylphosphonium bromide in 50 ml. of ether with 12.3 ml. of 0.82 N (10 mmoles) phenyllithium in ether. After 45 min. the bright red-orange solution gave a negative Gilman Color Test I. Methyltriphenylphosphonium bromide (11 mmoles) then was added in one portion. The resulting reaction mixture was yellow after it had been stirred at room temperature for 24 hr. It then was quenched with 20 mmoles of cyclohexanone and refluxed overnight. All volatiles were removed by reduced pressure trap-to-trap distillation (to 135° at 0.1 mm.). Toluene (8.96 mmoles) was added to the distillate. Gas chromatographic analysis showed the presence of benzene (99%), methylenecyclohexane (85%), and ethylidenecyclohexane (5%). Another reaction carried out in a similar manner gave methylenecyclohexane (78%) and ethylidenecyclohexane (4%).

Essentially the same procedure was used in studying the reaction of triphenylphosphinemethylene with ethyltriphenylphosphonium bromide, and in those experiments were 1 molar equiv. each of two different phosphonium salts were treated with 1 molar equiv. of phenyllithium.

A related experiment, carried out using this general procedure, is that in which 1 molar equiv. of ethylmethyldiphenylphosphonium bromide was treated with 1 molar equiv. of phenyllithium, followed by quenching of the reaction mixture with cyclohexanone. The products obtained were benzene (91%), methylenecyclohexane (72%), and ethylidenecyclohexane (ca. 1%).

$$[(C_6H_5)_2P^+(CH_3)(C_2H_5)]Br^- + C_6H_5Li \longrightarrow$$
$$(C_6H_5)_2(C_2H_5)\overset{+}{P}\overset{-}{C}H_2 + C_6H_6 + LiBr$$
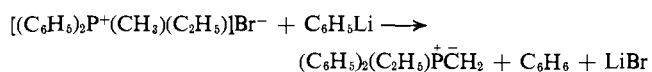
In the experiment where 1 molar equiv. each of $[(C_6H_5)_3P^+CD_3]I^-$ and $[(C_6H_5)_3P^+C_2H_5]I^-$ were treated with 1 molar equiv. of phenyllithium, the isotopic composition of the resulting benzene was the item of interest. For this reason the phenyllithium solution used was checked for benzene (C_6H_6). Reaction of an aliquot of the C_6H_5Li solution with freshly distilled trimethylchlorosilane, followed by g.l.c. analysis for C_6H_6 showed 2 mole % benzene in the phenyllithium solution. The double titration of this solution with 1,2-dibromoethane indicated the presence of 2% non-organometallic base.

Magnetic Resonance Spectroscopy. The Configurational Stability of Primary Grignard Reagents. 3,3-Dimethylbutylmagnesium Chloride[1]

George M. Whitesides, Michal Witanowski, and John D. Roberts

Contribution No. 3186 from the Gates and Crellin Laboratories of Chemistry, California Institute of Technology, Pasadena, California. Received January 9, 1965

Detailed examination of the temperature dependence of the n.m.r. spectra of 3,3-dimethylbutylmagnesium chloride and bis(3,3-dimethylbutyl)magnesium indicates that inversion of configuration at the $-CH_2Mg$ center occurs rapidly in ether solution at room temperature. Activation parameters for the inversion reactions are $E_a = 11 \pm 2$ kcal./mole, $A = 10^{9.5 \pm 1.5}$ sec.$^{-1}$, and $E_a = 20 \pm 2$ kcal./mole, $A = 10^{13.5 \pm 1.5}$ sec.$^{-1}$, respectively.

Introduction

The configurational stability of Grignard reagents is of interest not only to the classical problems of the structure of Grignard reagents and the stereochemistry of their reactions, but also in connection with the details of carbon–metal bonding. The best explored approach

to determining the configurational stability has been through comparison of the stereochemistry of products obtained from carbonation or oxidation of a Grignard reagent with that of the halide from which it was obtained. For those compounds in which the carbon bonded to the metal has the hybridization sp^2, it appears that inversion of configuration is slow.[2] Thus, both *cis* and *trans* isomers of 2-bromobutene-2 have been converted to the corresponding acids with complete retention of configuration *via* the Grignard reagents,[3] and the Grignard reagent from (+)-1-bromo-1-methyl-2,2-diphenylcyclopropane has been shown to possess a high degree of configurational stability.[4] These observations are in agreement with the configurational stability of the more carefully studied alkenyllithium[1,5] and cyclopropyllithium[4,6] compounds.

Attempts to measure the configurational stability of organomagnesium compounds in which the carbon bonded to metal is expected to be sp^3 hybridized have been less fruitful.[7] Careful examination of the optical purity of products obtained from optically active halides by means of the corresponding Grignard reagents has led to the conclusion that complete racemization takes place at some point during the reaction sequence.[8]

Unfortunately, this observation of racemization in products of at least two reactions removed from starting material does not allow a decision to be made concerning the optical stability of the organometallic compound itself. Racemization might have occurred during formation or reaction of the Grignard reagent, as well as during its lifetime. Although little evidence is available concerning the importance of racemization during reaction, several data suggest that extensive racemization may occur during preparation of the Grignard reagent under the usual conditions from magnesium metal and halide.

The most direct of these is Walborsky's observation that the acid obtained on carbonation of 1-methyl-2,2-diphenylcyclopropyl Grignard reagent displayed a complete retention of optical activity only if prepared by the reaction of its lithium analog with magnesium bromide or methylmagnesium bromide.[4] The organolithium compound, in turn, was prepared by metal-halogen exchange between the cyclopropyl bromide and *n*-butyllithium. If the Grignard reagent was prepared by direct reaction between halide and magnesium turnings, then only 10–15% optical purity was observed in the products.

Walborsky concluded from these experiments that racemization on the metal surface occurred to an important extent during formation of the Grignard reagent. Subsequently, other workers have obtained
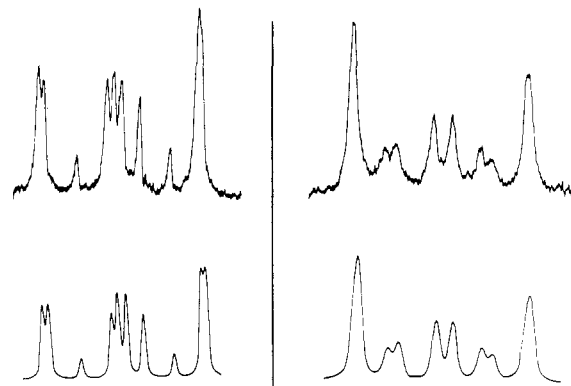

Figure 1. Observed (upper) and calculated (lower) spectra for the $-CH_2X$ protons of 3,3-dimethylbutyl chloride (left) and bis(3,3-dimethylbutyl)magnesium (right).

data which suggest that the intermediate formed initially in reaction between an alkyl halide and magnesium metal may resemble an alkyl radical. Thus, Rüchardt[9] has isolated products from the reaction of neophyl chloride with magnesium which are characteristic of rearrangement of the neophyl free radical,[10] and Hamilton has shown that the formation of allylcarbinyl Grignard reagent from the reaction of cyclopropylcarbinyl chloride with magnesium is well explained on the basis of a free-radical mechanism.[11]

Nonetheless, despite the difficulties associated with interpretation of the numerous experiments directed toward determination of the configurational stability of Grignard reagents, it seems likely that not all of the racemization observed in products derived from these organometallics occurs during their formation or subsequent reaction.

The work reported here was initiated in the hope that examination of Grignard reagents in solution by n.m.r. spectroscopy might help to eliminate some of the ambiguities associated with interpretation of reaction product studies.

Results and Discussion

The n.m.r. spectrum of the methylene protons of 3,3-dimethylbutyl chloride in carbon tetrachloride or carbon disulfide solution is a typical AA′XX′ spectrum[12] (see Figure 1). Of the 24 theoretical possible transitions, 20 have sufficient intensity to be observable. In contrast, the spectra of the $-CH_2X$ protons of 3-methylbutyl chloride, 3-methylbutyl bromide, 3-methylbutyl iodide, *n*-butyl chloride, *n*-butyl iodide, and propyl chloride are all triplets to at least a first approximation. The difference in the spectra of 3,3-dimethylbutyl chloride and these halides is reasonably explained on the basis of the relative sizes of the substituents on the ethylene fragment. In 3,3-dimethylbutyl chloride,

(2) D. Seyferth in "Progress in Inorganic Chemistry," Vol. 3, F. A. Cotton, Ed., Interscience Publishers, Inc., New York, N. Y., 1962, pp. 150–170; H. D. Kaesz and F. G. A. Stone in "Organometallic Chemistry," H. Zeiss, Ed., Reinhold Publishing Corp., New York, N. Y., 1960, Chapter 3.

(3) H. Normant and P. Maitte, *Bull. soc. chim. France*, 1439 (1956).

(4) H. M. Walborsky, *Rec. Chem. Progr.* (Kresge-Hooker Sci. Lib.), 23, 75 (1962); H. M. Walborsky and A. E. Young, *J. Am. Chem. Soc.*, 86, 3288 (1964).

(5) D. Y. Curtin and W. J. Koehl, Jr., *ibid.*, 84, 1967 (1962).

(6) D. E. Applequist and A. H. Peterson, *ibid.*, 83, 862 (1961).

(7) For references to early work on this subject, see H. L. Goering and F. H. McCarron, *ibid.*, 80, 2287 (1958).

(8) It has been reported that configurationally stable tertiary dialkylmagnesium compounds can be prepared by a transmetalation reaction from optically active organomercury compounds: O. Reutov, *Bull. soc. chim. France*, 1383 (1963).

(9) C. Rüchardt and H. Trautwein, *Ber.*, 95, 1197 (1962).

(10) W. H. Urry and M. S. Kharasch, *J. Am. Chem. Soc.*, 66, 1438 (1944); S. Winstein and F. Seubold, Jr., *ibid.*, 69, 2916 (1947); C. Rüchardt and R. Hecht, *Tetrahedron Letters*, 957, 961 (1962), and references therein.

(11) C. Hamilton, Ph.D. Thesis, California Institute of Technology, 1963.

(12) (a) J. A. Pople, W. G. Schneider, and H. J. Bernstein, "High-Resolution Nuclear Magnetic Resonance," McGraw-Hill Book Co., Inc., New York, N. Y., 1959, Chapter 6; (b) J. D. Roberts, "An Introduction to the Analysis of Spin-Spin Coupling in High-Resolution Nuclear Magnetic Resonance Spectra," W. A. Benjamin, Inc., New York, N. Y., 1962, Chapter 4.

steric hindrance between the bulky *t*-butyl group and the chlorine atom is expected to be such that the conformation I having these two groups *trans* would be of appreciably lower energy than the corresponding *gauche* conformation II and III. If I is more populated in solution than II or III, the two $-CH_2Cl$ protons will be magnetically nonequivalent although chemically in-

I   II   III
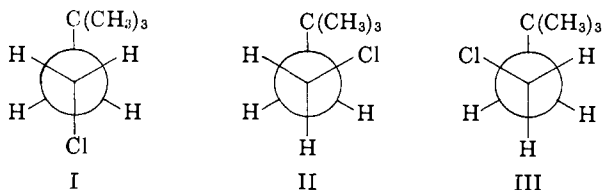
distinguishable, because any one of the $-CH_2Cl$ protons has *two different* coupling constants to the two $(CH_3)_3$-CCH_2- protons.

Observation of an AA'XX' spectrum is not compatible with an energetically favored *gauche* conformation, because a mixture of II and III would have only an averaged vicinal coupling constant if their interconversion were rapid, and would be expected to show an ABXY spectrum with appreciable chemical shift differences between the hydrogens of the methylene groups if interconversion were slow. The chemical shift between the two protons of each methylene group would of course be zero if interconversion between II and III were sufficiently rapid, even if the *gauche* conformers were energetically favored.

The size of the alkyl groups attached to the ethylene group in the other halides is much smaller than the *t*-butyl group of 3,3-dimethylbutyl chloride. Apparently the difference in energy between *trans* and *gauche* conformations for the alkyl halides not containing the *t*-butyl group is not large enough to produce significantly different vicinal coupling constants.

The n.m.r. spectrum of 3,3-dimethylbutyl Grignard reagent is much simpler than that of 3,3-dimethylbutyl chloride. The $-CH_2Mg$ resonance of this organometallic compound in diethyl ether solution at room temperature is a clean triplet, with $J = 9.1$ c.p.s. The chemical shift between the two methylene groups is approximately 123 c.p.s. (the resonance of the β-methylene group is partially hidden by the ether methyl peaks); the chemical shift of the $-CH_2Mg$ protons is 39 c.p.s. upfield from tetramethylsilane.

Addition of a stoichiometric excess of dry dioxane to an ether solution of this Grignard reagent removes most of the magnesium chloride as the insoluble magnesium chloride dioxanate,[13,14] leaving bis(3,3-dimethylbutyl)magnesium in solution. The amount of magnesium halide left in solution was not measured; however, Cope has reported that more than 99.6% of the halide ion present in ether solutions of phenylmagnesium bromide and methylmagnesium chloride is removed by dioxane precipitation.

The n.m.r. spectrum of bis(3,3-dimethylbutyl)magnesium in diethyl ether at $+33°$ is an AA'XX' spectrum (Figure 1). Chemical shift and coupling constant data obtained by analysis of the spectrum of this compound and of the spectra of the corresponding Gri-

gnard reagent and chloride are compared in Table I; details of these analyses are given in the Experimental section.

Table I. Chemical Shifts and Coupling Constants for the Ethylene Protons of 3,3-Dimethylbutyl Derivatives at 60.0 Mc.p.s. and 32°. Protons 1 and 2 are α to the Substituent X

$\nu_1 - \nu_3$[b]	I (X = Cl),[a] c.p.s.	II (X = MgCl),[c] c.p.s.	III (X = MgR),[d] c.p.s.
	103.2	−123	−128
J_{12}[e]	∓13.9	f	∓13.4
$J_{13} = J_{24}$[e]	±5.4	9.1	±4.2
$J_{14} = J_{23}$	±11.2	9.1	±14.0
J_{34}	∓10.7	f	∓12.5

[a] $10 \pm 1\%$ in carbon disulfide. [b] $\nu_1 - \nu_3 = \nu_2 - \nu_4$ by symmetry. [c] $10 \pm 2\%$ in diethyl ether, concentration estimated by comparing the area of the $-CH_2Mg$ resonance with that of the upfield ^{13}C methyl resonance of ether. [d] $5 \pm 1\%$ in diethyl ether containing approximately 5% dioxane. Concentration estimated as in *b*. [e] J_{12} and J_{34} are the two geminal coupling constants. [f] Geminal coupling constants cannot be obtained from an A_2X_2 spectrum of this type.

The data require that inversion of configuration at the $-CH_2Mg$ center of III is slow on the n.m.r. time scale, because fast inversion would result in an averaging of the vicinal coupling constants. Moreover, the magnitudes of the vicinal coupling constants make possible a qualitative estimation of the relative "size" of the $-MgR$ group and a chlorine atom, since the value of 14.0 c.p.s. observed for the larger vicinal coupling constant of bis(3,3-dimethylbutyl)magnesium suggests an average HCCH dihedral angle near $180°$.[15,16] Although the uncertainties associated with the use of coupling constants to obtain information about conformation populations are well known,[17] the lower value observed for the larger vicinal coupling constant of 3,3-dimethylbutyl chloride suggests that the *gauche* conformer has a relatively lower energy for this compound than for its alkylmagnesium analog. Although it is not possible to give a precise measure of this difference in size on the basis of available information, a slightly more quantitative description will be possible after the temperature variation of the spectra of these organometallics has been described.

The range of a variable-temperature examination of an ether solution of a Grignard reagent is limited by two considerations: at temperatures much below $-50°$ the solutions become too viscous to give interpretable spectra; at temperatures much above $+120°$, the possibility of explosion of the sample tube in the probe becomes important. This limited temperature range was fortunately large enough to yield several data important to the interpretation of the room-temperature spectra of the organomagnesium compound studied in the present work. In particular, the A_2X_2 spectrum observed for 3,3-dimethylbutylmagnesium chloride changes to an AA'XX' spectrum between $+20$ and $-60°$; correspondingly, the AA'XX' spectrum of bis(3,3-dimethylbutyl)magnesium collapses to an A_2X_2-type spectrum at $+110°$.

(13) M. S. Kharasch and O. Reinmuth, "Grignard Reactions of Nonmetallic Substances," Prentice-Hall Co., Inc., New York, N. Y., 1954, Chapter 4.
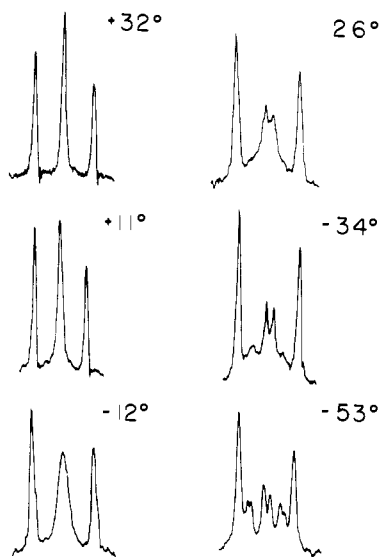(14) A. C. Cope, *J. Am. Chem. Soc.*, **57**, 2238 (1935); *ibid.*, **60**, 2215 (1938).

(15) M. Karplus, *J. Chem. Phys.*, **30**, 11 (1959).
(16) H. Conroy, "Advances in Organic Chemistry," Vol. 2, Interscience Publishers, Inc., New York, N. Y., 1960, pp. 265–328.
(17) M. Karplus, *J. Am. Chem. Soc.*, **85**, 2870 (1963).

Figure 2. N.m.r. spectra of the CH_2Mg protons of 3,3-dimethyl-butylmagnesium chloride in diethyl ether solution as a function of temperature.

Figure 3. N.m.r. spectra of the CH_2Mg protons of bis(3,3-dimethylbutyl)magnesium chloride in diethyl ether solution as a function of temperature.

The similarity of the spectral behavior of this Grignard reagent and its corresponding dialkylmagnesium compound demonstrates clearly that a temperature-dependent equilibrium between "RMgCl" and "R₂Mg" in solution (a Schlenk equilibrium) is not responsible for the variation in the spectra, because little or no

$$2RMgX \rightleftharpoons R_2Mg \cdot MgX_2 \rightleftharpoons R_2Mg + MgX_2$$
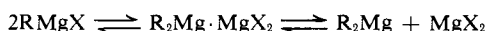
magnesium halide was present in the dialkylmagnesium solutions. This conclusion is reinforced by the observation that the spectrum of bis(3,3-dimethylbutyl)-magnesium prepared by reaction between halogen-free bis(3,3-dimethylbutyl)mercury and magnesium metal shows the same temperature dependence as that of the material prepared from 3,3-dimethylbutyl Grignard reagent by dioxane precipitation. Clearly, therefore, catalytic traces of magnesium halide are not important for the exchange reaction.

The averaged vicinal coupling constants observed at +33° for the Grignard reagent and at +110° for the dialkylmagnesium compound might be the result of either rapid inversion of configuration at the carbon carrying the magnesium (such inversion exchanging the magnetic environments of the hydrogens at the α-carbon atom) or else a change in relative populations of the conformations I, II, and III (if all conformations were equally populated and had the same gauche and trans couplings the CH_2 resonances would each be simple triplets).
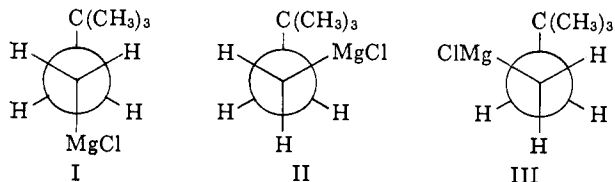
Ten of the twelve theoretical lines for the A part of an AA'XX' spectrum[12] can be identified in the low-temperature spectra of Figure 2 and 3. The 1,2 and 3,4 transitions are easily identified on the basis of intensity and position as the strong outer lines in these
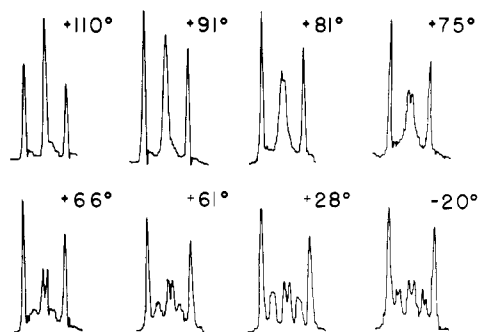
spectra; their separation is equal to the sum of the two vicinal coupling constants $J + J'$.[12] On the assumption[18] that trans and gauche coupling constants, J_t and J_g have the same respective values for each conformation (I–III), the separation of the outer lines for I should be $(J_t + J_g)$ while the corresponding separation for a rapidly interconverting mixture of II and III would be $1/2(J_t + 3J_g)$. The values reported in Table I permit a crude estimate to be made of the magnitude of J_t and J_g and consequently of the conformational populations of I, II, and III.

If x is the mole fraction of conformer I in solution, $1/2(1 - x)$ will be the corresponding mole fraction of conformer II and of conformer III. Assuming the trans coupling constant to be larger than the cis coupling constant.

$$J_{14} = xJ_t + (1 - x)J_g \qquad (1)$$

$$J_{13} = [x + 1/2(1 - x)]J_g + 1/2(1 - x)J_t =$$
$$1/2(1 + x)J_g + 1/2(1 - x)J_t \qquad (2)$$

In order to obtain an estimate of x, it is necessary to have values for J_t and J_g; these values cannot be obtained from the experimental data in Table I alone. However, the magnitude of the coupling constants in substituted ethanes can be correlated with the Huggins electronegativity[20] of the substituent by the relation[21]

$$J_{vic} = 7.9 - 0.7 (E_X - E_H) \qquad (3)$$

Assuming the difference in electronegativity between chlorine and magnesium to be approximately the same on the Huggins scale as on the Pauling scale ($E_{Cl} - E_{Mg} = 1.8$), the vicinal coupling constant in CH_3CH_2X would be predicted to increase by 1.3 c.p.s. on changing X from Cl to MgCl. The agreement between prediction and experiment suggests that there is nothing anomalous about the effect of the magnesium elec-

(18) There is little evidence on which to judge the reasonableness of this assumption. Gutowsky[19] has reported a difference of 4 c.p.s. between $J_g{}^{HH}$ for two different conformations of $CHCl_2CHFCl$. However, as these authors have noted, the treatment neglects any variation in chemical shift with temperature due to changes in solvation and is therefore somewhat suspect. Fortunately, the magnitudes of the coupling constants observed for our organometallics suggests that they exist predominantly in conformation I, and consequently that only one kind of J_g is important.

(19) H. S. Gutowsky, G. G. Belford, and P. E. McMahon, J. Chem. Phys., 36, 3353 (1962).

(20) M. L. Huggins, J. Am. Chem. Soc., 75, 4123 (1953).

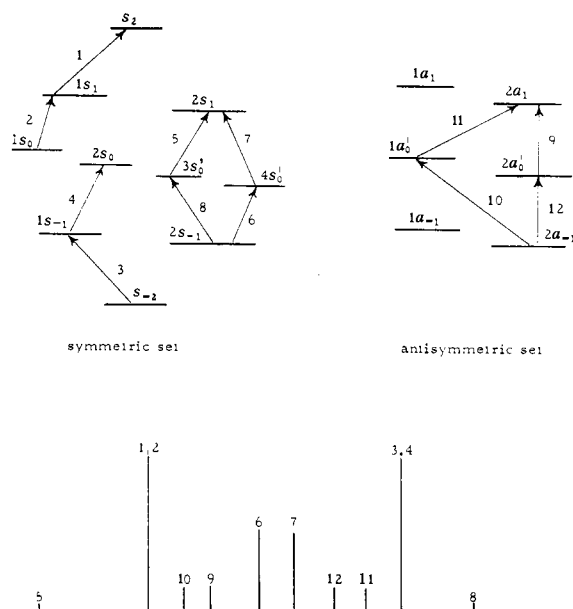(21) C. N. Banwell and N. Sheppard, Discussions Faraday Soc., 34 (1962).

Figure 4. Schematic energy-level diagram and transition assignments for bis(3,3-dimethylbutyl)magnesium.

$J_{vic}^{CH_3CH_2Cl} = 7.23$ c.p.s.[22]; $J_{vic}^{CH_3CH_2MgCl} = 8.6$ c.p.s.

$J_{vic}^{CH_3CH_2Br} = 7.33$ c.p.s.[22]; $J_{vic}^{CH_3CH_2MgBr} = 8.6$ c.p.s.

tronegativity on the vicinal coupling constants, and consequently that eq. 3 might be used to estimate J_t and J_g in bis(3,3-dimethylbutyl)magnesium from structurally similar ethanes.

A more sophisticated equation developed by Bothner-By from statistical evaluation of the effect of substituents on vicinal coupling constants indicates that J_g and J_t should have the values 4.5 and 14.7 c.p.s., respectively, for 3,3-dimethylbutylmagnesium chloride.[23] Although these values are probably both too large by approximately 0.5 c.p.s. (see the observed value for J_{13} in bis(3,3-dimethylbutyl)magnesium), they strongly suggest that this Grignard reagent exists almost entirely in the conformation with magnesium atom and t-butyl group *trans*.

With approximate values of J_t and J_g for bis(3,3-dimethylbutyl)magnesium, we are in a position to decide whether changes in the conformational populations I, II, and III or change in the rate of inversion at the α-carbon atom is responsible for the variation in the spectra of 3,3-dimethylbutylmagnesium chloride and bis(3,3-dimethylbutyl)magnesium with temperature. The separation of the strong outer lines of the room-temperature spectrum of bis(3,3-dimethylbutyl)magnesium is $(J_{13} + J_{14})$ and corresponds approximately to 1.0 mole fraction of the *trans* conformation I. At $+110°$, the spectrum is a triplet. Abraham and Bernstein have shown that if

$$J - J' < [2\Delta\nu_{1/2}(J_A - J_X)]^{1/2} \qquad (4)$$

the A part of an AA'XX' spectrum will appear as a triplet ($\Delta\nu_{1/2}$ is the width at half-height of the component lines).[24] In the present case, $\Delta\nu_{1/2} = 0.9$ c.p.s.

and $J_A - J_X = 1.2$ c.p.s.; consequently, eq. 4 will be satisfied if $J_{14} - J_{13} < 1.5$ c.p.s. As shown by Abraham and Pachler[25] the value of $3/2N + 1/2L$ should be independent of the population of the rotational isomers; N represents $J + J'$ and L is equal to $J - J'$ (negative if the *trans* conformer is more stable). In the case of bis(3,3-dimethylbutyl)magnesium, the separation between the outer lines (N) should therefore change from 18.0 c.p.s. at room temperature to 14.7 c.p.s. at $+110°$ if the internal rotation is responsible for the averaging of the vicinal coupling constants. This behavior is clearly illustrated by the calculated spectra in Figure 6 (see below for a discussion of the assumptions involved in the calculations).

If the inversion of configuration at the $-CH_2Mg$ center is responsible for the averaging, the separation of the outer lines (N) should remain approximately constant.

Experimentally, the temperature variation in the separation of the 1,2 and 3,4 transitions is small. This separation in the spectrum of bis(3,3-dimethylbutyl)-magnesium remains unchanged at 18.0 ± 0.2 c.p.s. from $+33$ to $+110°$; the corresponding separation in 3,3-dimethylbutylmagnesium chloride changes only from 18.2 ± 0.1 at $+33°$ to 18.4 ± 0.3 c.p.s. at $-50°$.

These data are incompatible with a temperature-dependent variation in populations of the conformers of sufficient magnitude to explain the averaging of the vicinal coupling constants and indicate that changes in the rate of inversion are responsible for the changes in the spectra.

This conclusion has been confirmed by comparison of the observed spectra with spectra explicitly calculated for an AA'XX' spectrum in which the two A protons are exchanging by a process whose rate constant is approximately the same order of magnitude as the sum of the vicinal coupling constants. These calculations, based on the density-matrix approach suggested by Kaplan[26] and developed by Alexander,[27] are lengthy and will be published in detail elsewhere. The important results are however listed below, along with a calculation of the activation parameters for the exchange process obtained from these calculations.

The schematic spectrum and energy-level diagram for the AA'XX' spectrum is given in Figure 4. The symmetric and antisymmetric sets are separated for clarity. Transitions for the A protons are numbered to correspond to the schematic spectrum below.

The exchange process which determines the appearance of the spectrum of these organometallics is an interchange of the two α-protons. The effect of this exchange is to average the two vicinal coupling constants J and J'.[28] In the slow-exchange limit, $L = J + J'$ will be different from zero (in the particular case of bis(3,3-dimethylbutyl)magnesium in diethyl ether solution at room temperature, $L = 9.8$ c.p.s.); in the

(22) See S. Ebersole, S. Castellano, and A. A. Bothner-By, *J. Phys. Chem.*, **68**, 3430 (1964).

(23) A. A. Bothner-By, seminar given at Harvard University, January 21, 1964.

(24) R. J. Abraham and H. J. Bernstein, *Can. J. Chem.*, **39**, 216 (1961).

(25) R. J. Abraham and K. G. R. Pachler, *Mol. Phys.*, **7**, 165 (1964).

(26) J. I. Kaplan, *J. Chem. Phys.*, **28**, 278 (1958); *ibid.*, **29**, 462 (1958).

(27) S. Alexander, *ibid.*, **37**, 967, 974 (1962); *ibid.*, **38**, 1787 (1963). Variations of this technique have been used to obtain thermodynamic parameters for several rate processes involving n.m.r. spectra complicated by spin-spin splitting. See for examples J. Heidberg, J. A. Weil, G. A. Janusonis, and J. K. Anderson, *ibid.*, **41**, 1033 (1964); R. J. Kurland and W. B. Wise, *J. Am. Chem. Soc.*, **86**, 1877 (1964); M. Saunders and F. Yamada, *ibid.*, **85**, 1822 (1963); C. S. Johnson, Jr., and J. C. Tully, *J. Chem. Phys.*, **40**, 1744 (1964), and references in each.

(28) The notation used in this section will be that of Chapter 6 of ref. 12a.

fast-exchange limit, L will be zero. Examination of the energies of an AA'XX' spectrum reveals that only the $3s_0'$, $4s_0'$, $1a_0'$, and $2a_0'$ levels depend on L. These are given in Table II.

Table II. Selected Stationary-State Wave Functions and Energies of an AA'XX' System

State	Energy
$3s_0'$	$-\frac{1}{2}K - \frac{1}{2}(K^2 + L^2)^{1/2}$
$4s_0'$	$-\frac{1}{2}K + \frac{1}{2}(K^2 + L^2)^{1/2}$
$1a_0'$	$-\frac{1}{2}K + \frac{1}{2}(M^2 + L^2)^{1/2}$
$2a_0'$	$-\frac{1}{2}K - \frac{1}{2}(M^2 + L^2)^{1/2}$

Here, $K = J_A + J_B$, $L = J - J'$, $M = J_A - J_B$, $N = J + J'$.

Rapid exchange would therefore be predicted to average transitions between symmetric states with $|F_z| = 1$ and the $3s_0$ and $4s_0$ states, and correspondingly between antisymmetric states with $|F_z| = 1$ and the $1a_0$ and $2a_0$ states.

Our approach to this problem was to assume that the symmetric quartet (lines 5, 6, 7, and 8) and the antisymmetric quartet (lines 9, 10, 11, and 12) could be separated and treated individually. Since the 1,2 and 3,4 transitions involved energy levels which are not appreciably affected by the exchange process, line shapes for these transitions were assumed to be unchanged and were not calculated explicitly. The total spectrum was obtained for each value of the pre-exchange lifetime τ[29] by adding the line-shape functions for the symmetric quartet, the antisymmetric quartet, and the 1,2 and 3,4 transitions.

Using as the basis set for the quartet of antisymmetric transitions a correctly antisymmetrized combination of basic product functions and proceeding through the procedure outlined by Alexander, it becomes clear that the temperature dependence of the antisymmetric quartet can be treated as if it were an AB-type quartet with an "apparent chemical shift" equal to L and an "apparent AB coupling constant" equal to M. The symmetric quartet can be treated in an analogous fashion, using an apparent chemical shift equal to L and an apparent AB coupling constant equal to K. Line shapes were calculated separately for each of these quartets at several values of τ, making the assumption that $1/T_2$ (approximately the natural linewidth in the absence of exchange) remained unaffected by the exchange process or by variation in temperature.

A selection of some 25 summed spectra[30] calculated using these assumptions are shown in Figure 5. Qualitatively, two features of these spectra are of particular interest. First, the asymmetric transitions broaden and coalesce appreciably before the two observable symmetric transitions (lines 6 and 7). Although the two weak symmetric transitions (lines 5 and 8) are of low

(29) In these spectra, τ is the lifetime of a proton at each site. Note that this τ is twice that used by Gutowsky and Holm in their classic treatment of exchange processes in n.m.r, based on the Bloch equations: cf. H. S. Gutowsky and C. H. Holm, *J. Chem. Phys.*, **25**, 1228 (1956).

(30) These spectra were made up with the aid of a program written for an IBM 7094 computer equipped with a curve plotter which calculates theoretical spectra for AB systems with A and B exchanging as a function of τ, chemical shift, J_{AB}, and $T_2[T_2(A)$ assumed to be equal to $T_2(B)]$. This program was developed by Mr. Jesse L. Beauchamp (Undergraduate Thesis, California Institute of Technology, 1964) and has been extended in usefulness by Dr. J. Thomas C. Gerig.
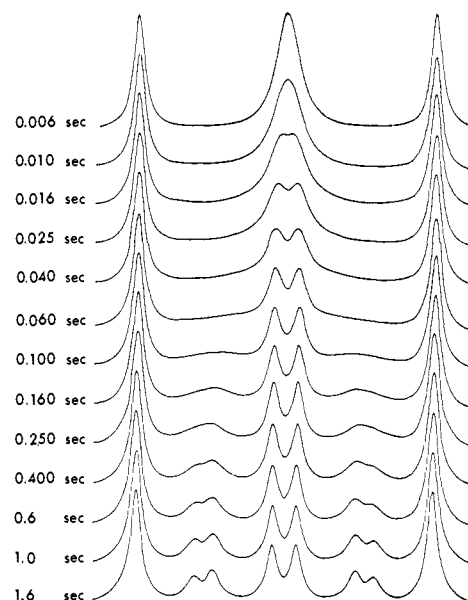

Figure 5. Calculated line shapes for the six central lines of the A part of the AA'XX' spectrum of 3,3-dimethylbutylmagnesium compounds, at different values of the pre-exchange lifetime τ. The parameters used and the method of calculation are described in the text.

intensity and are not shown in the calculated spectra, these lines also broaden and coalesce much more rapidly than the 6 and 7 transitions. The difference in response of the calculated line shapes of transitions involving energy levels which are affected by the exchange process is clearly evident in the experimental spectra; the two center lines of the symmetric quartet coalesce at an appreciably higher temperature than do the transitions belonging to the antisymmetric quartet. Second, the transitions (1,2 and 3,4) which did not involve the $3s_0'$, $4s_0'$, $1a_0'$, and $2a_0'$ energy levels were assumed to be independent of the exchange process; in consequence, the line width and position of these transitions does not change over the range of τ shown in Figure 5. Examination of the observed spectra indicates that the line width of these lines is in fact independent of τ to a very good approximation, and suggests that any mixing of the $1s_0$ and $2s_0$ states with the other $F_z = 0$ states is probably of small importance. Thus the approximation that the 1,2 and 3,4 transitions can be regarded as independent of the exchange appears to be justified.

The close agreement between the relative sensitivity of the different transitions to the exchange process provides another confirmation that exchange rather than change in conformational populations is responsible for the observed simplification of the spectra at high temperatures. Figure 6 reproduces the spectra that would have been expected on the basis of major changes in conformational populations. These spectra were calculated on the assumption that the sum of the larger vicinal coupling constants and twice the smaller vicinal coupling constant would be a constant independent of rotamer populations.[25]

As the value of L is decreased in these spectra, the corresponding decrease in the separation between the 6 and 7 transitions is approximately proportional to the decrease in the separation between the 9,10 and 11,12
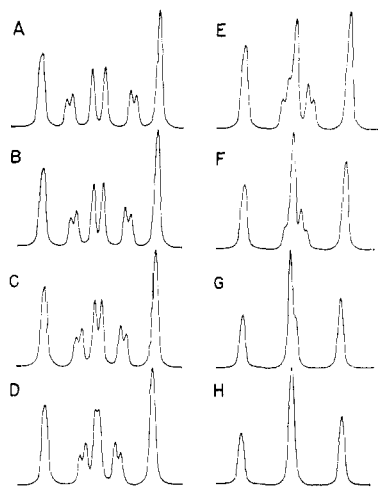
Figure 6. Calculated spectra for the A part of an AA'XX' spectrum as a function of the vicinal coupling constants J and J', respectively (in c.p.s.): A, 14.0, 4.2; B, 13.0, 4.7; C, 12.0, 5.2; D, 11.0, 5.7; E, 10.0, 6.2; F, 9.0, 6.7; G, 8.0, 7.2; H, 7.8, 7.8. In all of these spectra, $\nu_A - \nu_B = 128.00$; $J_{AA} = -13.40$ and $J_B = -12.50$. The variations of J and J' were made so as to have $J + 2J' = 22.4$.
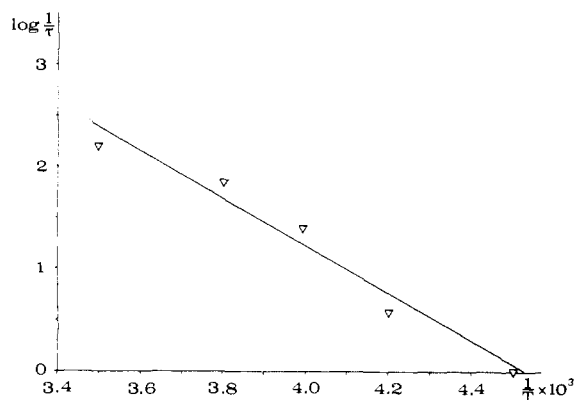

Figure 7. Plot of log $(1/\tau)$ as a function of $1/T$ for 3,3-dimethylbutylmagnesium chloride.

transitions. In other words, corresponding separations between transitions within the symmetric and antisymmetric quartets would be equally to responsive to changes in conformer populations. This conclusion seems particularly reasonable if the transitions under discussion are considered as the superposition of two AB quartets, each having an effective chemical shift of L. As L is decreased, the changes in the two quartets would be expected to be roughly parallel.

Moreover, the spectra of Figure 6 indicate that no line-broadening effects would be expected, were changes in conformations responsible for the simplification of the spectra. For example, the separation between the 9 and 10 transitions remains clearly visible until these lines merge with the 6,7 transitions in the calculated spectra. By contrast, the separation between the 9 and 10 transitions in the observed spectra is lost in the broadening of these lines appreciably before the lines collapse. This behavior is in agreement with the spectra calculated on the basis of exchange between the two A protons. Strictly speaking, the treatment used in this paper does not identify whether the protons taking part in the exchange are those α or β to the
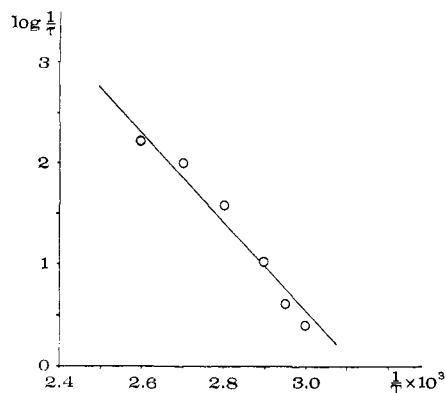

Figure 8. Plot of log $(1/\tau)$ as a function of $1/T$ for bis(3,3-dimethyl-butyl)magnesium.

magnesium atom; however, intramolecular exchange of the β-protons would seem chemically much less probable than exchange involving the α-protons.

Qualitatively, the spectra calculated from Alexander's treatment of exchange broadening confirm that the temperature dependence of the spectra of the 3,3-dimethylbutylmagnesium compounds is a primary consequence of the rate of intramolecular interchange of the two α-protons, and not of a change in any conformational equilibrium associated with these compounds. The problem of obtaining quantitative values for the activation parameters for the exchange process is not so straightforward.

The procedure adopted here was to calculate theoretical spectra for a large number of values of τ spanning the range of pre-exchange lifetimes, and then to compare the observed spectra with the calculated to obtain the observed dependence of τ on temperature. Activation parameters for the exchange process were then obtained from plots of $1/\tau$ vs. $1/T$ by the familiar treatment based on the Arrhenius equation

$$1/\tau = k$$

$$k = Ae^{-E_a/RT}$$

where k is the rate constant for the exchange process, E_a is the activation energy for the process, and A is the pre-exponential term.

Figures 7 and 8 are plots of log $(1/\tau)$ vs. $1/T \times 10^3$ for bis(3,3-dimethylbutyl)magnesium and 3,3-dimethylbutylmagnesium chloride in diethyl ether solution. These plots are reasonably linear. The slope of the plot for bis(3,3-dimethylbutyl)magnesium yields an activation energy of $E_a = 20 \pm 2$ kcal./mole; its intercept at $T = 45° (1/T = 3.14 \times 10^{-3})$ yields a value for the pre-exponential factor of $A = 10^{13.5 \pm 1.5}$. The corresponding values for 3,3-dimethylbutylmagnesium chloride are $E_a = 11 \pm 2$ kcal./mole[31] and $A = 10^{9.5 \pm 1.5}$ (Tables III and IV).

The magnitude of experimental uncertainty in these values is a consequence of errors in making comparison between the theoretical spectra and the experimental ones, where the background noise makes the assignments less accurate for broad resonance peaks.

(31) In a recent communication, G. Fraenkel, D. T. Dix, and D. G. Adams, *Tetrahedron Letters*, 3155 (1964), give $E_a = 12 \pm 1$ kcal. for inversion of 2-methylbutylmagnesium bromide, in good agreement with the value reported here.

Table III. Rate of Inversion of Configuration for Bis(3,3-dimethylbutyl)magnesium

Temp., °C.	$1/T$ (°K.) $\times 10^3$	τ	Log $1/\tau$
110	2.6	0.006	2.2
91	2.7	0.010	2.0
81	2.8	0.016	1.8
75	2.9	0.10	1.0
66	2.95	0.25	0.6
61	3.0	0.4	0.4

Table IV. Rate of Inversion of Configuration for 3,3-Dimethylbutylmagnesium Chloride

Temp., °C.	$1/T$ (°K.) $\times 10^3$	τ	Log $1/\tau$
+11	3.5	0.006	2.2
−12	3.8	0.016	1.8
−34	4.2	0.25	0.60
−53	4.5	1.0	0.00

Experimental

Apparatus and Materials. The n.m.r. spectra were obtained at 60 Mc.p.s. using a Varian Associates Model A-60 spectrometer for the bulk of the room-temperature spectra, and a Varian Associates V-4300B spectrometer for the variable-temperature work. Temperature control in the probe of the latter instrument was achieved by blowing dry nitrogen gas at a selected temperature over the sample and insert through an appropriate dewar system. Temperatures could be maintained constant within a degree for 15–20 min. if several minutes were allowed for equilibration following a change of temperature. Most temperatures reported are estimated to be accurate to ±2°.

Measurement of line positions was accomplished by the usual side-band method using a Hewlett-Packard Model 200AB audio-oscillator and Model 521-C frequency counter, when accurate measurement were required. For the majority of spectra run in diethyl ether, however, it was found more convenient to use the triplet resonance of the upfield ^{13}C satellite of the solvent methyl protons to calibrate the chart sweep rate. The vicinal coupling constant in diethyl ether is 6.97 c.p.s.[22] This signal occurs conveniently 10–50 c.p.s. downfield from the α-methylene resonance of the organometallic compounds. In addition, comparison of the intensity of the ^{13}C satellite resonance with that of the organometallic provides a direct measure of the concentration of the latter, because the concentration of naturally abundant [13]$CH_3CH_2OCH_2CH_3$ in diethyl ether is known to be 2.2%. Comparison of the linewidth of the ^{13}C satellite resonances with that of the organometallic compound furnishes a simple if crude method of estimating the relative importance of exchange broadening and other less interesting broadening effects such as viscosity broadening and broadening due to field inhomogeneity.

Instrument settings for these spectra were unexceptional, except that a high radiofrequency power level and a broad filter band width were necessary for satisfactory signal to noise ratios when low concentrations of organometallic compound were used. Consequently, in some dilute samples there was evidence of signal saturation, but ordinarily this was not important in determining line shapes. Spinning noise seemed to be the principal source of noise at low temperatures, and was particularly objectionable with warped sample tubes.

The magnesium used in these Grignard reagent preparations was in the form of turnings from a bar of resublimed metal. An analysis of this material was kindly supplied by Dr. Ronald R. Weyenberg of Dow-Corning Corp.: Al, <0.0039; Ba, <0.0004; Ca, 0.0010; Co, <0.0020; Cu, <0.0004; Cr, <0.0004; Fe, 0.022; Mn, <0.0004; Ni, <0.0020; Pb, 0.0027; Si, <0.0078; Sn, <0.0020; Sr, <0.0004; Ti, <0.0020; V, <0.0020; and Zr, <0.0039. Use of ordinary "Grignard grade" magnesium was found to give broad poorly resolved n.m.r. spectra, apparently due to the presence of paramagnetic impurities in solution.

Mallinckrodt anhydrous ether was used without further purification. Tetrahydrofuran and diglyme were dried by distillation from sodium and stored over sodium or Linde Type 5A Molecular Sieves prior to use. Dioxane was distilled from lithium aluminum hydride and stored over sodium. 3,3-Dimethylbutyl chloride was obtained from the Eastern Chemical Corp., and was used without further purification.

Preparation of Grignard Reagents. All Grignard reagents examined were prepared in n.m.r. tubes, following the same general procedure. To a clean, dry n.m.r. tube containing approximately 50 mg. of magnesium turnings was added 0.1 ml. of solvent and 0.1 ml. of alkyl halide by means of a 0.5-ml. syringe. Reaction was initiated by punching the magnesium with a sharpened tantalum rod; then 0.4 ml. more solvent was added and the tube was capped temporarily. When the initial vigorous reaction had subsided, the neck of the n.m.r. tube was cleaned with a pipe cleaner and the tube sealed to give a strong rounded end. The tube was then placed in a steam bath and heated at 100° for 6–10 hr. with occasional shaking. The actual heating time did not appear to be critical, but at least 4 hr. of heating was required for high yields of Grignard reagent. There was no evidence of decomposition of the Grignard reagents at this temperature.

After heating, the tube was cooled and centrifuged for 10–120 min. at 1600 r.p.m. using an International Equipment Co. Size 2 centrifuge with a Type 267 head. The centrifuge buckets were packed with towels to accommodate the n.m.r. tube. Centrifugation was continued until the solution was completely free of visible magnesium chips and suspended solids. The length of time required depended on the nature and quantity of solids present in the tube and on the solvent. The tube was positioned in the centrifuge so that the solids would be centrifuged into the upper end of the tube; spectra were obtained after centrifugation by decanting the clear solution away from the packed solids into the bottom end of the tube, and proceeding in the usual manner.

Grignard reagent solutions prepared in this manner in ether solution were perfectly colorless with approximately the same viscosity as water.

No rigorous efforts were made to dry the n.m.r. tubes or the magnesium used in these studies, nor was an effort made to carry out the reactions under an inert atmosphere. In the short periods in which the n.m.r.

tubes were open to the atmosphere (as during the cleaning and sealing operations) the Grignard reagent solutions were probably adequately protected by the 10-cm. column of ether vapor above the solution in the n.m.r. tube.

Dialkylmagnesium solutions were prepared from the corresponding Grignard reagents by opening the n.m.r. tube, adding 100 μl. of dry dioxane and then capping and shaking the tube. The dioxane addition resulted in immediate production of a voluminous white precipitate in such quantity that the sample frequently became almost solid.

The neck of the tube was cleaned with pipe cleaner and sealed in the usual manner. After sealing, the solution was allowed to stand in contact with the precipitate for 10–12 hr. with frequent shaking and then centrifuged in the manner described previously. Centrifugation at 1600 r.p.m. (3 to 4 hr.) were frequently required to compact completely the voluminous precipitate of magnesium halide dioxanate. The volume of the compacted precipitate was usually approximately one-third that of the original Grignard reagent solution. This precipitate was usually removed from dialkylmagnesium samples to be examined at high temperature by cutting off the part of the tube containing the precipitate and immediately sealing the tube again.

Yields of Grignard reagent in diethyl ether solution were estimated to be 85–95%, by comparison with the ^{13}C satellite of ether.

Analyses of n.m.r. spectra were performed using an iterative program.[32] The solution for 3,3-dimethylbutyl chloride (and by inference for bis(3,3-dimethylbutyl)magnesium) is not unique; an equally close fit between observed and calculated spectra could be obtained using all positive signs for the coupling constants. In the latter solution, the magnitudes J_{12} and J_{34} were different than those reported in Table I; the magnitudes of the vicinal coupling constants were the same.

(32) J. D. Swalen and C. A. Reilly, *J. Chem. Phys.*, 37, 21 (1962).

Nuclear Magnetic Resonance Spectroscopy.   Temperature Dependence of the Spectrum of Fluorocyclooctatetraene[1]

Donald E. Gwynn, George M. Whitesides, and John D. Roberts

Contribution No. 3184 from the Gates and Crellin Laboratories of Chemistry, California Institute of Technology, Pasadena, California. Received March 5, 1965

The fluorine n.m.r. spectrum of fluorocyclooctatetraene has been shown to be temperature dependent between 30 and $-65°$. This is attributed to changes in the rate of an inversion–bond-shift process which is slow on the n.m.r. time scale at low temperatures. The free energy of activation for inversion is approximately 12 kcal./ mole at $-33°$.

Cyclooctatetraene and some of its derivatives appear to undergo inversion with or without accompanying bond shifts (most likely through considerably strained planar intermediates or transition states). The activation energy required for this kind of dynamic process is of considerable theoretical interest.[2] Anet and co-workers[2a,b] and Whitesides[3] have shown that the rate of establishment of the equilibrium represented by Ia $\rightleftarrows$ Ib can be studied by n.m.r. spectroscopy. In a further investigation of this phenomenon, we have investigated the temperature dependence of the fluorine n.m.r. spectrum of fluorocyclooctatetraene (II).

Fluorocyclooctatetraene was prepared for this study in 10% yield by reaction of perchloryl fluoride with an ethereal solution of cyclooctatetraenyllithium at $-75°$. The product was purified by preparative gas chromatog-

Ia, R = H
IIa, R = F

III

Ib, R = H
IIb, R = F
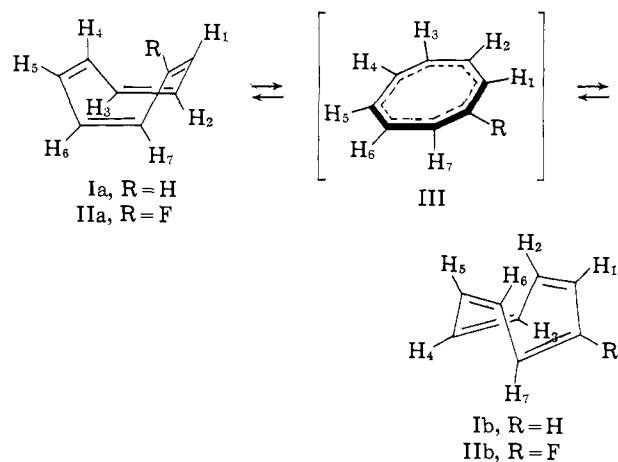
raphy and the structure was confirmed by spectroscopic evidence. The proton n.m.r. spectrum of II showed a main signal at 345 with much weaker peaks at 329

II
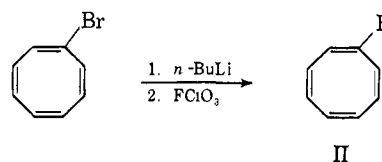
and 322 c.p.s. This spectrum is compatible with a structure possessing only olefinic hydrogens. The ultraviolet spectrum of II with strong end absorption at 220 mμ and a broad λ_{max} at 285.5 mμ (ϵ 225) very

(1) Supported in part by the Office of Naval Research.

(2) (a) F. A. L. Anet, *J. Am. Chem. Soc.*, 84, 671 (1962); (b) F. A. L. Anet, A. J. R. Brown, and Y. S. Lin, *ibid.*, 86, 3576 (1964); (c) K. Mislow and H. D. Perlmutter, *ibid.*, 84, 3591 (1962); (d) N. L. Allinger, *J. Org. Chem.*, 27, 443 (1962).

(3) G. M. Whitesides and J. D. Roberts, unpublished results, California Institute of Technology; *cf.* J. D. Roberts, *J. Vsuesnoe Chem.* (USSR), 7, 367 (1962).